MOTT MACDONALD

NORTH NORFOLK DISTRICT COUNCIL

COASTWISE

Understanding water and cliff failure at Happisburgh

May 2025

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May 2025

Issue and Revision Record

Revision	Date	Originator	Checker	Approver	Description
P01	17/04/2025	C. Davis / L. Salmon	G Mason	A. Drake	DRAFT issue for comment
P02	16/05/2025	C. Davis / L. Salmon	G Mason	A. Drake	Updated following client comments

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Contents

1 Introduction

Mott MacDonald has been commissioned by North Norfolk District Council (NNDC) to undertake a focused investigation into understanding water and cliff failure at Happisburgh.

The project is part of Coastwise, an initiative being delivered by NNDC, which is nationally funded scheme, through the Coastal Transition Acceleration Programme, funded by DEFRA and the Environment Agency.

The study area is described as per the client request document which states, "Approximate area to be included in the assessment is the main part of the village of Happisburgh, including Whimpwell Street, Lantern Lane, Grubb Street to Lantern Lane junction, North Walsham Road to Blacksmiths land junction, Blacksmiths Lane, Church Street, Beach Road, and land to the cliff from west of old caravan park site to 300m east of lighthouse. Note that investigations may identify that some areas have limited relevant drainage assets and can then be excluded and that some relevant areas of interest may extend beyond to indicative area."

A visual representation of the study area is present in Figure 1-1.

Figure 1-1: Annotated study area map

Source: Satellite imagery taken from Bing maps @ 2025 Microsoft

1.1 Objectives

- To draw together existing technical knowledge alongside seeking local knowledge to better inform local understanding of the relationship between water and cliff failures at Happisburgh.
- To summarise and present this knowledge in a clear and accessible way.
- To identify limitations, issues and risks associated with the current drainage system.

This report presents a summary of the relationship between water and cliff failure at Happisburgh. The following pages of this report will cover the following topics:

- Summary of existing technical and scientific knowledge, local knowledge from the community members, impact from sewers and drains, and rainfall data.
- An account of the relationship between water and cliff failures between Happisburgh.
- Realistic practical approaches that may assist with managing water locally in order to seek to potentially manage the rate of cliff failures.

1.2 Report format

This report presents a summary of the research undertaken by Mott MacDonald to present the data in a clear and accessible way.

1.3 Limitations

While undertaking research for the project, every external contact has been extremely helpful but there have been some constraints on the information available. Below is a list of the limitations from the research:

- Historical boreholes – the majority of the publicly available boreholes on BGS GeoIndex were for water wells and not logged in detail so individual superficial layers were not recorded. Therefore, building an accurate 3D ground model could not be undertaken.
- Recorded landslides – only three landslides were publicly available on BGS GeoIndex, with only one provided a date of the event. Minor landslides or cliff failures have limited recorded dates. Therefore, building a trend of cliff failure and rainfall was challenging.

Please note that the impact of coastal processes on the stability of the cliffs is not considered in this report as it is outside the scope of works for Mott MacDonald. Furthermore, the options presented later do not consider any work to improve coastal protection or reinforce / stabilise the existing cliff slopes (i.e. with anchors) as they are not considered to be realistic practical measures in the context of the site and Mott MacDonald's scope of works.

Additionally, some of the options presented may be outside of the scope of Coastwise's current funding remit and would require further discussion with DEFRA, EA and other funders.

1.4 Potential constraints

The study area in Happisburgh is within the vicinity or nearby several significant constraints. Each option has considered (at a high level) the environmental designations but consultation with the respective organisation has not been undertaken as it is outside the scope of work.

The list below highlights some of the most significant constraints. Specialist input and further work is required to identify the full list of constraints and stakeholders once the preferred option(s) have been identified.

Significant site constraints include:

- Sites of special scientific interest (SSSI) – Natural England has designated part of the cliffs as a SSSI for geological features and dating the Pleistocene succession of East Anglia https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1001304.pdf.
- This site is designated as a Geological Conservation Review (GCR) site by virtue of these features of geological interest, including the Pleistocene deposits of East Anglia.
- Source Protection Zone (SPZ) – Approximately 2km south-west of the study area, the ground is designated a SPZ (Zone III). Approximately 9km to the north-west, the ground is designated a SPZ (Zone I to III) to safeguard drinking water quality through constraining the proximity of an activity that may impact upon a drinking water abstraction. The underlying chalk (at depth) in the study area could have a flow direction to the source of the water extracted in Mundesley.
- Shoreline Management Plan (SMP) – The site is within the Environment Agency's SMP 6 (Ostend to Eccles 6.12) and the current approach is set as Managed Realignment (MR6), where the overall intention is for a natural shoreline, not to encourage new defences. In some areas, where specified in the SMP, works to repair or construct short stretches of defence to provide localised protection (such as to a slipway, access point or isolated properties) may be considered by the Local Planning Authority. All works require relevant permissions. Ostend to Eccles 6.12 | Shoreline Management Plans
- Proposed landfall location – Vattenfall's Norfolk Vanguard and Norfolk Boreas projects are proposed to have landfall compounds in the south Happisburgh with the cables connecting to Necton. Proposed cable and compound locations will need to be considered for the optioneering.

2 Existing technical knowledge on water driven cliff failures

This section of the report will summarise the main areas of research in relation to water and cliff failures in the study area. The general scope of works for the research followed these topics:

- Draw together key existing technical and scientific knowledge of water driven cliff failures at Happisburgh.
- Pull together local knowledge from community members on the matter including relevant historical water management at Happisburgh.
- Identify limitations, issues and risks associated with the current drainage system.
- Investigate how ground and surface water impact cliff erosion at Happisburgh.

Groundwater and surface water flow significantly impacts the cliff slope stability. Therefore, research into the nature and occurrence of water flow is required. Below is a list of the potential sources of water inflow and water outflow in the study area:

Water inflow

- Rainfall onto:
  - Fields
  - Trees/vegetation
  - Roads
  - Roofs/gardens
  - Cliff slope
- Domestic water piped into the area:
  - Water or sewer pipe leaks
  - Soakaways
- Groundwater borehole pumping from deep aquifer:
  - Used for irrigation of fields

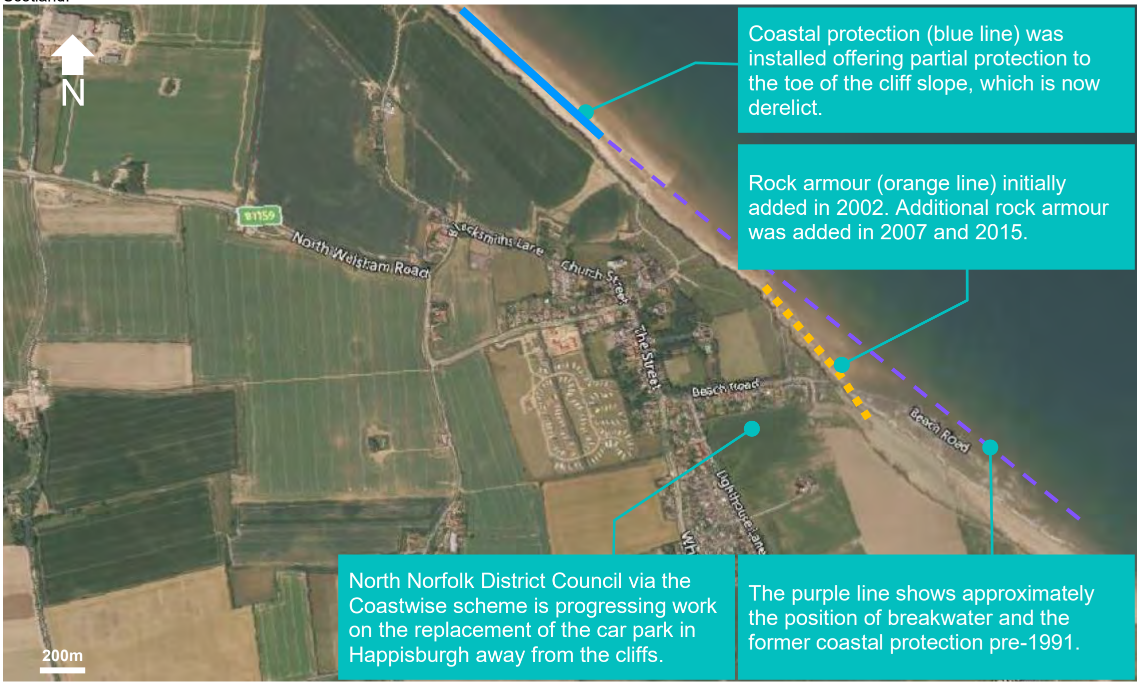
Water outflow

- Water infiltration into shallow and perched groundwater
- Surface water flow onto cliffs
- Underlying deep groundwater chalk aquifer
- Surface water flow inland
- Evaporation
- Transpiration (plants)

The following sections assess the characteristics of these water sources in relation to the ground and environment.

2.1 Summary of change in land use

Source: An extract from Norfolk Sheet XXX.NW, revised: 1905, published: 1907. Historical map reproduced with the permission of the National Library of Scotland.

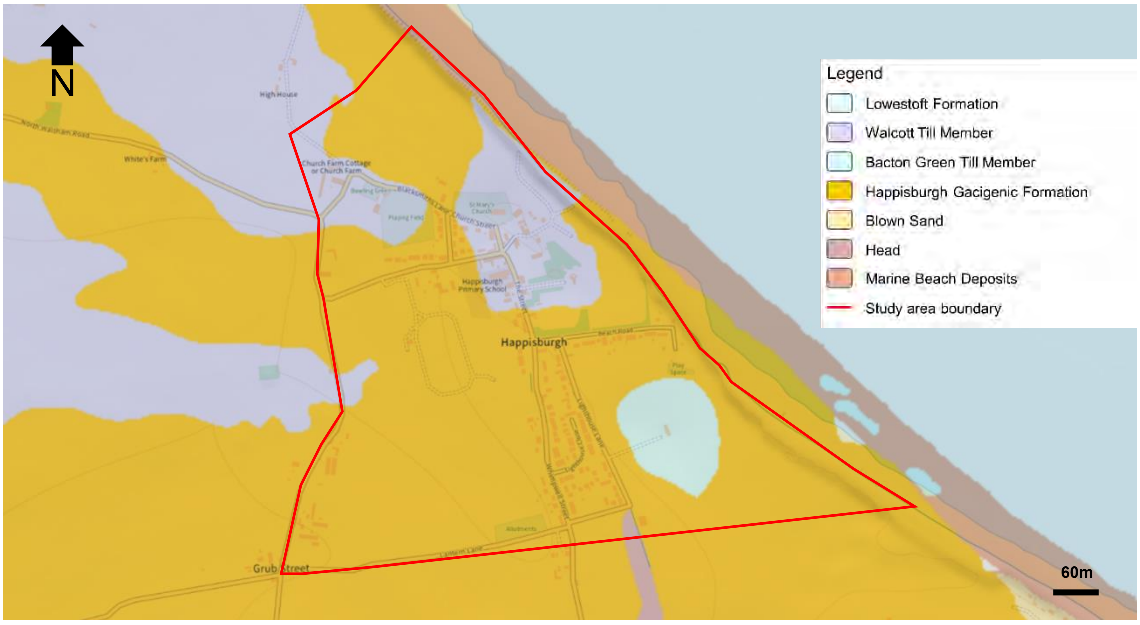


Source: Aerial image from ESRI ArcGIS World Imagery. Note – only recent and significant land use changes have been highlighted.

The study area and surrounding land has a long history of farming. The main land changes identified were from properties and infrastructure loss from cliff regression, the relocation of properties and the coastal protection starting in the 1950s. The Manor Caravan Park arrived in 1960s along the coast and moved to a new inland site in 2019. Coastal protection is now nearing the end of its effective life and intervention was required with rock armour placed in 2002, 2007 and 2015.

From the earliest available mapping in 1885, most of the area was used for farming. This was in small, privately owned parcels of land. It is likely that during the 1960s that the fields were expanded by the combination of multiple small fields into bigger fields (farmland consolidation). Previous field boundaries (e.g. hedgerows and possibly drainage) which would have reduced the flow of surface runoff were lost in farmland consolidation.

2.2 Onshore surface geology of the area



Source: Onshore superficial geology reproduced from BGS Geology - 50k (DiGMapGB-50) Bedrock version 8 published by British Geological Survey (BGS).

A layered sequence of superficial geology deposited in the Quaternary Period is controlling the slope stability and groundwater levels.

The British Geological Survey (BGS) mapping and borehole log database Onshore GeoIndex has been used to supplement existing technical knowledge (see Appendix A).

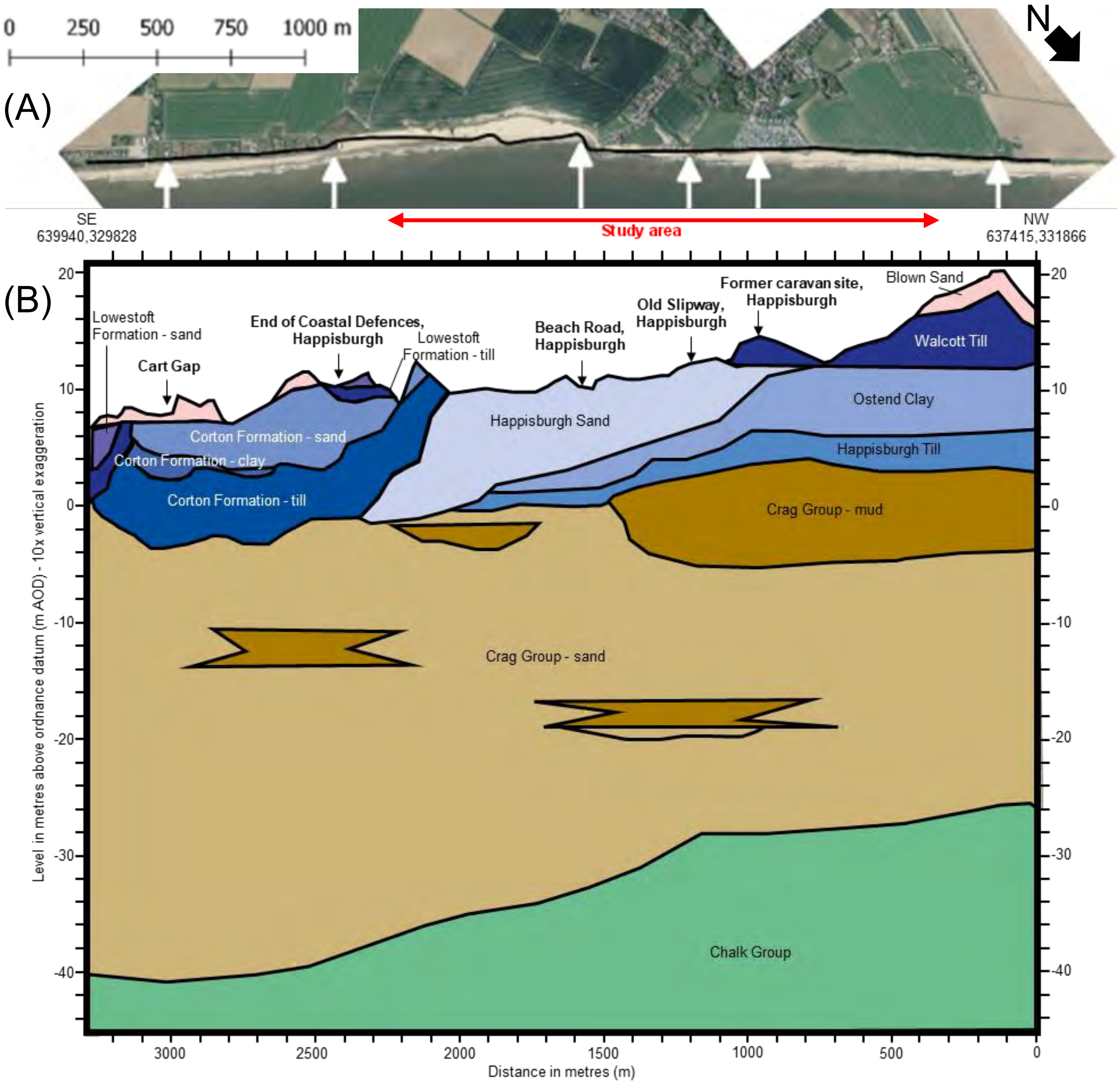
Generally, the local geology is dominated by Happisburgh Glacigenic Formation, a geological unit that consists of sand at the surface and overlying bands of clay and silts. Sections of Happisburgh is covered at the surface by younger glacial deposits from the Lowestoft Formation (including the Walcott Till Member).

The table below presents the Superficial deposits encountered at the cliffs (youngest to oldest) and the underlying bedrock geology. Relative permeability (from low to high) has been included to show potential geological units that stop water migrating down to the chalk.

Stratigraphy		General composition	Relative permeability	Estimated Thickness (m)
Geological unit	Geological name			
Mass movement deposits	Head	Clay, silt, sand, gravel	Low	Unknown
Sheringham Cliffs Formation	Bacton Green Till	Clay and sand	Medium	Locally seen offshore
Lowestoft Formation	Lowestoft Formation	Clay/silt	Low	Locally seen at surface inland
	Walcott Till	Clay/silt	Low	2.0
Happisburgh Glacigenic Formation	Happisburgh Sand	Sand and gravel	High	4.0
	Ostend Clay	Clay/silt	Low	2.0
	Happisburgh Till	Sand and gravel in clay	Low	3.0
Crag Group		Sand, gravel, silt, clay	High	5.0
White Chalk Group		Chalk	High	>50

Table reproduced from BGS Slope Dynamics Project Report: Norfolk Coast (2000 – 2006). Research report OR/08/018.

2.3 Geology of the cliffs



Source: Reproduced from Figure 4 in A Quantitative Assessment of the Annual Contribution of Platform Downwearing to Beach Sediment Budget: Happisburgh, England, UK by Payo et. al. 2018. (A) cliff top line of year 1999 is shown as solid black line on top of year 2010 aerial photography of the study site; (B) main lithological units. Key landmarks along the cliff cross section are named in (b), approximate locations on (a) are indicated by white arrows.

The cliffs at Happisburgh range in height from 6 to 10 m and are composed of a sequence of glacial and pre-glacial deposits which comprise of beds of sand, silt and clay.

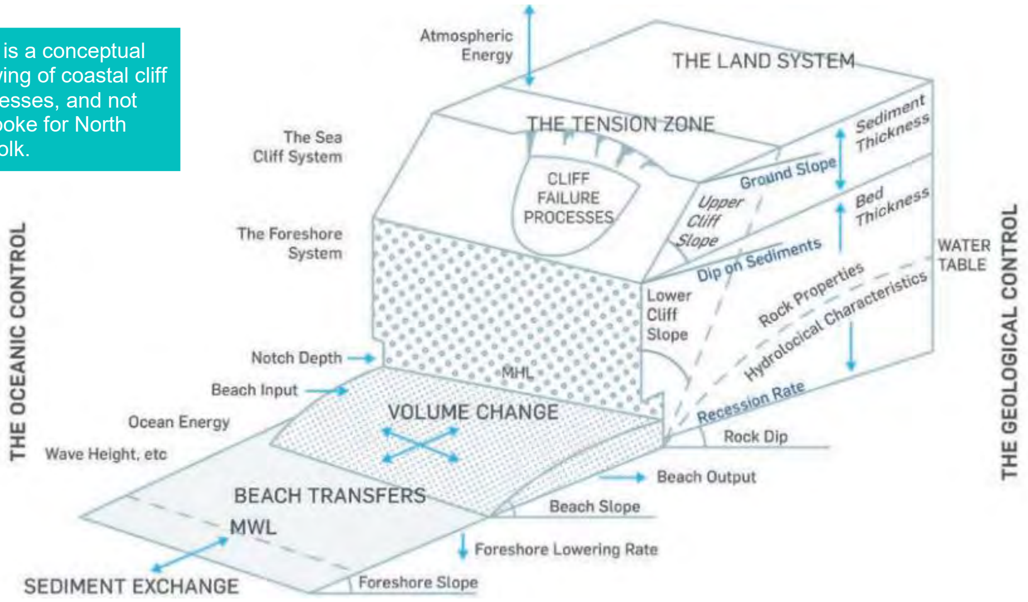
The upper surface of the Happisburgh Till undulates and comprises a series of ridges and troughs that formed beneath the ice margin during phases of both active and passive flow behaviour. The overlying Ostend Clay member infills these troughs (Hobbs et al., 2008).

The southward dipping of the upper surface of the Ostend Clay Member is overlain by the Happisburgh Sand Member. The sand unit thickens considerably southwards as the beds are gently inclined in this direction forming the northern limb of a syncline (Hobbs et al., 2008).

The Walcott Till Member unconformably overlies the Happisburgh Glacigenic Formation in the centre of the syncline to the south of the study location. Walcott Till Member was deposited subglacially by grounded ice crossing the region from the north-west (Hobbs et al., 2008).

2.4 Cliff slope failure mechanisms

This is a conceptual drawing of coastal cliff processes, and not bespoke for North Norfolk.



Source: Reproduced from Figure 2.6 in CIRIA C810, 2023 (taken from Lee and Brunsden, 2001) Titled "*Process model of forcing functions and system responses around a coastal cliff*".

Slopes are generally formed through erosional, weathering or depositional processes and are affected by both relict and active processes which influence stability.

The stratigraphy of the Happisburgh cliffs consist of various geological materials that form different slope angles. Typical stable slope angles for different geological materials are presented in the adjacent table. Generally, if slopes are steeper than the typical slope angles, then they will fail (landslide).

The existing slope angles vary due to different geology and landslides. Most of the cliff slopes are >50 degrees.

Geological material	Typical slope angles from horizontal (°)
Glacial till – compacted	30 – 70
Glacial till – uncompacted	30 – 40
Sands/gravels	28 – 40
Clays	8 – 20
Quick/sensitive clays	0.5 – 8

Soil slopes can have locally high angles due to matric suctions in soils, or weak carbonate cementation common in tills.

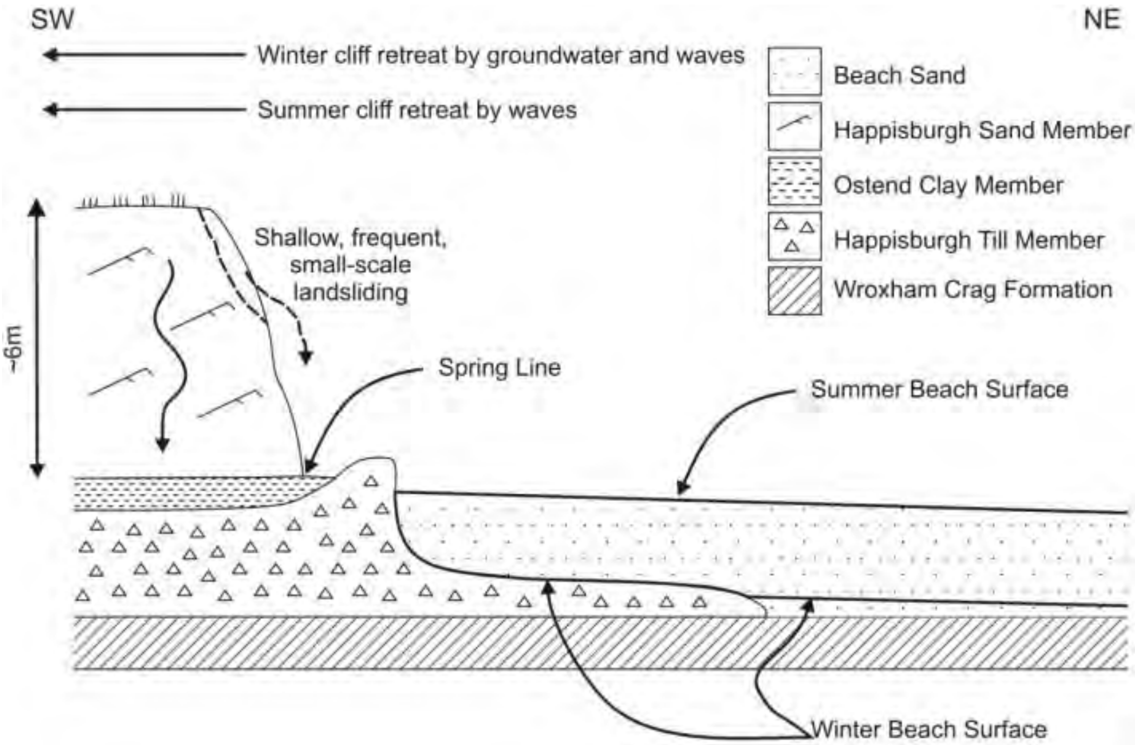
Source: Reproduced from Table 2.3 in CIRIA C810, 2023.

Factors impacting slope conditions (reproduced from CIRIA C810, 2023):

- **External processes on slopes -** Coastal erosion and the removal of material from the base can result in oversteepening leading to changes in stability conditions.
  (Note - the effects of coastal erosion on slope stability is outside of the scope of works for this report.)
- **Internal processes on slopes -** Relates to what happens at a grain-to-grain scale in soils and effects of water flow. Water flow can remove fine material (clay and silt) from soil (suffusion) resulting in a general weakening of the soil slope.
- **Deterioration (weathering) -** The *in-situ* degradation of the minerals that make up the soils. Soils contain significant quantities of minerals prone to alteration or dissolve in water such as mica. This can occur from chemical, physical and biological processes.

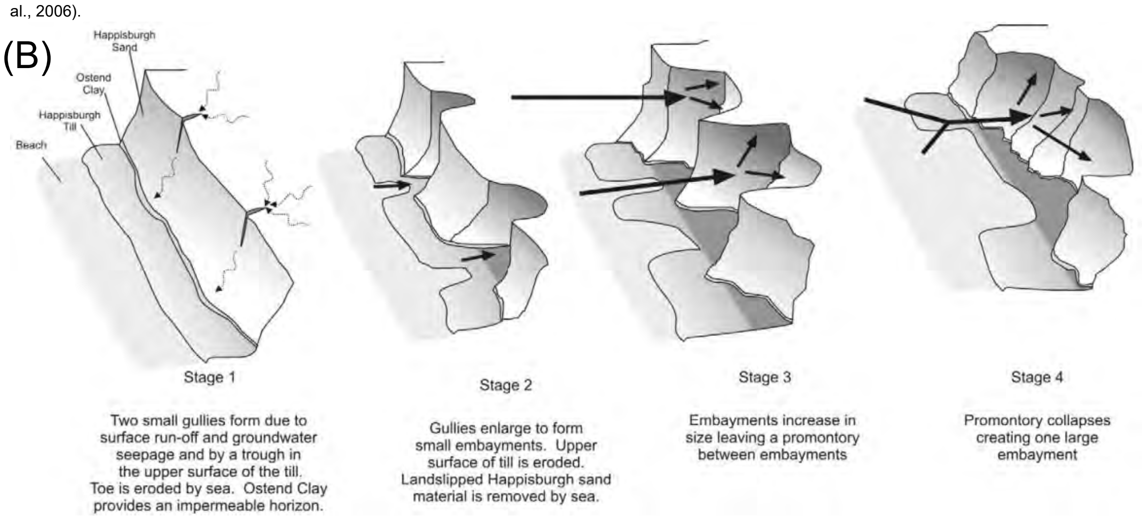
2.5 Cliff regression conceptual model

(A)



Source: Reproduced from Figure 4-28 in BGS Slope Dynamics Project Report: Norfolk Coast (2000 – 2006) Research report OR/08/018 (taken from Poulton et al., 2006).

(B)

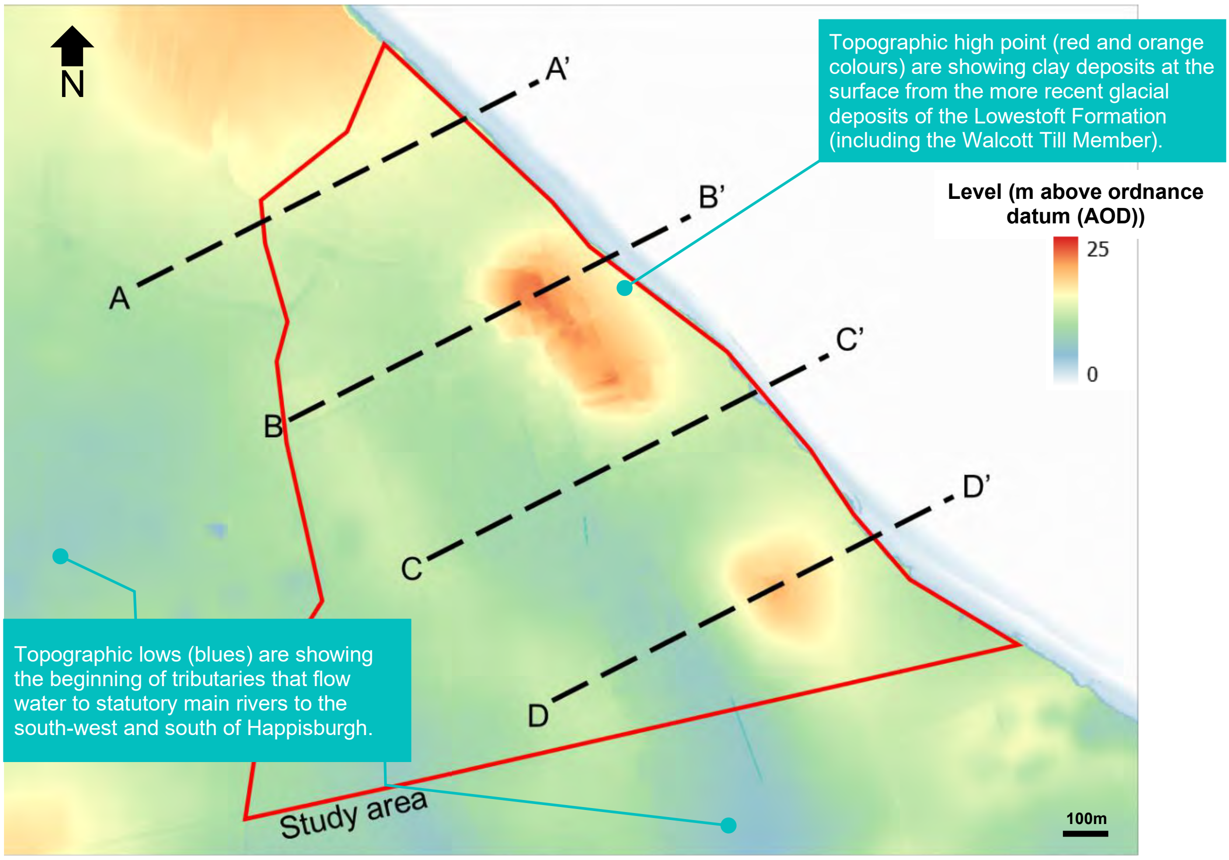


Source: Reproduced from Figure 4-29 in BGS Slope Dynamics Project Report: Norfolk Coast (2000 – 2006) Research report OR/08/018 (taken from Poulton et al., 2006).

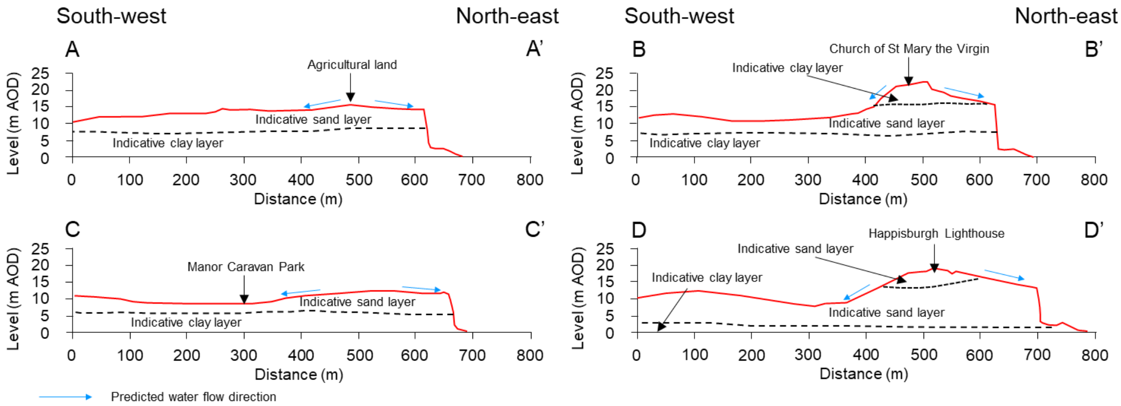
Cliff regression is not a single model but previously literature presents the influence of groundwater in the erosion at Happisburgh.

Seasonal and yearly beach-level changes at Happisburgh have a considerable effect on the erosion and landsliding process. Generally in winter (or periods of high rainfall), erosion is caused by surface runoff and groundwater seepage as seen in the gullying of the cliff face and creating embayments (see image B from Hobbs et al., 2008).

2.6 Topography



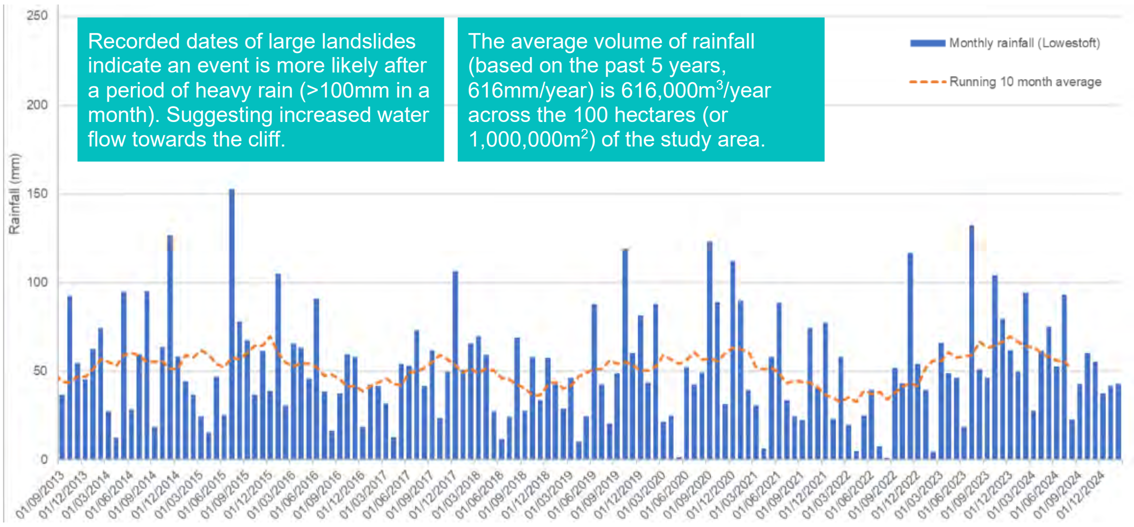
Source: LIDAR Composite Digital Terrain Model (DTM) 1m from 2022 produced by the Environment Agency for tile TG33se.



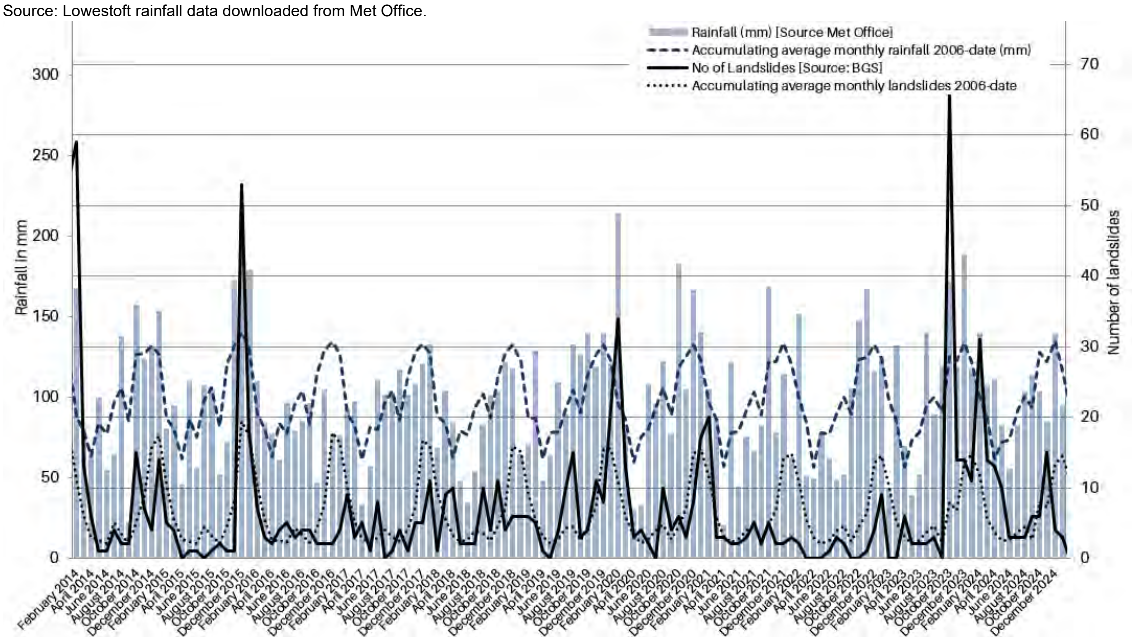
The landscape of Happisburgh has been determined by the ancient route of the River Thames and glaciation. This contributed layers of sand and clays, with noticeable topographic highs from recent glacial clay infills. All of which dictate the groundwater and surface water flow.

Generally, the land 100 to 200m from the cliff line falls towards the sea. Factoring in the underlying ground conditions being permeable sand deposits, it is likely any water in this zone will move towards the cliff.

2.7 Rainfall



Source: Lowestoft rainfall data downloaded from Met Office.



Source: Reproduced from the BGS on UK rainfall and UK landslides. Rainfall sourced from Met Office and national landslides sourced from BGS.

Rainfall is a significant factor in triggering landslides.

The processes associated with rainfall (e.g. infiltration, erosion) are considered a trigger of landslides. Generally, when rainfall infiltrates into the ground, this results in an increased pore water pressure in soils which has the effect of reducing the strength of a natural slope and reducing stability (CIRIA C810, 2023).

Short and intense rainfall typically causes shallow landslides, deeper landslides generally require prolonged rainfall events. The graphs above show there is a correlation between the average monthly rainfall being >100mm and landslides occurring.

Future predictions indicate that rising air temperatures will make winters wetter (+6% in winter rain by 2050 (UK Climate Risk, 2021)), summers drier, and any seasonal rainfall heavier.

2.8 Surface water flow

Understanding where rainwater goes is vital for cliff stability. The topography near the cliff edge generally dips towards the sea and there is visible surface water scarring along the cliff face.

Water runoff peak event - a review of the Flood Estimation Handbook (FEH) was undertaken at the study area and this assumes a loamy soil at the surface, which is considered freely draining, allowing for prominent levels of infiltration.

Model calculation: 1 in 100 year event (FEH22)

Rainfall – FEH22	60mm (depth)
Total rainfall	36mm (depth)
Peak rainfall	12mm (depth)
Please note that urbanisation and existing sewer network information has been excluded at this stage from the above calculation. A full hydrological study should incorporate this information.	

A hydrology calculation was completed through a Revitalised Flood Hydrograph method (ReFH2) for a high level flood estimation for a 1 in 100 year rainfall event (using 1% Annual Exceedance Probability (AEP) and FEH22 rainfall depth-duration-frequency model). The results are shown in the adjacent table.

When comparing the (peak rainfall event) total runoff and the total flow results, the proportion of total flow compared to total runoff is around 37%, which suggests there is a high level of infiltration.

Water flow at the base of the cliffs - Water seepages and outlets are seen along the beach at the base of the cliffs (normally at the top of the clay layer). The speed of water was generally slow during the site visit on 13/03/25, but at the location of the large failure by the old car park, the water seeping out was fast flowing. A flow test was undertaken by filling a water bottle and recorded a flow rate of 0.14 litres/second, where the test captured approximately 70% of the flow.

According to Meteoblue.com approximately 2mm of precipitation occurred on the day of the test and limited rain before. Either the general dip of the clay (Ostend Clay and Happisburgh Till) to the south forces rainfall to accumulate here and/or other landward water is influencing the flow rate. Further water monitoring would be required.

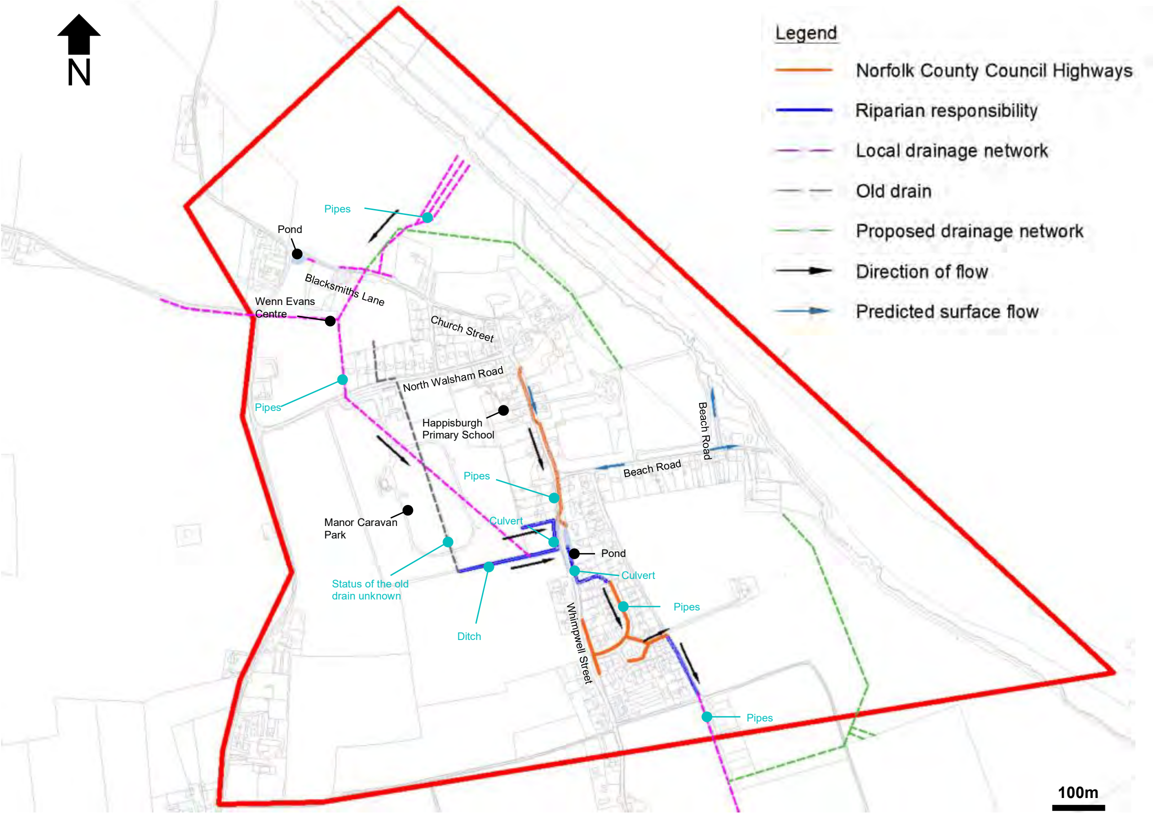
Rainfall onto houses - Based on an average roof area for a house of 75m^2 and annual rainfall of 673mm in 2024, the volume of water per house in Happisburgh would be about 50,000 litres annually. Overall, it is anticapted this volume of water would have a limited impact on the water entering the cliff system.

The average person uses around 142 litres of water per day (Energy Saving Trust webpage). However, the amount of water used varies depending on the number of people in a household and their personal needs.

The 2021 Census reported a population of 870 in Happisburgh, but this will seasonally increase from tourism. The Consumer Council for Water (CCW) report around 114 litres of water per property is lost through leakage every day.

It is not clear at this stage if private soakaways for houses are present and if so, how many there are and the proximity to the cliff edge. This will require further investigation for potential water leakages.

2.9 Drainage Network



Source: Reproduced image from the following sources: Norfolk County Council Highways, Riparian responsibility and direction of flow taken from North Norfolk Happisburgh Whimpwell Street Flood Investigation Report 000240 by Norfolk County Council in September 2016. Local drainage, old drain and proposed drainage network provided by local landowner Thomas Love. Predicted surface flow provided by local community members from the meeting on 13/03/25. Base map taken from Happisburgh Cliff Monitoring drawings VES 1900_A produced by NPS Property Consultants Ltd - Land survey team that was provided by North Norfolk District Council.

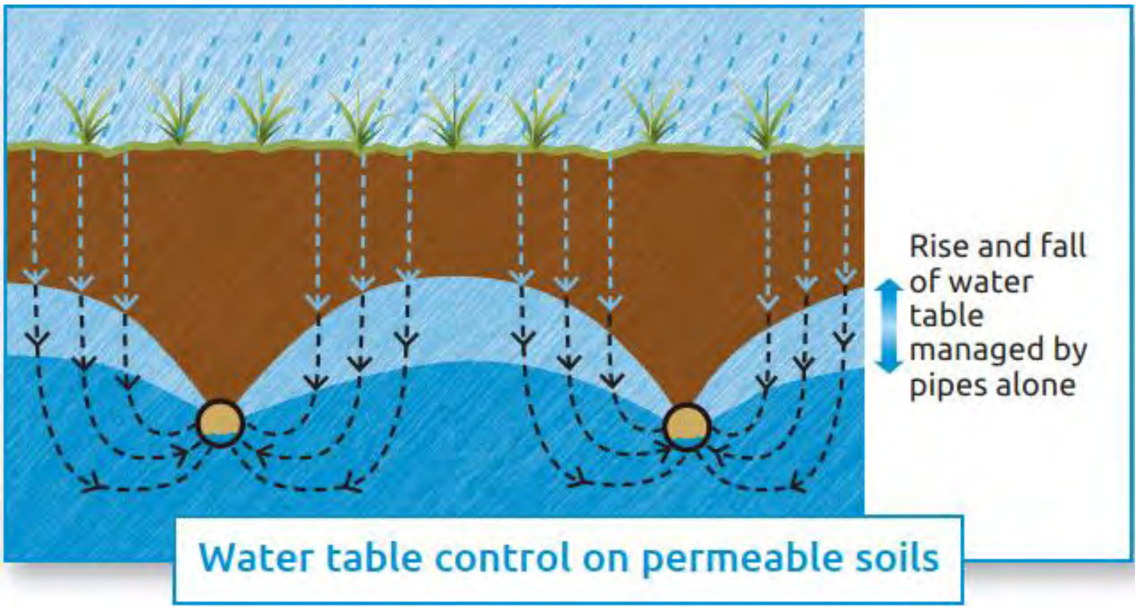
A combination of Norfolk County Council Highways drainage and private/riparian connects water flow from the north to the south of Happisburgh. Surface water flooding has been seen recently.

A piped drainage network exists from the village primary school to the north, to the edge of Happisburgh in the south, where the piped network outfalls into a ditch, and ultimately taken away from the area to the south of the site. A pond lies in the middle of this network, again at a local low point. The pond on Whimpwell Street provides drainage for the road and flood storage capacity. However, recent surface water flooding has been seen in Happisburgh from heavy rainfall.

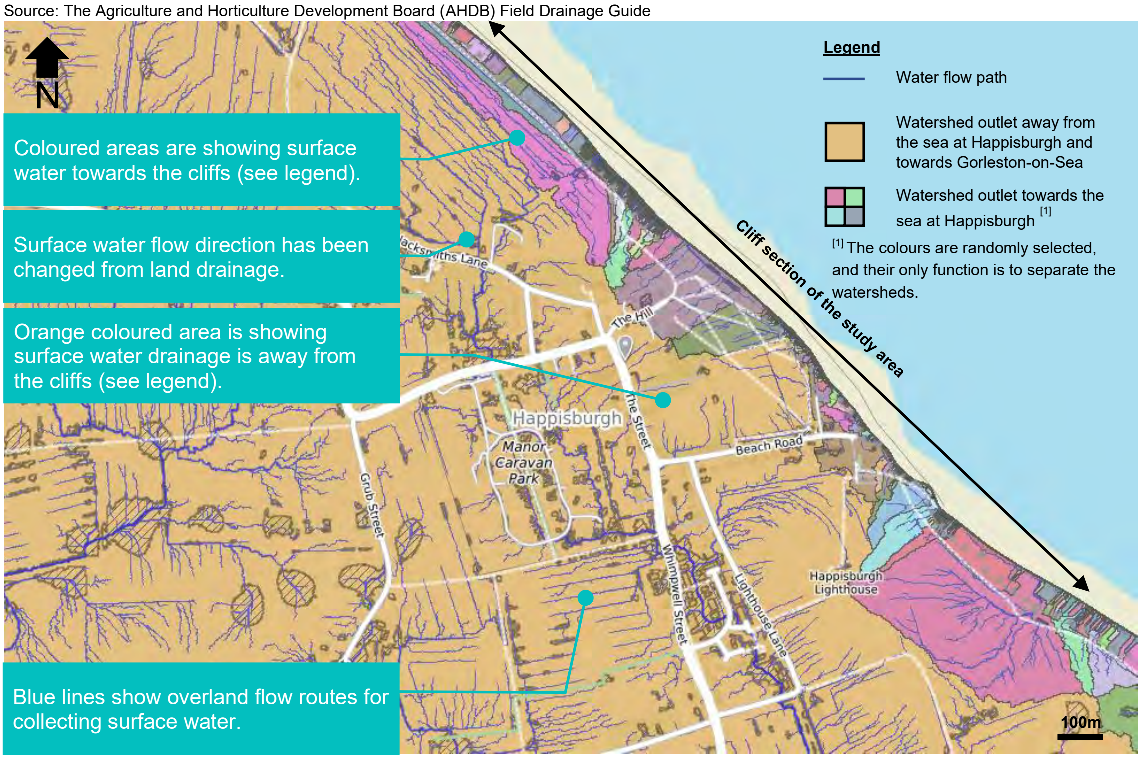
Along Blacksmiths Lane and Church Street there is no formal highway drainage. However, adjacent to the Wenn Evans Centre there is a surface water pond, which is fed partially from highway drainage. The pond and gullies, serving North Walsham Road are connected via a pipe to a ditch that runs through Manor Caravan Park.

As the drainage network is approximately 300m from the cliffs, it is unlikely that any water entering the surface water networks are impacting cliff erosion rates in a significant way as the water is taken away to the south. However, where road surfacing reaches the edge of a cliff (Beach Road), this will likely generate an increased cliff erosion risk due to the surface water runoff not being controlled sufficiently. This is especially true for those roads that do not have an existing surface water drainage method above and beyond highway shedding (overland flow).

2.10 Land Drainage



Source: The Agriculture and Horticulture Development Board (AHDB) Field Drainage Guide



Source: Surface water flow path and depression-free water shed model taken from SCALGO. Watershed model is based on a depression-free flow analysis corresponds to the maximum topographic watershed of a river mouth or surface flow path leading to the ocean.

The pattern of surface water flow is dictated by the subsurface geology, topography and drainage. The flow paths show surface water near the shoreline is flowing towards the cliff.

The influence from land drainage to surface water flow path is shown in the computer model SCALGO. Limited control of surface water is shown around Beach Road and the former caravan site.

2.11 Evaporation, interception and transpiration

Evaporation and transpiration from plants (or evapotranspiration) reduces the amount of water that enters the ground.

Evaporation - There are numerous factors that affect the rate of evaporation (water depth, wind speed, humidity, air temperature etc) and the accuracy of monthly evaporation estimates will vary by season, but in general it is estimated to be around 40% of land precipitation (Environment Agency – see Appendix A). The current trend with the UK's climate is showing it is changing, with an increase in winter rainfall and longer dry spells, which could lead to more evaporation in the warmer periods. At this current stage there is not enough data to provide accurate evaporation rates at Happisburgh and this would need to be undertaken if a design option was selected that used evaporation.

Interception - The process by which water held on the surface of leaves, branches and trunk during and after rainfall is directly evaporated back to the atmosphere. Often expressed as a proportion of annual precipitation (interception ratio).

Transpiration - Numerous factors affect the transpiration rate (temperature, humidity, light intensity etc). Based off information from Forest Research webpage and the ICE (see Appendix A) it is understood conifers lose 25-45% of annual rainfall through interception, while broadleaved trees lose 10-25%. Conifers also lose 300-350mm of water per year through transpiration, while broadleaved trees lose 300-390mm. Grass loses almost no water through interception, but transpiration rates are higher than for trees.

The below table indicates the typical range of annual evaporation losses (mm) for different land covers receiving 1000mm of annual rainfall.

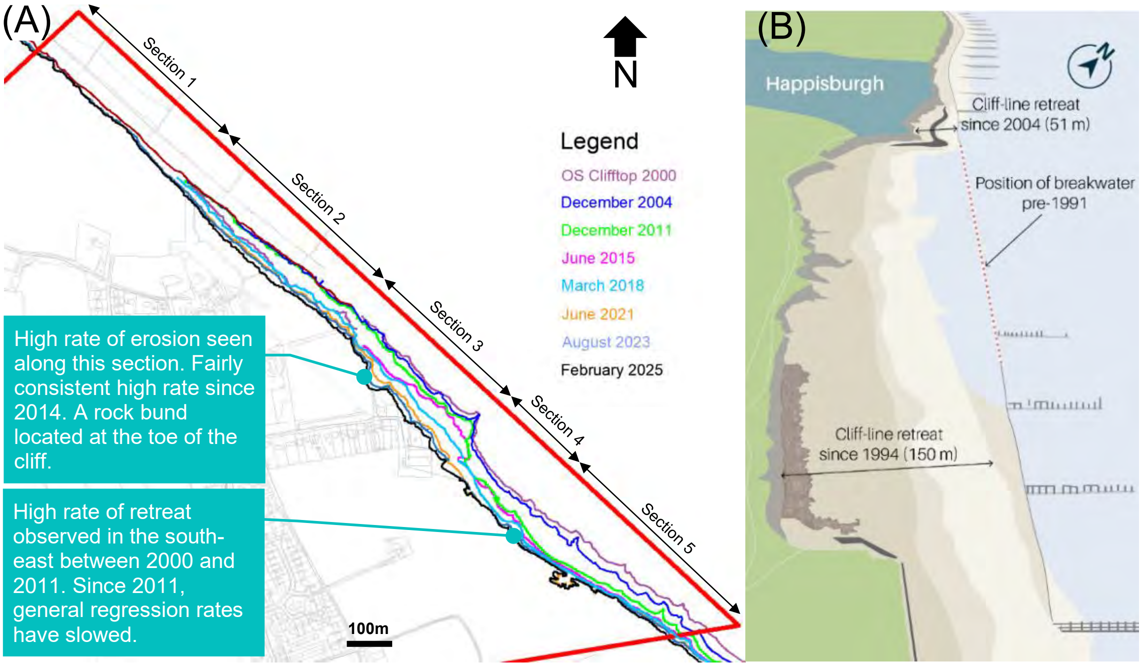
Land cover	Transpiration (mm/year)	Interception (mm/year)	Total evaporation (mm/year)
Conifers	300 - 350	250 - 450	550 - 800
Broadleaves	300 - 390	100 - 250	400 - 640
Grass	400 - 600	-	400 - 600
Heather	200 - 420	160 - 190	360 - 610
Bracken	400 - 600	200	600 - 800
Arable*	370 - 430	-	370 - 430

*assuming no irrigation
Source: Reproduced from 'Water Use by Trees' Forestry Commission Information Note, FCIN065, April 2005.

Rainfall and total evaporation are usually expressed as an equivalent depth of water in mm across the land surface. For example, the addition or loss of 1mm of water to/from an area of 1m^2 of ground is equivalent to a total volume of 1 litre. Similarly, 1mm of rainfall or evaporation to/from 1 hectare (ha) is equivalent to 10m^3 or 10,000 litres of water (Nisbet, 2005).

The results indicate that trees and grass are more effective at reducing infiltration than arable land.

2.12 Cliff regression rates



Source: (A) An extract from Happisburgh Cliff Monitoring drawings VES 1900_A produced by NPS Property Consultants Ltd - Land survey team that was provided by North Norfolk District Council and (B) reproduced from BGS on Happisburgh Coastal Case Study issued 01/09/23.

Coastal erosion has been happening for thousands of years in North Norfolk. Rates of regression has been heavily researched but it is still difficult to predict accurately.

The BGS (Hobbs et al., 2008) suggested that the cliffs of North Norfolk have retreated at an average rate of 1m per year over the past 5000 years. The rate of regression is not uniform across North Norfolk due to numerous factors (wave angle, cliff geology, annual beach wedge, groundwater, etc) and at Happisburgh various rates of regression have been observed.

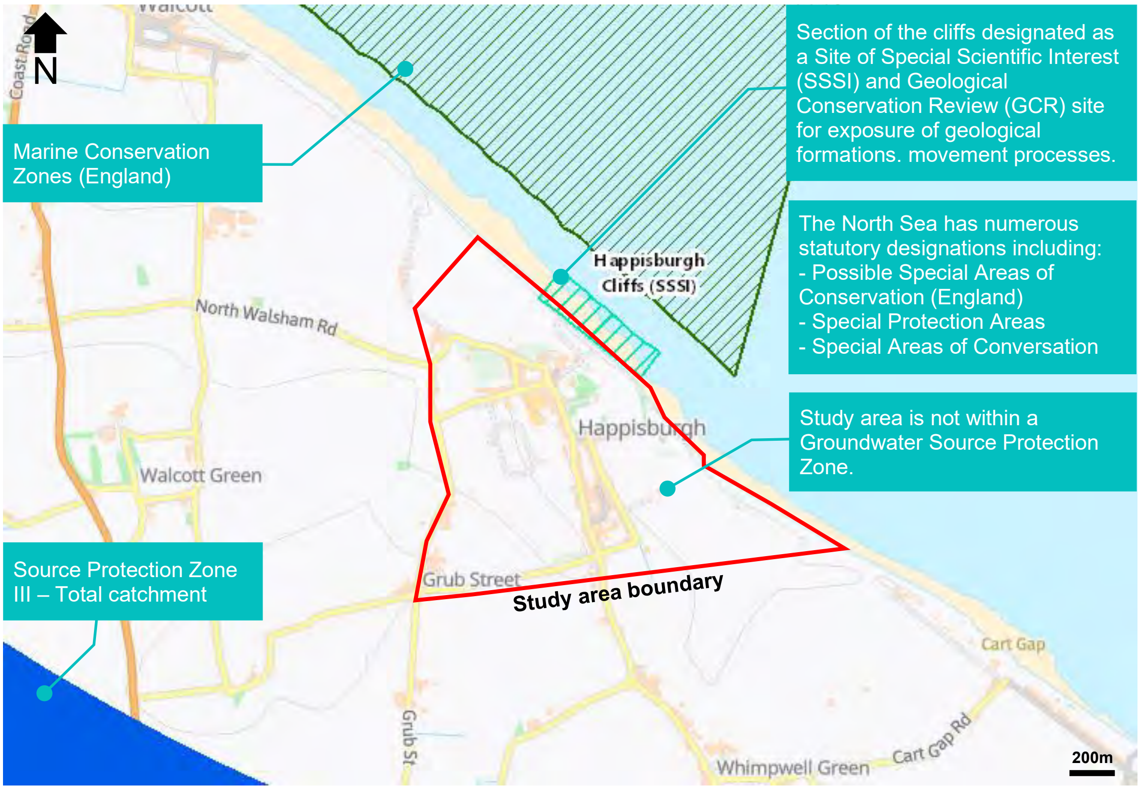
Following the removal of existing defences after significant damage from storms in 1991 and 1996, the shoreline regression was up to 140m (7 metre/year (m/yr)) between 1992 and 2012, and even reached retreat rates of up to 10 m/yr between 1992 to 2007. The average erosion rate after the removal of the defences is in the order of 7 to 17 times larger than annual average erosion rates before the construction of the defences (Payo et al., 2018). Since 2012, regression rates have generally dropped but fluctuate in rates along the cliff.

As cliff erosion is episodic (from occasional landslides) and not continuous, it is better to express the long-term recession rate at Happisburgh as up to cliff-line retreat every 10 years or 25 years rather than metres per year. A summary of cliff regression along the study area is presented below.

Location (see drawing A above)	Regression from 2015 to 2025		Regression from 2000 to 2025	
	Distance (m)	Rate (m/yr)	Distance (m)	Rate (m/yr)
Cliff section 1	3 - 5	0.3 - 0.5	7 - 10	0.3 - 0.4
Cliff section 2	20 - 25	2.0 - 2.5	40 - 55	1.6 - 2.2
Cliff section 3	45 - 60	4.5 - 6.0	70 - 110	2.8 - 4.4
Cliff section 4	20 - 30	2.0 - 3.0	55 - 60	2.2 - 2.4
Cliff section 5	7 - 10	0.7 - 1.0	60 - 75	2.4 - 3.0

Source: NPS Property Consultants Ltd - Land survey VES 1900_A drawing.

2.13 Environmental



Source: Map produced by MAGIC on 10/04/25. © Crown Copyright and database rights [2025]. Ordnance Survey 100022861. Copyright resides with the data suppliers and the map must not be reproduced without their permission. Some information in MAGIC is a snapshot of information that is being maintained or continually updated by the originating organisation. Please refer to the documentation for details, as information may be illustrative or representative rather than definitive at this stage.

Understanding the land-based designations is critical for developing potential measures for controlling water flow towards the cliff.

Groundwater Source Protection Zones (SPZs) are defined around large and public potable groundwater abstraction sites. The purpose of SPZs is to provide additional protection to safeguard drinking water quality through constraining the proximity of an activity that may impact upon a drinking water abstraction. SPZ III (3) - Total catchment is defined as the total area needed to support the abstraction or discharge from the protected groundwater source.

The study area in Happisburgh is not within a SPZ but it is recommended to inform the Environment Agency of any works.

Any potential options will need to consider impact on these environmental designations and consultation with the respective organisation will need to be undertaken, including; Environment Agency, Natural England, Internal Drainage Board and Department for Environment, Food & Rural Affairs.

3 Optioneering

To assist with identifying areas where the options are potentially suitable for controlling water, the study area has been subdivided into the following sections: Northern fields, Village and Southern fields.

The study area has been split based solely on the land type near the edge of the cliff. Note that the village section does not represent the true area of the Happisburgh village.

A visual representation of the areas is present in Figure 3-1.

Figure 3-1: Annotated study area map

Source: Satellite imagery taken from Bing maps @ 2025 Microsoft

This section presents a summary of realistic practical measures that may be considered to help manage water locally to reduce water driven failures of the cliff. These measures will be presented as individual options and each will consider the following topics:

- Impact on groundwater
- Constructability
- Design life assessment
- Social value
- Impact on land users/owners
- Environmental impacts
- Sustainability (relative estimate of embodied carbon production)
- Relative cost (estimate)
- Future steps
- Likelihood of success

The main factor impacting stability of the cliffs (apart from coastal processes) is the groundwater flow through the cliff and surface water running over the cliff. The main criteria for each option proposed is to either:

- reduce infiltration of rainwater into the ground, and/or
- reduce groundwater flow towards the cliff, and/or
- lower groundwater levels at the cliff.

Based on information above and the key aspects above, the following options have been proposed:

Improving drainage

Option 1 - Remediate existing highway drainage

Option 2 - Remediate existing field drainage

Option 3 - Upgrade / install new drainage

Improving drainage and creating storage

Option 4 - Swales and small ponds

Option 5 - Retention pond with discharge drainage

Strategic planting

Option 6 - Plant or buffer strips

Option 7 – Ploughing farmland parallel to the cliffs

Option 8 - Convert cropland to grassland

Option 9 - Agroforestry (planting of specific flora)

Reducing groundwater levels

Option 10 - Vertical dewatering pipes

Each option is presented and assessed individually. It is envisaged that a combination of two or more options could be the optimum solution and the combination of options may vary for different areas (Northern fields, village and Southern fields sections – see Figure 3-1).

At this stage, the options are based on engineering judgement and experience. If an option is selected that is beyond normal maintenance of water management systems or normal land management practices, then further work will be required to prove the viability of the proposals which will include design, calculations and drawings. In particular, because these options seek to change the flow/level of water in the ground over a large area, the impacts on adjacent infrastructure and environment would need to be considered as part of the design. This design may require hydrology and hydrogeological studies to assess impacts.

Optioneering on the cliff face

As mentioned in Section 1.4, part of the cliff face in the village section is designated as SSSI by Natural England and Vattenfall's Norfolk Vanguard and Norfolk Boreas projects are proposed in the Southern fields. Therefore, at this stage, no design option (such as: seeding, soil nailing, regrading, drainage pipes) has been presented for this study area.

Cliff slope stabilisation and coastal protection measures are outside of the scope of this work but should be considered for any future works.

Improving drainage

3.1 Option 1 - Remediate existing highway drainage

Description of the option

Clean the existing road gullies and pipework to remove any blockages. An additional review the road drainage design by drainage engineers. Further investigate the condition of the existing highways drainage network with a CCTV survey and prove the location of the drainage outlet and/or soakaway. This will allow a drainage engineer to assess drainage flow direction and condition of the asset.

This solution will reduce surface water run-off from the highway network running onto and infiltrating the surrounding ground.

Section of the study area effected	Village section only
Constructability	Easy and routine work which will have an immediate impact.
Design life	Likely a high percentage of "silting up" in the gullies and pipework over time that would require cleaning and maintenance.
Social value impacts	Positive social impact due to less surface water flooding.
Land user impacts	• Positive impact on landowners and road users. • The maintenance work will require traffic management such as temporary road works or closure.
Environmental impacts	• Cleaning road gullies can have a positive impact by reducing the risk of flooding and surface water runoff. • Material arising from road drainage emptying and cleaning has potential implications for pollution and should be disposed of correctly in accordance with waste management procedures.
Sustainability (embodied carbon production)	Low impact • Limited embodied carbon produced from the works. • However, if gullies require regular cleaning, then the embodied carbon impact would increase.
Relative cost (estimate)	Low (but recurring maintenance cost)
Likelihood of success	• The survey should identify the outlet or soakaway for the road drainage but there is potential it could be inconclusive. • This option will only impact sections of the study area where the road is near the cliff edge (Beach Road). • The overall impact of clean gullies and pipework will not stop water infiltration across the full study area. • The cleaning of gullies and pipework will likely need to be a regular task and may not be undertaken consistently by Norfolk County Council.
Future steps	The proposal for the remedial works and investigation survey will need to be undertaken in cooperation with Norfolk County Council.

3.2 Option 2 - Remediate existing field drainage

Description of the option

Clear any existing blocked drainage channels and pipes that are restricting water flow. Vegetation clearance along the drainage or water course may be required.

The solution will direct rain and surface water away from the cliff face rather than infiltrating ground and potentially heading towards the cliffs.

Section of the study area effected	Fields section
Constructability	Easy and routine work which will have an immediate impact.
Design life	Regular cleaning and maintenance should be undertaken.
Social value impacts	Neutral social impact.
Land user impacts	● Works will require landowner permission. ● The option only considers existing field drainage systems and drainage by ponds in Happisburgh.
Environmental impacts	● Remediating existing field drainage may require Environment Agency (EA) approval (or the local Internal Drainage Board (IDB)), depending on the nature of the work and its potential impact on the environment. ● The land owner may already have an environmental permit for the existing field drainage.
Sustainability (embodied carbon production)	Low impact ● Limited embodied carbon produced from the works.
Relative cost (estimate)	Likely to be low (but potential recurring cost) ● The work would only require a small team and equipment. ● Costs could increase if the works need to happen regularly.
Likelihood of success	● From the site walkover and research there are partially blocked drains or unsuitable drains on Whimpwell Street and Blacksmiths Lane that contribute to surface flooding of the roads during heavy rainfall. ● The works should be routine works but only limited to the section of fields.
Future steps	● Investigation to determine existing drainage network. ● Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions. ● Approval required from landowners, EA and others.

3.3 Option 3 - Upgrade / install new drainage

Description of the option

Upgrade/install new field drainage to catch and direct surface water. The drainage system would need to be designed to be suitable for the intended land use. The option will likely require the excavation of trenches to install the new drainage network.

The solution will reduce standing water, direct rain and surface water to an outlet rather than infiltrating into the ground and towards the cliff.

Section of the study area effected	Fields and village sections
Constructability	Easy and routine work which will have an immediate impact.
Design life	The design life of field drains can be at least 20 years with regular cleaning and maintenance.
Social value impacts	Neutral social impact.
Land user impacts	• Works will require landowner permission. • The option only considers existing fields and not gardens. • Currently proposed by a local landowner. • Potentially land will not be available from the proposed Vattenfall's projects.
Environmental impacts	• Upgrading drainage might require approval from the EA, but it depends on the specific nature of the upgrade and the potential impact on water resources. • The land owner may already have an environmental permit that allows for upgrading or adding new field drainage. It is recommended to notify the EA of the proposed works.
Sustainability (embodied carbon production)	Low impact • Low embodied carbon produced from the works.
Relative cost (estimate)	Moderate to high • The cost to install field drainage varies depending on the scale and intensity of the system and can range from £1,400 - £3,500 per hectare (source: AHDB). • Costs associated with new drainage and the excavation works. • Potential cost for loss of land or crops.
Likelihood of success	• A network of field drains will help to intercept water infiltrating into the ground and lower groundwater. • Likely limited to the fields section and would only impact part of the village section unless significant drainage infrastructure is placed within existing roads.
Future steps	• Detailed design of the new drainage network would be required to ensure the long-term future of the pipes in relation to potential cliff failures. • Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions. • Approval required from landowners and potentially the EA.

Note on proposed drainage:

There are proposals by a local landowner to install further land drainage along the cliff lines north and south of Beach Road. The proposed drains are shown in Section 2.9. There are potentially minor advantages to these proposals for reducing groundwater penetration towards the cliff face. However, these minor advantages must be balanced with the risk of overcapacity in the existing surface water drainage through Happisburgh which has already flooded on several occasions. It is recommended that land drainage installed in the area follows the principles set out in the AHDB Field Drainage Guide Field drainage guide (2024).pdf, which provides a simple, helpful overview of how land drainage is intended to work. Section 2.10 is an example on how drains may work in the soil types present in the Happisburgh area.

Slope stability analysis would be recommended to check the cliff stability in the new drained conditions from the drainage. Further information on future steps is presented in Section 4.

Improving drainage and storage

3.4 Option 4 - Swales and small ponds

Description of the option

Excavate swales (V-shaped lined shallow channels) that will collect and redirect rainwater away from the cliff towards existing and new lined ponds.

This option will reduce infiltration and downstream flooding and promote evaporation and rainwater storage.

Section of the study area effected	Fields section only and potentially in the village section
Constructability	● Excavation is required to create the new swales and ponds and/or enhance the use of existing ponds. ● The swales and ponds will likely need to be lined (e.g. puddle clay) to prevent infiltration.
Design life	If maintained, the swales and ponds should last for decades.
Social value impacts	● This option is potentially difficult to replicate in Happisburgh village with connecting the swales to ponds. ● Potentially land will not be available from the proposed Vattenfall's projects in the Southern fields section.
Land user impacts	The excavation works will require land from landowners. This will reduce arable land.
Environmental impacts	● The introduction of swales and ponds can help with the biodiversity in the area. ● If the rainwater can be effectively retained and stored in the swales and ponds, it is unlikely to impact the nearby rivers flooding and may not require further consents. ● The EA may need to be notified of the works.
Sustainability (embodied carbon production)	Moderate impact to becoming positive impact ● Construction will require earthworks and landscaping. ● Long-term benefits to the environment from increased vegetation.
Relative cost (estimate)	Moderate to high (construction) ● The construction of swales and ponds will be moderate, with costs increasing as lining clay is likely needed to be imported. High (potential land use change) ● There could be a cost to secure land use change from landowners. Possibility for grants to assist with costs.
Likelihood of success	● Likely an effective way of collecting and redirecting rainwater. ● Potential uncertainty if the rate of evaporation will be an effective method to remove water.
Future steps	● The location of the swales and ponds will require design, including a flood risk assessment. ● Rate of evaporation will need to be calculated to ensure it is a suitable method to improve groundwater conditions.

3.5 Option 5 - Retention pond with discharge drainage

Description of the option

Construct ponds to hold excess rainwater and allow for evaporation but with added discharge chambers or overflow structures to remove water quickly if high rainfall is predicted. Ponds would need to be designed with a clay lining.

This option will reduce infiltration and downstream flooding and promote evaporation and rainwater storage.

Section of the study area effected	Fields and village sections
Constructability	• This will require excavation of a deep pond. • Discharge drainage will require considerable excavation and infrastructure.
Design life	Retention ponds and other storage and treatment systems typically have a lifespan of greater than 20 years.
Social value impacts	• The excavation works would require a large area(s) of land. • This option is potentially difficult to replicate in Happisburgh village with connecting the swales to ponds.
Land user impacts	• Potential for change of land use. • Potentially land will not be available from the proposed Vattenfall's projects in the Southern fields section.
Environmental impacts	• The introduction of a pond can help with the biodiversity in the area. • Any water discharge will need to be consider influence on the surrounding rivers and the EA will need to be consulted.
Sustainability (embodied carbon production)	Moderate to high impact to becoming environmental beneficial • Construction will require earthworks and landscaping. • Added impact from importing lining (puddle) clay from a different location. • Significant works to excavate and install discharge drainage. • Long-term benefits to the environment from increased vegetation.
Relative cost (estimate)	High to very high (construction) • The excavation and landscaping will likely have a high cost, with costs increasing as lining clay is likely needed to be imported. • Adding drainage will require significant works. High (potential land use change) • There could be a cost to secure land use change from landowners. Possibility for grants to assist with costs.
Likelihood of success	• Likely an effective way of collecting rainwater. • Discharge drainage allows water to be removed before incoming rainfall. • Discharging water into the surrounding river catchment might not be accepted.
Future steps	• Design and calculations are required to locate areas for the pond and the discharge pipes. • Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions.

Strategic planting

3.6 Option 6 - Plant or buffer strips

Description of the option

Buffer strips of selected vegetation bordering fields can be added to any cropped open field areas.

Vegetation will reduce infiltration of rainwater and promote evapotranspiration.

Section of the study area effected	Fields and village sections
Constructability	● Easy and routine work which will take a few years (<2) to establish benefits. ● Limited construction is required for planting the buffer strips.
Design life	This option will have a long life if properly maintained.
Social value impacts	Positive social impact due to adding greenspace in the fields.
Land user impacts	● More difficult to assess impact if this is proposed for private gardens and agricultural land. ● Potentially land will not be available from the proposed Vattenfall's projects in the Southern fields section.
Environmental impacts	● Natural England will likely need to be informed given the proximity to the SSSI in the village section. ● Increased biodiversity.
Sustainability (embodied carbon production)	Low impact to becoming environmental beneficial ● Limited construction is required. ● Long-term benefits to the environment from increased vegetation.
Relative cost (estimate)	Low (construction) ● Planting of the buffer strip will be low. High (potential land use change) ● There could be a cost to secure land use change from landowners. Environmental Land Management Schemes may provide funding.
Likelihood of success	● The buffer strip will help absorb surface runoff and shallow water but potential not impacting deeper water. ● Consider acceptability and interest from landowners alongside compatibility with farming practices.
Future steps	● Consultation with specialists would be required to ensure the correct flora is planted. ● Width of the buffer strip will need to be calculated. ● Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions.

3.7 Option 7 – Ploughing farmland parallel to the cliffs

Description of the option

Ensure that all farmland is ploughed parallel with the cliff face to prevent surface runoff towards the cliff face.

Section of the study area effected	Fields section only
Constructability	• Easy and routine work which can happen <1 year. • In parts this is already observed to be happening.
Design life	This option will have a long life if properly maintained.
Social value impacts	This option will likely only impact the northern and southern fields.
Land user impacts	Potential change in yield from the land for the current landowner.
Environmental impacts	Neutral.
Sustainability (embodied carbon production)	Low or positive impact • Neutral embodied carbon production from change. • Long-term benefits to the environment from continued farming.
Relative cost (estimate)	Low • The process of changing the ploughing direction will be relatively low.
Likelihood of success	• There will likely only be a limited improvement to the surface runoff towards the cliff section. • The option will help with surface runoff and shallow water but potentially will not impact deeper water and infiltration of water from heavy rainfall.
Future steps	• Landowner interests would need to be met. • Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions.

3.8 Option 8 - Convert cropland to grassland

Description of the option

Convert existing cropland to grassland through suitable land management measures and activities.

Grassland will reduce infiltration of rainwater and promote evaporation and transpiration compared to cropland.

Section of the study area effected	Fields section only
Constructability	Easy and routine work which will take a few years (<2) to fully establish benefits.
Design life	This option will have a long life if properly maintained.
Social value impacts	This option will likely only impact the northern and southern fields.
Land user impacts	Change of land use for the landowner currently using it as cropland.
Environmental impacts	Increased biodiversity.
Sustainability (embodied carbon production)	Low or positive impact ● Low embodied carbon production from construction. ● Long-term benefits to the environment from increased vegetation.
Relative cost (estimate)	Low to moderate (construction) ● The process of changing the land to grassland will be relatively low. High (potential land use change) ● There could be a cost to secure land use change from landowners. Environmental Land Management Schemes may provide funding.
Likelihood of success	● There will likely only be a limited improvement to the reduction in infiltration from changing land use from cropland to grassland. ● May have a limited impact of the water infiltration within 100m of the cliff edge.
Future steps	● Landowner interests would need to be met. ● Consultation with specialists would be required to ensure the correct flora is planted. ● Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions.

3.9 Option 9 - Agroforestry (planting of specific flora)

Description of the option

Plant specific trees and vegetation to reduce rainwater infiltration and promote interception, evaporation and transpiration.

Section of the study area effected	Fields section only
Constructability	• Easy and routine work • Will take many years for the trees to establish and the benefits to be fully realised. • Consideration for the rate of erosion and location of the trees.
Design life	This option will have a long life if properly maintained.
Social value impacts	• Increase in trees and vegetation to the area.
Land user impacts	Change of land use for the landowner currently using it as agricultural land.
Environmental impacts	• Planting of trees has the potential to block views or conversely provide landscape enhancements. • Increased biodiversity.
Sustainability (embodied carbon production)	Low impact to becoming positive impact • Low embodied carbon production from construction. • Long-term benefits to the environment from increased vegetation.
Relative cost (estimate)	Moderate (construction) • The cost of buying trees and hedgerows will varying based on the type and maturity. High (potential land use change) • There could be a cost to secure land use change from landowners. Possibility for grants to assist with costs.
Likelihood of success	• Agroforestry will help absorb surface runoff and shallow water but potential not impacting deeper water. • Where land will be impacted by erosion in future years, tree planting may not mature significantly before it is at risk of loss. • Only limited to the fields section along the cliff edge. • Selected of suitable flora is critical as invasive flora can contribute to cliff instability and failure.
Future steps	• Consultation with specialists would be required to ensure the correct flora is planted. • Calculations will need to be undertaken to estimate how much benefit this proposal would have on the groundwater conditions.

Reducing groundwater levels

3.10 Option 10 - Vertical dewatering pipes

Description of the option

Drill a series of deep (up to 40m) vertical boreholes along the study area and install slotted pipe drains. This will allow higher perched groundwater to drain into the lower geological layers. This will lower the groundwater level adjacent to the cliff. This option has been proposed based on no design or modelling and significant work would be required to determine the suitability of this method for lowering groundwater levels.

Section of the study area effected	Fields and village sections
Constructability	Specialist plant to drill deep boreholes will be required.
Design life	• Inspection and removal of silt in pipes will be required. • Previous attempts for vertical boreholes failed from “silting up” or breaking when located on/near an active landslide. Full construction details are unknown. • Maintenance and monitoring will be required.
Social value impacts	The locations of the pipes would need to be carefully considered.
Land user impacts	• Works may need to be undertaken on privately owned land. • Groundwater lowering can cause settlement of nearby buildings.
Environmental impacts	Deeper drains may locally increase water flow into the underlying chalk aquifer. This and other aspects of the proposal would need approval from the EA as the nearby area is a groundwater SPZ.
Sustainability (embodied carbon production)	Moderate to high • Requires specialist equipment and numerous drilling locations.
Relative cost (estimate)	High to very high (construction) • The cost of vertical boreholes and dewatering pipes can vary depending on several factors like pipe length, thickness, material and ground conditions. • The dewatering pipes may need to be at least 40m long to achieve an effective depth. High (potential land use change) • There could be a cost to secure land use change from landowners depending on the dewatering pipe locations. Possibility for grants to assist with costs. Medium (ongoing maintenance) • Regular inspections, cleaning and monitoring will be required to maintain the effectiveness of the pipes.
Likelihood of success	• This method would likely be successful in lowering the groundwater but potentially too expensive and environmentally may not be feasible. • The drains need to be designed to allow maintenance and cleaning to prevent becoming blocked with silt which would reduce effectiveness.
Future steps	• Geotechnical and hydrogeological design. • Further design and investigation required to ensure the system can be effective at permanently lowering the groundwater or by a significant amount.

4 Future steps

The following steps are recommended in addition to the current scope of work:

- High level assessments to aid understanding:
    - Drainage – provide further drainage considerations for surface water of existing infrastructure and proposed works with calculations and assessments.
    - Environmental – Consideration and recommendations for future works on the following environment topics such as: ecology, landscape and visual impact, materials and waste.
    - Hydrogeology – Further consideration of relevant precipitation data, hydrogeological model and parameters. Undertake hydrogeological 2D modelling to assess relative change in groundwater surface.
- Undertake a workshop to discuss and assess each option based on multi-criteria assessments (MCA).
- Discussions and input from stakeholders and landowners on options.
- Selection of the preferred option(s) following the scoring workshop and stakeholder / landowner input.
- Investigate source of near surface groundwater using remote sensing techniques (e.g. thermal imaging from a drone).
- Further assessment for the proposed drainage solution presented by a local landowner.
- Develop the preferred option(s) with further consultation with specialist engineers (drainage/environmental/hydrogeological/geotechnical) and town planning to support funding and/or consents.
- Prepare a hydrology and hydrogeological model to ensure the option(s) are effective in reducing water entering the cliff and do not adversely impact adjacent assets.
- Calculate the relative percentage of landslide failures due to surface water or groundwater flow through the cliff versus failures due to coastal erosion of the toe leading to over steepened slopes.

5 Glossary

AHDB	Agriculture and Horticulture Development Board is an executive non-departmental public body, sponsored by the Department for Environment, Food & Rural Affairs.
AOD	Abbreviation for above ordnance datum and is used to specify heights above mean sea level.
Aquifer	Is a geological formation that stores and provides water by allowing groundwater to flow through it.
Buried valleys	An ancient river or subglacial (beneath a glacier) drainage network that is now abandoned and has become either partly or completely buried by more recent sediment.
Compacted	A process when material is pressed together over time, reducing the space between the pieces.
Cretaceous Period	A geological period that lasted from 145 to 66 million years ago. This time period is when chalk formed during Earth's warming phase and high sea levels.
Depositional	The location where sediments are deposited to form soils and rocks.
Embayment	A recess in a coastline forming a bay.
Evaporation	A process that occurs when a liquid changes into a gas.
Evapotranspiration	The process by which water is transferred from the land to the atmosphere, by water leaving the soil (evaporation) and water lost through plant leaves and stems (transpiration).
Failure plane	Also known as a slip plane, is a surface along which a mass of soil or rock slides.
Farmland consolidation	A process that reorganises land into larger, more efficient farms.
FEH22	Flood Estimation Handbook (FEH). The FEH22 rainfall model is the FEH's latest UK-wide statistical model for rainfall depth-duration-frequency (DDF) estimation.
Geological fault	The movement of blocks of ground in a different direction relative to each other. Faults are classified by the direction and type of movement that occurs along the fault plane.
Geological formation	A body of rock having a consistent set of physical characteristics that distinguishes it from adjacent bodies of rock, and which occupies a particular position exposed in a geographical region (the stratigraphic column).
Glacigenic	Sediments laid down within or under glacier ice or deposited by an ice sheet.

Glaciotectonics	Is defined as the glacially induced structural deformation of bedrock or sediment masses due to glacier-ice movement or loading.
Gully	A landform created by running water, mass movement, or both, that erodes soil.
Infiltration	The moving of surface water into the soil.
Interbedded	When layers of rock (or soil) alternate with beds of a different lithology (material).
Landslide	The mass movement of material, such as rock, earth or debris, down a slope.
Mass movement	The downhill movement of cliff material under the influence of gravity.
Permeability	A soil or rock's ability to transmit fluids like water. It is a measure of how easily fluids can flow through the interconnected pores and fractures within a rock or soil. A high permeability allows fluids to move quickly and easily, while a low permeability restricts fluid flow.
Pore water pressure	The pressure of groundwater held between soil or rocks in the gaps (or 'pores') between soil particles. This can increase when soils become saturated and the pressure increases. When pore water pressure increases the shear strength of the soil reduces.
Post-glacial	The time after a glacial period when large ice sheets melted and the Earth's landscape changed.
Pre-glacial	The time prior to a period of glaciation.
Quaternary Period	A geological time period that spans from about 2.6 million years from the present day. The Quaternary Period has seen many cycles of glacial growth and retreat, with ice sheets covering large areas of continents.
Saturated	A soil that cannot absorb any more water.
Seepage	Refers to the slow, subsurface movement of water or other fluids through porous materials like soil and rock.
Shear strength	A term used in soil mechanics to describe the magnitude of the shear stress that a soil can sustain.
Slope stability	The condition of inclined soil or rock slopes to withstand or undergo movement.
Subglacial	Relating to the bottom of a glacier or the area immediately underlying a glacier.
Subsidence	A general term for downward vertical movement of the ground surface.
Subsurface	The rock and soil located beneath the surface.

Suffusion	A process that involves the migration of fine soil particles through the voids between coarse soil particles.
Superficial deposits	Superficial deposits are the youngest geological deposits formed during the most recent period of geological time, the Quaternary.
Synclines	A fold in the ground where the layers of rock curve downward and the younger layers are closer to the centre.
Transpiration	The process by which water is taken up by a plant's roots and evaporated through the stomata, or pores, on the leaves.
Uncompacted	Sediments that are loosely arranged and not compacted or cemented together.
Uplift	An increase in the vertical elevation of the ground surface in response to natural causes (e.g. following removal of glacial ice mass).

Appendix

A. References

Resources used by Mott MacDonald during the project.

Resources used by Mott MacDonald used during Cliff and Water Assessment project in Happisburgh

Reference	Title	Author(s)	Tag	Nature	Publication	Date	URL
1	Effect of Soil Strength Degradation on Slope Stability	Chun Li, Yi Cai	Parameters	Paper	International Journal of Design & Nature and Ecodynamics, Vol. 15, No. 4, pp. 483-489	05/06/2020	https://www.iieta.org/download/file/fid/39344
2	Broad Scale Coastal Simulation, New Techniques to understand and manage shorelines in the third Millennium	Robert J. Nicholl, Richard J. Dawson and Sophie A. Day (née Nicholson-Cole)	Stability	Book	Advances in Global Change Research 49 by Springer	26/08/2015	Available on request via the permission of Robert Nicholls
3	Adapting to coastal change in north Norfolk, UK	Peter Frew	Stability	Report	Proceedings of the Institution of Civil Engineers - Maritime Engineering Volume 165 Issue 3, pp. 131-138	25/05/2015	https://www.icevirtuallibrary.com/doi/10.1680/maen.2011.23?mobileUi=0
4	Slope Dynamics Project Report: Norfolk Coast (2000 - 2006)	P.R.N. Hobbs, C.V.L. Pennington, S.G. Pearson, L.D. Jones, C. Foster, J.R. Lee & A. Gibson	Stability	Report	British Geological Survey Research Report, OR/08/018. 166p	2008	BGS Report, single column layout (nerc.ac.uk)
5	Classification of minerals according to their critical surface tension of wetting values	O. Ozcan	Mineralogy	Paper	International Journal of Mineral Processing Volume 34, Issue 3, Pages 191-204	01/03/1992	Sign in (elsevier.com)
6	Geology of the Cromer district — a brief explanation of the geological map Sheet 131 Cromer	B S P Moorlock, R J O Hamblin, S J Booth, H Kessler, M A Woods and P R N Hobbs	Geology	Report	British Geological Survey	2002	Cromer district, sheet 131, a brief explanation (bgs.ac.uk)
7	Document 1 - An Introduction to the North Norfolk Coastal Environment	Peter Frew	Geology	Report	Coastal Management Unit North Norfolk	2009	Document 1 - An Introduction to the North Norfolk Coastal Environment (north-norfolk.gov.uk)
8	Field Guide to the Geology of North Norfolk	Martin Warren	Geology	Web document	The Norfolk Project website	15/02/2011	Field Guide to the Geology of North Norfolk (northfolk.org.uk)
9	Document 8 - Clifton Way, Overstrand Coast Protection Scheme GEOTECHNICAL AND OTHER ASPECTS OF THE OVERSTRAND COAST PROTECTION SCHEME	Peter Frew, Steve Guest	Stabilisation	Report	Coastal Management Unit North Norfolk	2009	MAFF Paper (north-norfolk.gov.uk)
10	A Quantitative Assessment of the Annual Contribution of Platform Downwearing to Beach Sediment Budget: Happisburgh, England, UK	Andres Payo, Mike Walkden, Michael A. Ellis, Andrew Barkwith, David Favis-Mortlock, Holger Kessler, Benjamin Wood, Helen Burke and Jonathan Lee	Erosion	Paper	Journal of Marine Science and Engineering	10/10/2018	A Quantitative Assessment of the Annual Contribution of Platform Downwearing to Beach Sediment Budget: Happisburgh, England, UK
11	Spatial variability characteristics of the effective friction angle of Crag deposits and its effects on slope stability	Samzu Agbaje, Xue Zhang, Darren Ward, Luisa Dhimitri, Edoardo Patelli	Parameters	Paper	Computers and Geotechnics, Volume 141, 104532	18/11/2021	Spatial variability characteristics of the effective friction angle of Crag deposits and its effects on slope stability - ScienceDirect
12	A Method to Extract Measurable Indicators of Coastal Cliff Erosion from Topographical Cliff and Beach Profiles: Application to North Norfolk and Suffolk, East England, UK	Pablo Muñoz López, Andrés Payo, Michael A. Ellis, Francisco Criado-Aldeanueva and Gareth Owen Jenkins	Erosion	Paper	Journal of Marine Science and Engineering	02/01/2020	293753495.pdf (core.ac.uk)
13	Managing Coastal Change: Use of the Defra Coastal Change Fund in North Norfolk	Peter Frew and Alexandra Schofield	Erosion	Report	Innovative Coastal Zone Management: Sustainable Engineering for a Dynamic Coast	07/07/2015	Managing Coastal Change: Use of the Defra Coastal Change Fund in North Norfolk | Innovative Coastal Zone Management: Sustainable Engineering for a Dynamic Coast (icevirtuallibrary.com)
14	Geotechnical and geological investigation of slope stability of a section of road cut debris-slopes along NH-7, Uttarakhand, India	Gbétoglo Charles Komadja, Sarada Prasad Pradhan, Afolayan David Oluwasegun, Amulya Ratna Roul, Tido Tiwa Stanislas, Raoul Adéniyi Laïbi, Babatunde Adebayo, Azikiwe Peter Onwualu	Stability	Paper	Results in Engineering Volume 10	21/05/2021	Geotechnical and geological investigation of slope stability of a section of road cut debris-slopes along NH-7, Uttarakhand, India - ScienceDirect
15	Happisburgh: Where People Lived On The Thames A Million Years Ago	Matt Brown	History	Web document	Londonist	18/08/2023	Happisburgh In Norfolk: Oldest Human Footprints In Northern Europe | Londonist
16	The geology of the southern North Sea. United Kingdom offshore regional report	T D J Cameron, A Crosby, P S Balson, D H Jeffery, G K Lott, J Bulat and D J Harrison	Geology	Report	British Geological Survey	06/07/1992	The geology of the southern North Sea. UK offshore regional report (bgs.ac.uk)
17	What do we know about the future of rainfall capture in the UK, how it affects general hydrology, and the consequences for supply?	Government Office for Science	Rainfall	Research	Government Office for Science	21/11/2023	What do we know about the future of rainfall capture in the UK, how it affects general hydrology, and the consequences for supply? HTML - GOV.UK
18	Climate change in the UK	Met Office	Rainfall	Webpage article	Met Office		Climate change in the UK - Met Office
19	UK and Global extreme events – Heavy rainfall and floods	Met Office	Rainfall	Webpage article	Met Office		UK and Global extreme events – Heavy rainfall and floods - Met Office
20	New research shows increasing frequency of extreme rain	Met Office Press Office	Rainfall	News article	Met Office	07/03/2023	New research shows increasing frequency of extreme rain - Met Office
21	Trees and drought	Owen Davies	Trees	Briefing sheet	Institution of Civil Engineers (ICE), author from Forest Stewardship Council and input from Forest Research		briefing-sheet-trees-and-drought-final.pdf
22	The FEH22 rainfall depth duration-frequency (DDF) model	Gianni Vesuviano	Hydrology	Handbook	UK Centre of Ecology & Hydrology	13/12/2022	The FEH22 rainfall depth-duration-frequency (DDF) model-caa11347-4ff7-4c89-b707-bf5bb1c05d79.pdf
23	Estimation of Open Water Evaporation	J W Finch and R L Hall	Evaporation	Technical Report	Environment Agency	2001	Microsoft Word - OWE_FINAL_REPORT_FINAL1.doc
24	Water use by Trees	Tom Nisbet	Water use	Information sheet	Forestry Commission	01/04/2005	Forestry Commission Information Note: Water use by trees
25	Happisburgh: Coastal Case Study	British Geological Survey	Erosion	ArcGIS case study	British Geological Survey	01/09/2023	Happisburgh
26	History of erosion and defences at Happisburgh	Mary Trett	History	Webpage	Wordpress		History of erosion and defences at Happisburgh. – Happisburgh Village Website
27	Hydro-PE: gridded datasets of historical and future Penman–Monteith potential evaporation for the United Kingdom	Emma L. Robinson, Matthew J. Brown, Alison L. Kay, Rosanna A. Lane, Rhian Chapman, Victoria A. Bell, and Eleanor M. Blyth	Evaporation	Article	Earth System Science Data	06/10/2023	ESSD - Hydro-PE: gridded datasets of historical and future Penman–Monteith potential evaporation for the United Kingdom
28	Aggregate dredging and the Norfolk coastline, a regional perspective of marine sand and gravel off the Norfolk coast since the Ice Age	The Crown Estate & British Marine Aggregate Producers Association	Geology	Report	The Crown Estate & British Marine Aggregate Producers Association	2015	BMAPA_Norfolk_200115_FINAL.pdf (marineaggregates.info)

Footnote - publicly available data not included in the records but used during Cliff and Water Assessment project

EA Lidar, rainfall data, tide data, historical maps and CIRIA C810, Natural slopes and landslides – condition, assessment and mitigation, 2023, was used by Mott MacDonald through their licence but this guide is not available for free to the wider public.

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