Feasibility of multi-habitat coastal restoration in north Norfolk.

RQ1: What is the Quality and Extent of Coastal and Riverine Habitats in Scope?

Client: World Wide Fund for Nature
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1. Introduction

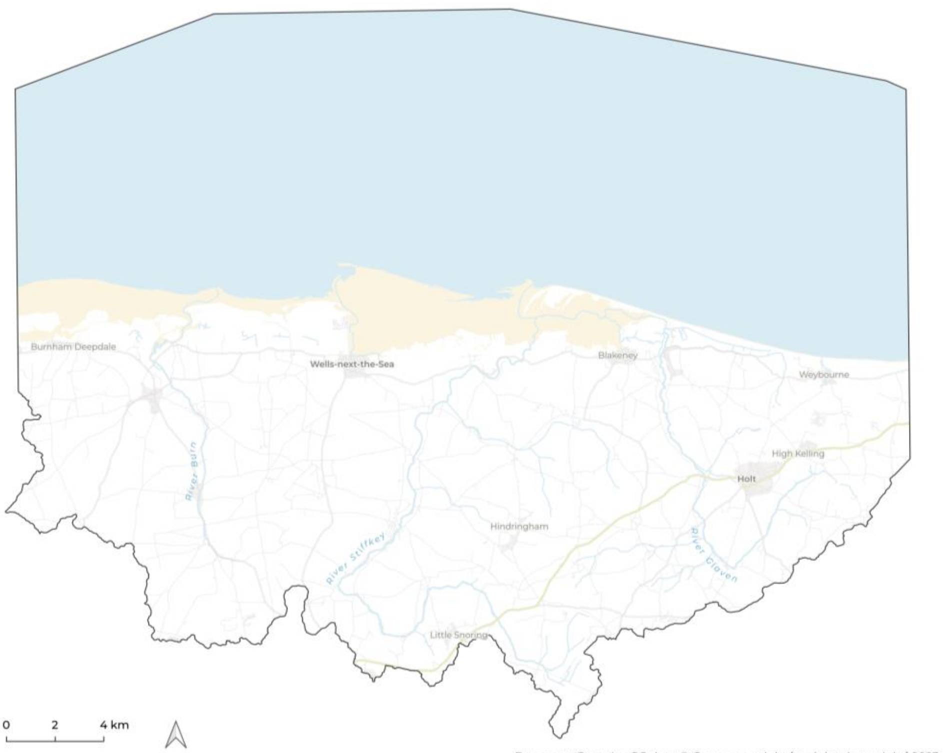
This report has been produced as part of a study into the feasibility of multi-habitat coastal restoration in North Norfolk. In particular, the project focuses on four key coastal habitats which have been shown to exhibit positive feedback mechanisms where each are present within the coastal system. This report relates to Research Question 1 (RQ1) of the project:

> *'What is the quality and extent of coastal and riverine habitats in scope?'*

The aim of RQ1 is threefold. First, to present the location of coastal habitats and quantify their geographical extent. Second, to provide an indication of the ecological quality of mapped habitats. Third, to map protected and actively monitored land and Rural Payments Agency (RPA) registered land. Finally, this information is drawn together to identify areas where multiple coastal habitat types co-exist.

The approach taken here involves three stages aligned with these aims: (i) mapping coastal and riverine habitats, (ii) mapping land use and management, and (iii) identifying priority coastal habitat restoration locations. A series of deliverables have been produced as the output of this work; these are presented as maps within this report and as supplemental GIS data.

The study area of this report encompasses three river catchments in North Norfolk and the surrounding coastal zone, shown below.



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2. Locating Coastal and Riverine Habitats

2.1. Methods

2.1.1. Data Gathering

The first stage of locating coastal and riverine habitats within the study area involved retrieving data from a variety of sources. This data included several datasets published by UK government bodies.

Natural England data retrieved here included the Priority Habitats Inventory and National Seagrass Mapping. Data produced by the Marine Management Organisation relating to the modelled historic locations of native oyster was also obtained. Oyster farm locations were retrieved from data published by the Centre for Environment, Fisheries, and Aquaculture Science (CEFAS, undated).

Records of key kelp and seaweed species were mapped using data retrieved from a search of the National Biodiversity Network (NBN) Atlas for confirmed observations licensed for commercial use. Species used as input into the NBN search query were bladder wrack, carrageen, channelled wrack, gutweed, mermaid's tresses, purple laver, spiral wrack, and toothed wrack. To supplement this data a search of the Ocean Biodiversity Information System (OBIS) database for '*Laminariales*' was undertaken. This search returned no records within the study area.

2.1.2. Data Processing

Next, the gathered data was processed to extract relevant features. The degree of processing required varied between each dataset, however, the process generally followed three stages: (i) a quality review, (ii) an attribute table review to identify relevant features and attributes, and (iii) defining queries to extract the relevant features. Several datasets required more complex processing, however.

The Priority Habitat Inventory data required the greatest level of processing, a result of the broad scope of the habitat types included within the dataset and the range of potential sources from which each feature was derived. In processing the Priority Habitat Inventory data, priority habitats with direct relevance to coastal or riverine systems were extracted from the data. In the cases of priority habitats with no main habitat type, but secondary habitat types including a coastal or riverine habitat, this secondary habitat type was treated as the primary habitat.

Observation records retrieved from NBN Atlas also required additional processing, in this instance to remove any low precision records from the data. For the purposes of this study, low precision records were any records considered to have a precision less than 70 m.

During this phase, a confidence value was also assigned to each data source. This was undertaken through consultation with marine science experts and a review of the metadata documentation available for each dataset. As Priority Habitat Inventory data is compiled by Natural England from a range of providers, the year of data capture was also used to inform confidence assessment.

Following consultation with marine science experts, records within the Natural England seagrass mapping data were initially classed as low. Seagrass survey work undertaken by *Project Seagrass* confirmed presence of seagrass at the locations mapped by Natural England, alongside additional locations (also included in the mapping). Confidence values in seagrass mapping were revised to 'high' in these areas of confirmed seagrass presence.

Table 1: Confidence values assigned by data record data.

Confidence Value	Capture Date
High	Capture date later than 2013.
Moderate	Capture date 2003 to 2013.
Low	Capture date earlier than 2003.
n/a	No data capture date given.

Additional attributes were included to detail habitat type, year, data provider, and a URL link pointing to the data source. A final set of attributes were included to detail the ecological quality of the habitat.

2.1.3. Assessing Habitat Ecological Quality

The approach taken to assess ecological quality of habitats varied for each of the four key coastal habitats included within the project.

Seagrass data retrieved from the National Seagrass Mapping dataset, for example, included an assessment of seagrass density at each habitat patch. In this instance, this attribute has been used to provide an assessment of seagrass condition.

Some records for kelp and seaweed data retrieved from NBN Atlas include a measure of abundance using either the SACFOR scale[1] or a direct measure of percentage cover. A total of 830 records contain a SACFOR scale value, and 10 a direct measure of percentage cover. Where present this measure has been applied to indicate the ecological status of the kelp and seaweed habitat.

Saltmarsh habitat ecological quality has been derived from the condition of SSSI units – using this as a proxy for habitat quality.

2.2. Results

2.2.1. Map 1: Key Coastal and Riverine Habitats

Reviewing the total areas of each habitat type included within the mapping of key coastal and riverine habitats (Figure 1), highlights that of the four core coastal habitats, saltmarsh covers the largest area (2,023 ha), followed by intertidal seagrass (27 ha). Native oyster and kelp are represented as point features in the mapping and consequently not displayed here. Also highlighted are the presence of mudflats and coastal and floodplain grazing marsh (both priority habitats) amongst key coastal and riverine habitats within the study area.

Habitats where multiple co-existing priority habitats are present are grouped as 'Other multiple priority habitats'. This is due to the number of combinations of multiple priority habitats within the data.

[1] The SACFOR abundance scale was developed by Hiscock (1998) for use in the survey of marine habitats. The scale records species abundance in terms of either species cover or count. Further detail on the classification is given by Strong and Johnson (2020).

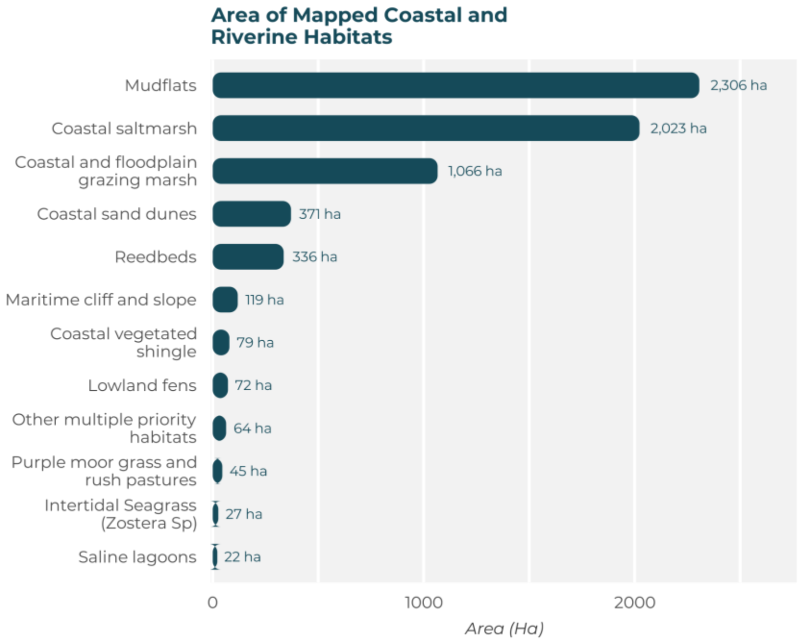

Figure 1: Areas of mapped coastal and riverine habitats within the study area.

2.2.2. Map 2: Habitat Mapping Confidence

The majority of records within the data were classed as high confidence, with records covering a total of 2,940 ha classed as high confidence (Figure 2). This is expected given the number of records which have been captured within the last 10 years – assigned a 'high' confidence value, and the narrow timeframe encapsulated by the 'medium' confidence class in comparison to 'medium' and 'high'.

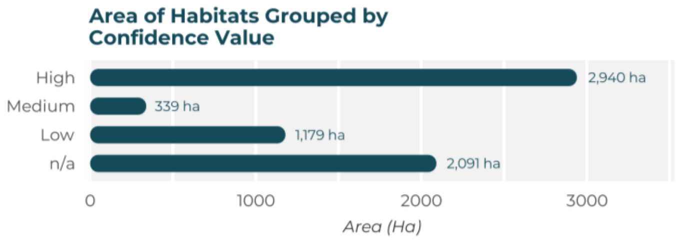

Figure 2: Areas of habitats grouped by confidence value.

2.2.3. Map 3: Habitat Ecological Quality

The vast majority of SSSIs within the study area are classed as being of '*favourable*' condition, with one SSSI site classed as being of '*unfavourable recovering*' condition. This is reflected in the distribution of condition values shown in Figure 3.

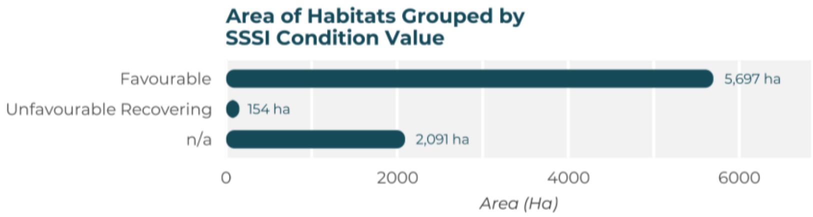

Figure 3: Areas of habitats grouped by associated SSSI condition value.

The vast majority of mapped seagrass habitats (24 ha) are classed as a density of greater than 5%, with 2 ha classed as having a mixed density where seagrass density is greater than and less than 5%. Finally, 1 ha of mapped seagrass recorded a density of less than 5%. This trend reflects the distribution of these density values within the national data.

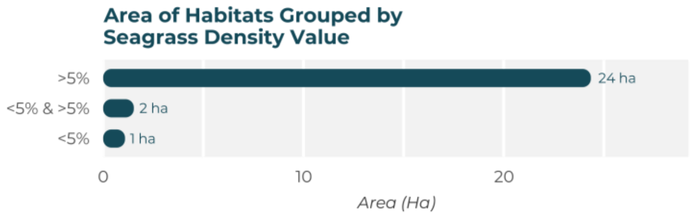

Figure 4: Areas of habitats grouped by associated seagrass density value.

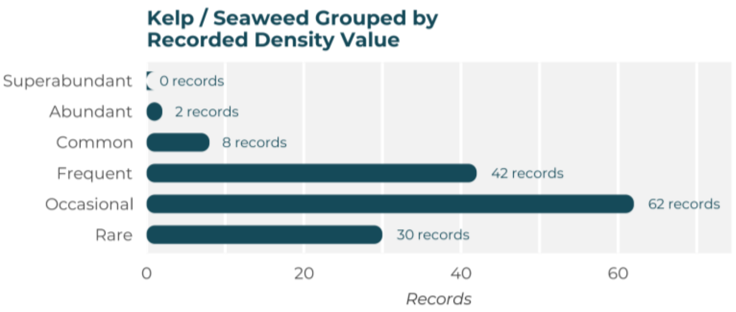

Figure 5: Areas of habitats grouped by associated SSSI condition value.

2.3. GIS Data Specification

A single data file is supplied under this element of the project. This file – in Geopackage (.gpkg) format contains two layers. The first of these – titled '*polygon*' contains polygon features – with the second – titled '*point*' – containing point features. Attributes included within the '*polygon*' layer are presented in Table 2, below.

Table 2: Attributes included within the *'polygon'* layer of '*rq1_1-1-keyCoastalRiverineHabitats.gpkg*'.

Name	Data Type	Description	Length	Precision
fid	Integer	Unique feature ID	0	0
Habitat	String	Habitat type	100	0
Year	Integer	Year of record	0	0
Licence	String	Data licence (NBN)	20	0
Rightsholder	String	Rightsholder (NBN)	100	0
Seagrass_Density	String	Measure of seagrass density	100	0
SSSI_Name	String	Name of SSSI habitat is located within	120	0
SSSI_Condition	String	Condition of SSSI habitat is located within	30	0
SSSI_CondDate	Date	Date of SSSI condition assessment	0	0
Historic	Boolean	Flag to indicate if record is considered historic	1	0
Coordinate_Precision	Double	Measure of record precision in meters	0	0
Confidence	String	Description of confidence in habitat record	10	0

Attributes included within the '*point*' layer are presented in Table 3, below. These are broadly like those included under the '*polygon*' layer, with the inclusion of habitat-specific condition measures.

Table 3: Attributes included within the *'point'* layer of '*rq1_1-1-keyCoastalRiverineHabitats.gpkg*'.

Name	Data Type	Description	Length	Precision
fid	Integer	Unique feature ID	0	0
Habitat	String	Habitat type	100	0
Year	Integer	Year of record	0	0
Licence	String	Data licence (NBN)	20	0
Rightsholder	String	Rightsholder (NBN)	100	0
Seagrass_Density	String	Measure of seagrass density	100	0
Seaweed_Abundance	String	Measure of species abundance at record site	20	0
Seaweed_AbundanceScale	String	Scale used for 'Seaweed_Abundance'	20	0
Historic	Boolean	Flag to indicate if record is considered historic	1	0
Coordinate_Precision	Double	Measure of record precision in meters	0	0
Confidence	String	Description of confidence in habitat record	10	0

3. Reviewing Land Use and Management

3.1. Methods

3.1.1. Data Gathering

Data gathered towards assessing land use and management within the study area falls into one of three groups: (i) land designated and protected as a statutory or non-statutory designated site, (ii) land managed under stewardship agreements and (iii) land managed by a charity of other body.

Statutory and non-statutory designated site location data is published by Natural England. This data includes the following designated sites: Local Nature Reserves (LNRs), National Nature Reserves (NNRs), Marine Conservation Zones (MCZs), Ramsar sites, Sites of Special Scientific Interest (SSSI), Special Areas of Conservation (SACs), and Special Protection Areas (SPAs).

Data relating to land management under stewardship schemes was gathered primarily from the Environmental Stewardship Scheme Agreements data published by Natural England on behalf of the Rural Payments Agency (Natural England, 2023). This was supplemented by data relating to National Trust land ownership (National Trust, 2023a, National Trust, 2023b).

3.1.2. Data Processing

The Environmental Stewardship Scheme Agreements data contains a list of all options (management prescriptions) being implemented under the scheme for each land parcel. As these are given as a list of codes, several processing steps were required to identify the relevant codes. A list of descriptive terms associated with each code was retrieved from Natural England documentation. This documentation was also used to identify codes relevant to water and soil health in lowland landscapes. This was used to create a new attribute in the data table containing a list of relevant lowland water and soil health options with codes replaced by descriptive terms.

Each dataset relating to statutory and non-statutory designated sites was processed in a similar manner, with the end-product being a single GIS file containing every designated site within the study area. A common set of attributes was first developed to enable relevant information relating to each designated site to be captured. These attributes detail the name of the site, the sites unique identifying code, the status of the site (where relevant), the area of the site (in hectares), the condition of the site and date of assessment (where relevant), and a URL pointing towards the data source. Eligible

3.2. Results

Reviewing the designated sites within the study area by area highlights that Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) are the largest designated sites by area (Figure 6). Sites of Special Scientific Interest (SSSIs), Ramsar sites, National Nature Reserves (NNRs), and Marine Conservation Zones (MCZs) all occupy between 4,900 to 6,900 ha of the study area. Several Local Nature Reserves (LNRs) within the study area occupy a total of 13 ha.

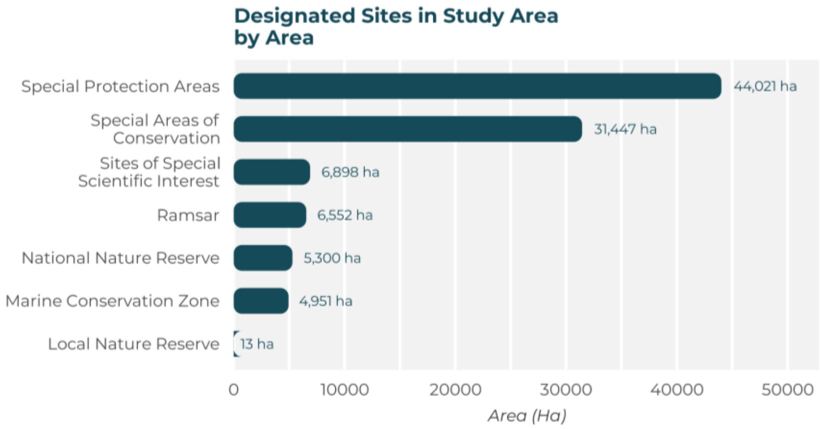

Figure 6: Designated sites within the study area, by area.

3.2.1. Map 4: Designated Sites Overlap

3.2.2. Map 5: Designated Sites Grid

3.2.3. Map 6: Stewardship Schemes

3.3. GIS Data Specification

Two data files – each in Geopackage format – are supplied under this element of the project. These files are '*rq1_1_2-protectedSites.gpkg*' and '*rq1_1_2-landManagement.gpkg*'. Attributes included within the '*rq1_1_2-protectedSites.gpkg*' file are presented in Table 4, below.

Table 4: Attributes included within '*rq1_1_2-protectedSites.gpkg*'.

Name	Data Type	Description	Length	Precision
fid	Integer	Unique feature ID	0	0
Name	String	Name of designated site	255	0
Code	String	Natural England site reference code	255	0
Type	String	Designation type	50	0
Status	String	Designation status	10	0
Hectares	Real	Area of site in hectares	0	0
Condition	String	Designated site condition	25	0
Condition_Date	Date	Date of last condition assessment	0	0
Source	String	URL to data source	150	0

Attributes included within the '*rq1_1_2-landManagement.gpkg*' file are presented in Table 5, below. These attributes are predominantly derived from Natural England Environmental Stewardship Scheme data.

Table 5: Attributes included within '*rq1_1_2-landManagement.gpkg*'.

Name	Data Type	Description	Length	Precision
fid	Integer	Unique feature ID	0	0
Scheme_Agref	String	Stewardship scheme ID	10	0
Scheme_CPH	String	Stewardship scheme customer ID	10	0
Scheme_Customer	String	Stewardship scheme customer name	60	0
Scheme_Class	String	Type of stewardship scheme implemented	50	0
Scheme_Options	String	Options implemented on land	240	0
Scheme_OptionsLowlandWater	String	Lowland water category options implemented	240	0
Scheme_DateStart	String	Start of scheme	10	0
Scheme_DateEnd	String	End of scheme	10	0
Scheme_AreaELS	Real	Area managed under ELS	0	0
Scheme_AreaHLS	Real	Area managed under HLS	0	0
Source	Double	URL to data source	100	0

4. Identifying Priority Coastal Habitat Locations

4.1. Methods

4.1.1. Grid Creation

Analysis in GIS was applied to identify areas of co-existing coastal habitats identified in the habitat mapping data. This analysis subdivided the area covered by the habitat mapping into a point grid with 50 m spacing. Each point in the grid was then buffered by 250 m with a square buffer. This created a series of overlapping squares with a side length of 500 m with each square centred on a point in the point grid. To ensure habitats within the edge

4.1.2. Intersection Analysis

Next, polygon habitat data was intersected by the square grid to divide habitat by the edge of each square grid cell. The output of this intersection was used to create a point on the surface of each habitat polygon feature. This ensured that a point was created for each instance of a habitat polygon overlapping a square grid cell. The habitat polygon features converted to points were then merged with the point habitat mapping data to form a single habitat layer where each feature is represented by a point. This produced a series of squares with a side length of 500 m containing a value representing the number of the four main coastal habitat types intersected by the square. These squares are shown in Map 7: Priority Areas.

4.2. Results

The analysis highlights a series of 500 m squares within the study area which contain each of the four key habitat types. These are located in three distinct regions (i) near Brancaster Staithe, (ii) near Wells-next-the-Sea, and (iii) near Stiffkey and Morston.

5. References

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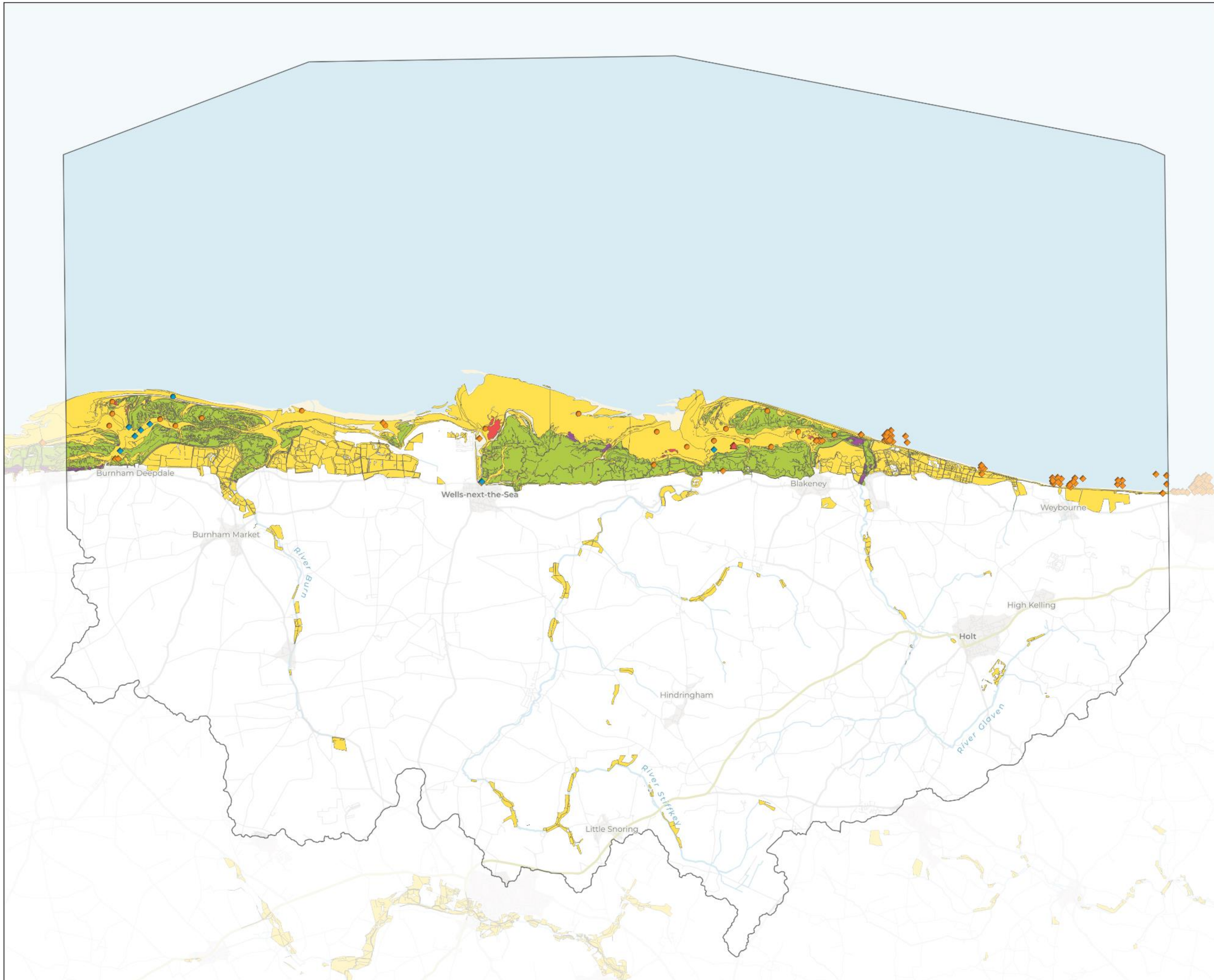

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Native oyster bed potential: Open Government Licence © Environment Agency copyright and/or database right 2020. All rights reserved. © Environment Agency copyright and/or database right 2020. All rights reserved.
Priority habitat and saltmarsh data: Attribution statement: © Natural England copyright. Contains Ordnance Survey data © Crown copyright and database right [year].
Basemap: Contains OS data © Crown copyright [and database right] 2023.

Key

- Oyster Farm
- Oyster (historic [pre-2003])
- Seaweed
- Seaweed (historic [pre-2003])
- Seagrass
- Saltmarsh and Other Priority Habitat(s)
- Saltmarsh
- Seagrass (Zostera sp.)
- Other Coastal or Floodplain Priority Habitats
- Native Oyster Bed Potential

Overview

Seaweed species retreived from NBN Atlas are as follows Bladder Wrack, Carrageen, Channelled Wrack, Gutweed, Mermaid's Tresses, Purple Laver, Spiral Wrack, and Toothed Wrack.

Native Oyster Historic Location data is produced by the Marine Management Organisation and describes the location of locations where native oyster may be present (currently or historically) based on modelling undertaken by the organisation.

Native Oyster Bed Potential is based on modelling undertaken by the Environment Agency which indicates at a high-level areas of potential suitability for oyster bed creation.

Oyster Farm location data has been extracted from the 'Public Register of Aquaculture Production Business in England and Wales' published by the Centre for Environment Fisheries and Aquaculture Science (Cefas).

Saltmarsh represents areas of coastal saltmarsh present in the Priority Habitat Inventory. Saltmarsh and Other Priority Habitat(s) represents areas of coastal habitats present in the Priority Habitats Inventory, where additional priority habitats are also present in the same location.

Seagrass (Zostera sp.) shows areas of seagrass habitat as mapped by Natural England in the 'National Seagrass Layer'. Mapped species in the study area include Zostera sp.

Other Coastal or Floodplain Priority Habitat shows priority habitats associated with coastal and riverine environments.

A search of the OBIS database for 'Laminariales' returned no records within the study area.

Seagrass observations made by project seagrass are also shown here as a point, it is estimated that this area of seagrass covers 0.02 ha in area.

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Client: WWF
Project: North Norfolk Coastal Restoration Feasibility
Title: Key Coastal and Riverine Habitats

Output 1.1

July 2023

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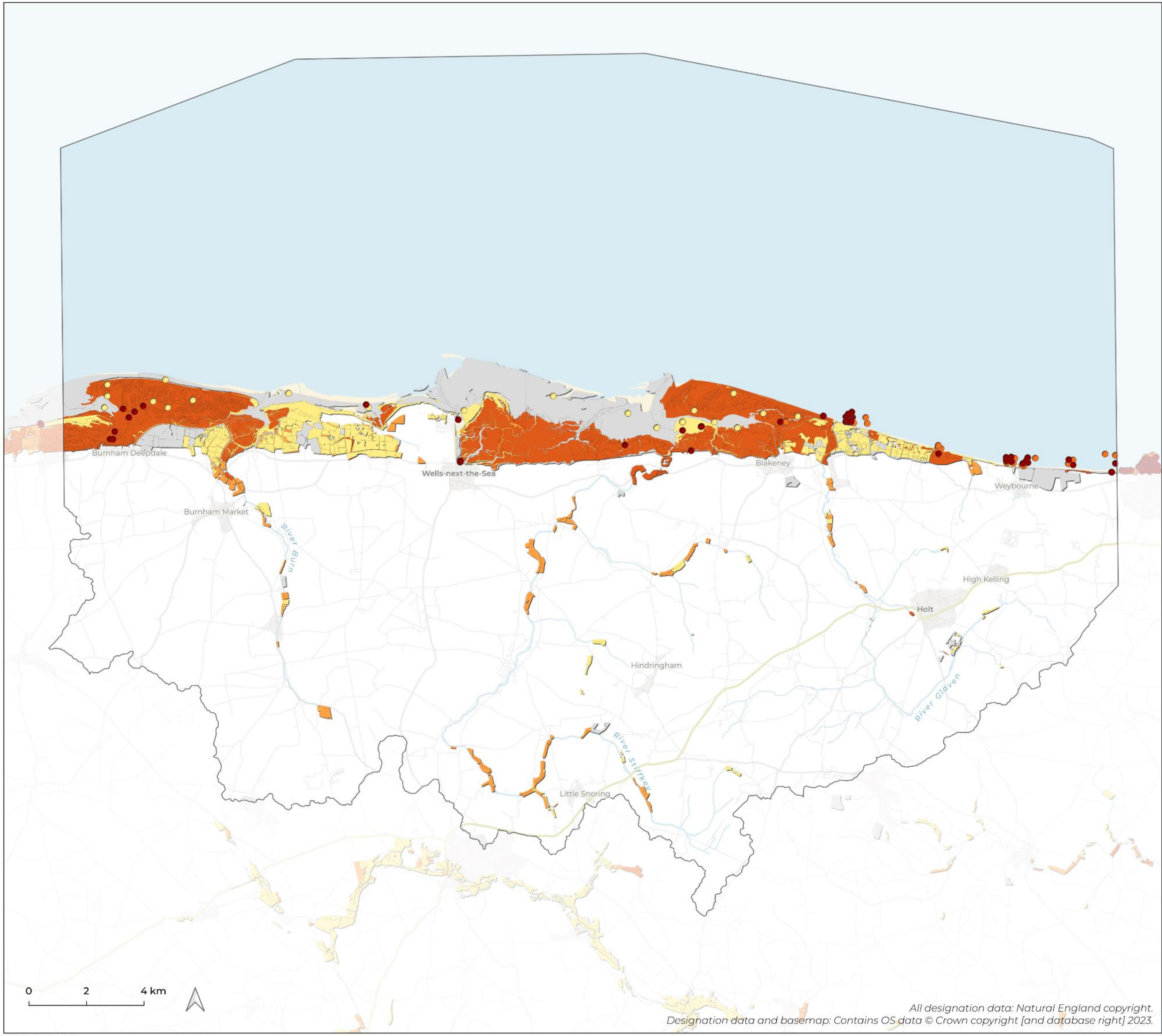
2023-07-17 : V1



Key

- High (EA Ground Survey)
- High (capture date of 2013 or later)
- Moderate (capture date of 2003 or later)
- Low (capture date before 2003)

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Client: WWF

Project: North Norfolk Coastal Restoration Feasibility

Title: Habitat Mapping Confidence

Output 1.1 (b)

July 2023

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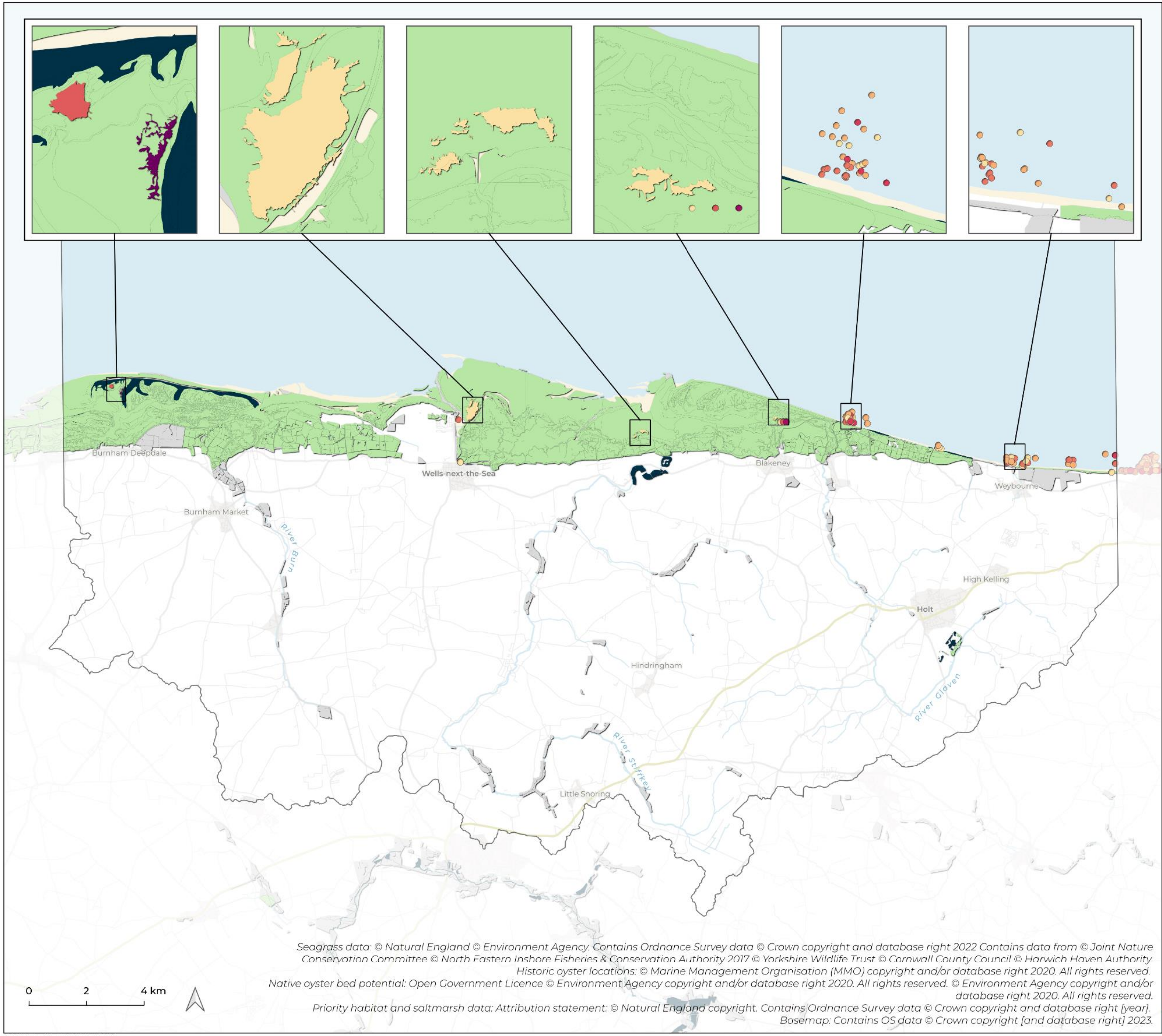

Key

Seagrass Density
- <5%
- <5% & >5%
- >5%

Kelp and Seaweed Abundance
- High
- Moderate
- Low

SSSI-attributed Condition
- Favourable
- Unfavourable No Change
- Unfavourable Recovering
- No Data

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Client: WWF
Project: North Norfolk Coastal Restoration Feasibility
Title: Habitat condition

Output 1.1 (c)

July 2023

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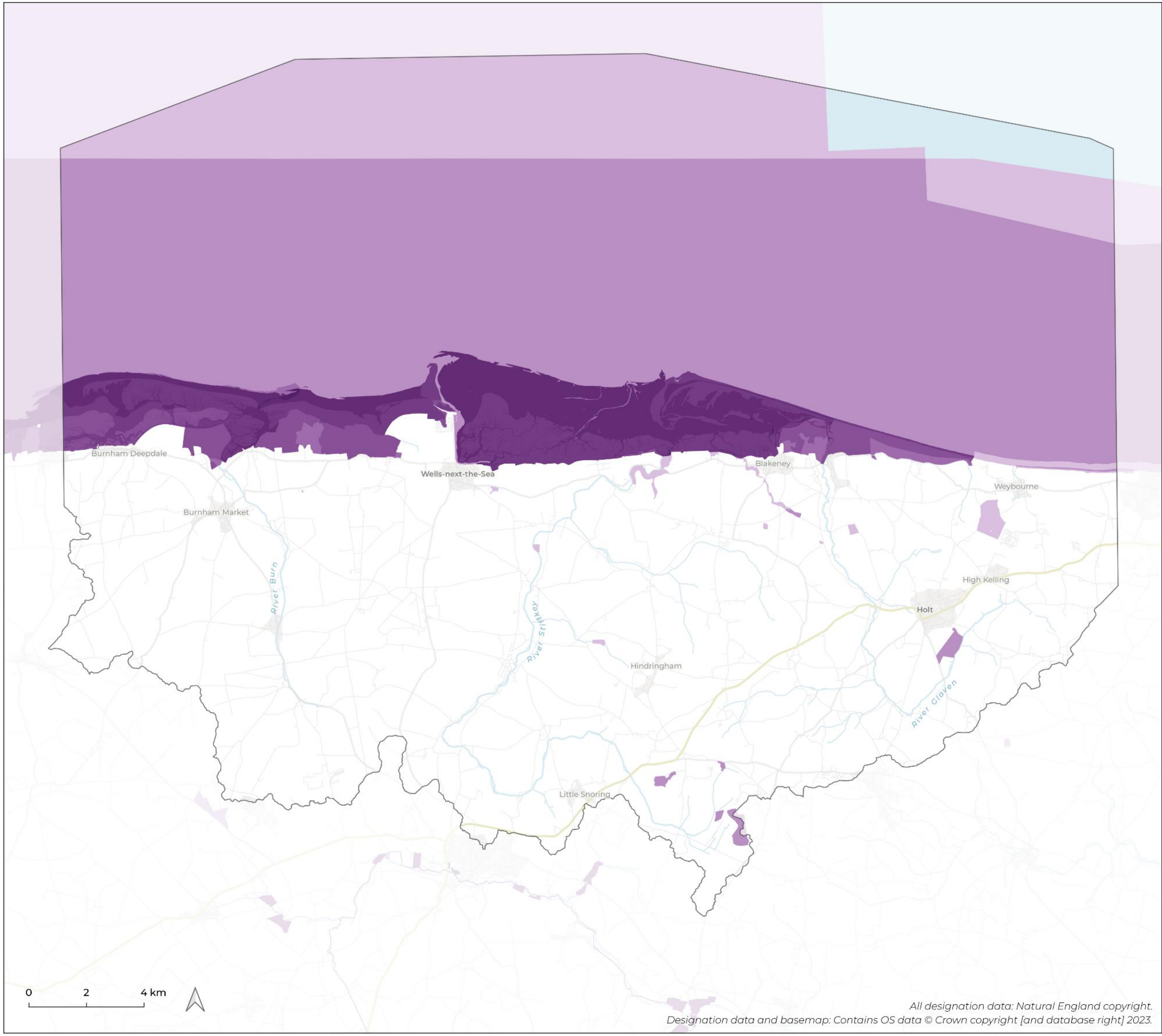

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Key

Protected Site Coverage

High

Low

Overview

Protected sites shown here include: Local Nature Reserves (LNRs), Marine Conservation Zones (MCZs), National Nature Reserves (NNRs), Ramsar Sites, Sites of Special Scientific Interest (SSSIs), Special Areas of Conservation (SACs), Special Protection Areas (SPAs).

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Client:	WWF
Project:	North Norfolk Coastal Restoration Feasibility
Title:	Protected Site Coverage

Output 1.2 (a)

July 2023

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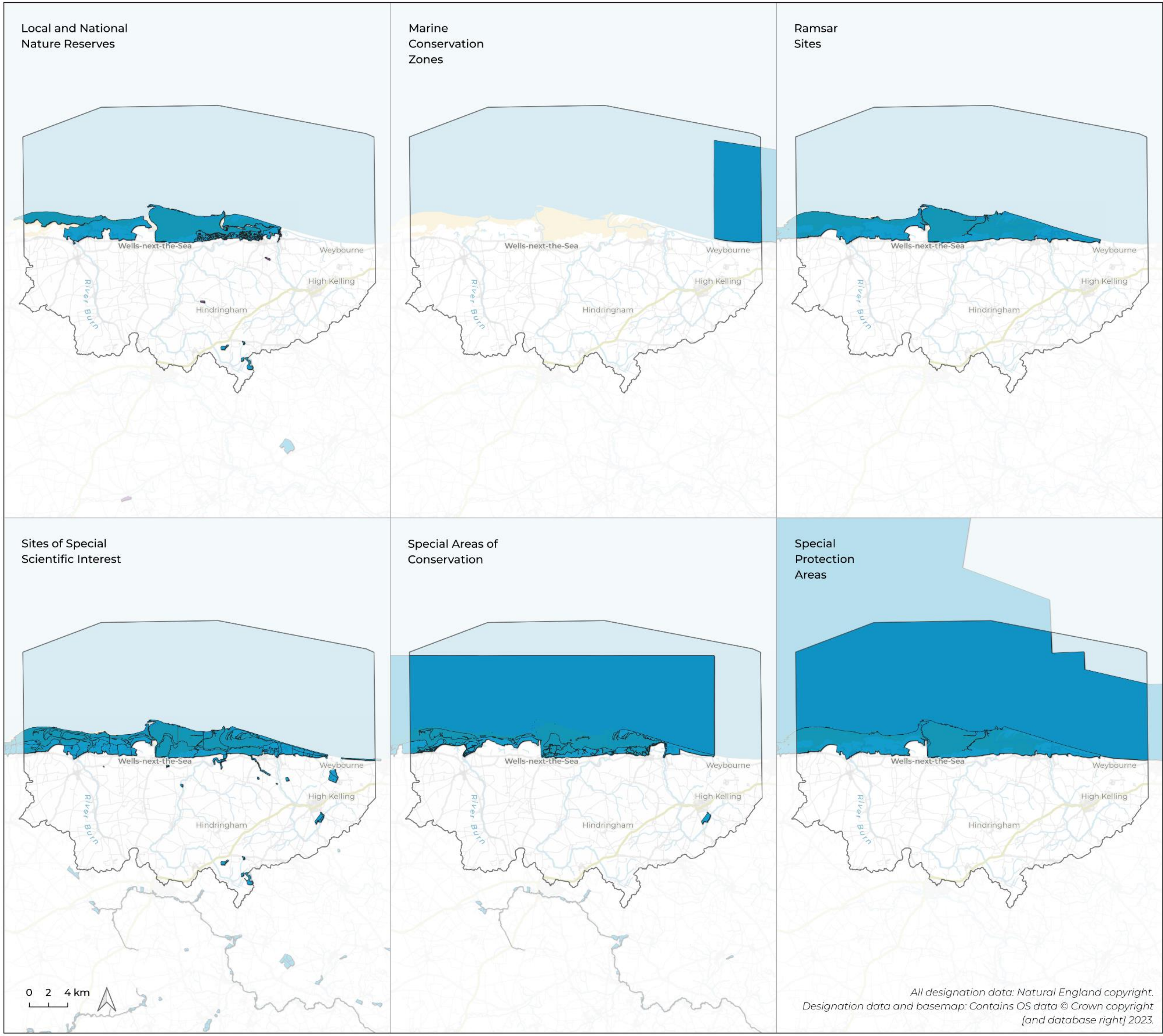

Key

- Local Nature Reserve
- All other protected sites

Overview

Protected sites shown here include: Local Nature Reserves (LNRs), Marine Conservation Zones (MCZs), National Nature Reserves (NNRs), Ramsar Sites, Sites of Special Scientific Interest (SSSIs), Special Areas of Conservation (SACs), Special Protection Areas (SPAs).

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Client:	WWF
Project:	North Norfolk Coastal Restoration Feasibility
Title:	Protected Site Coverage

Output 1.2 (b)

July 2023

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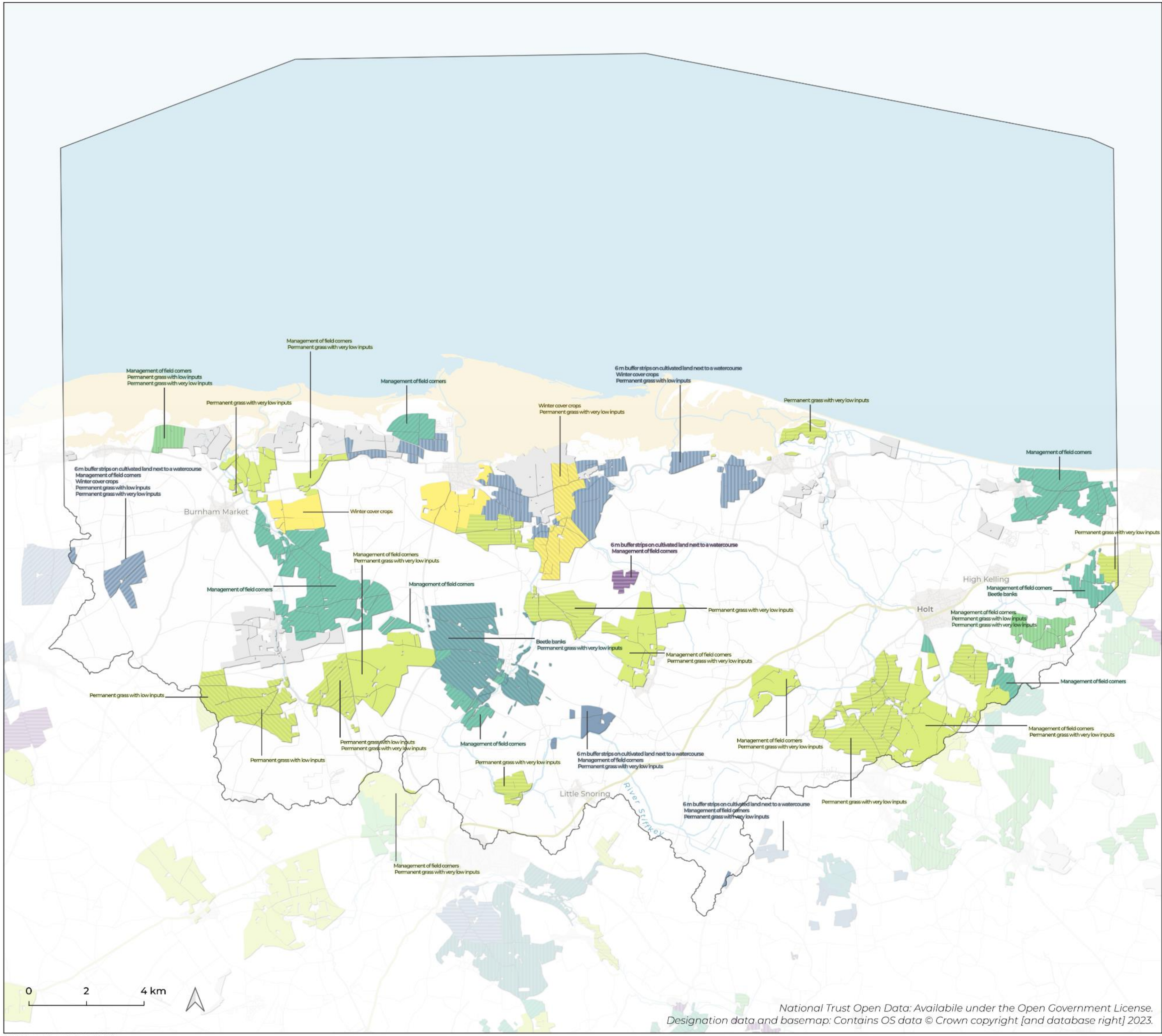

Key

- 6 m buffer strips on cultivated land next to a watercourse, Management of field corners
- 6 m buffer strips on cultivated land next to a watercourse, Management of field corners, Permanent grass with low inputs, Permanent grass with very low inputs
- 6 m buffer strips on cultivated land next to a watercourse, Management of field corners, Permanent grass with very low inputs
- 6 m buffer strips on cultivated land next to a watercourse, Management of field corners, Winter cover crops, Permanent grass with low inputs, Permanent grass with very low inputs
- 6 m buffer strips on cultivated land next to a watercourse, Management of field corners, Winter cover crops, Permanent grass with very low inputs
- 6 m buffer strips on cultivated land next to a watercourse, Winter cover crops, Permanent grass with low inputs
- 6 m buffer strips on intensive grassland next to a watercourse, 6 m buffer strips on cultivated land next to a watercourse, Permanent grass with very low inputs
- Beetle banks, Permanent grass with very low inputs
- Hedgerow restoration, 6 m buffer strips on cultivated land next to a watercourse, Management of field corners, In-field grass areas to prevent erosion and run-off, Permanent grass with low inputs, Permanent grass with very low inputs
- Hedgerow restoration, Management of field corners, Beetle banks, Permanent grass with low inputs, Permanent grass with very low inputs
- Maintenance of watercourse fencing
- Maintenance of watercourse fencing, Permanent grass with very low inputs
- Management of field corners
- Management of field corners, Beetle banks
- Management of field corners, Beetle banks, Permanent grass with very low inputs
- Management of field corners, Permanent grass with low inputs
- Management of field corners, Permanent grass with low inputs, Permanent grass with very low inputs
- Management of field corners, Permanent grass with very low inputs
- Permanent grass with low inputs
- Permanent grass with low inputs, Permanent grass with very low inputs
- Permanent grass with very low inputs
- Winter cover crops
- Winter cover crops, Permanent grass with very low inputs
- No options under Lowland Soil and Water Health

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Client: WWF

Project: North Norfolk Coastal Restoration Feasibility

Title: RPA Land Ownership Data

Output 1.2 (c)

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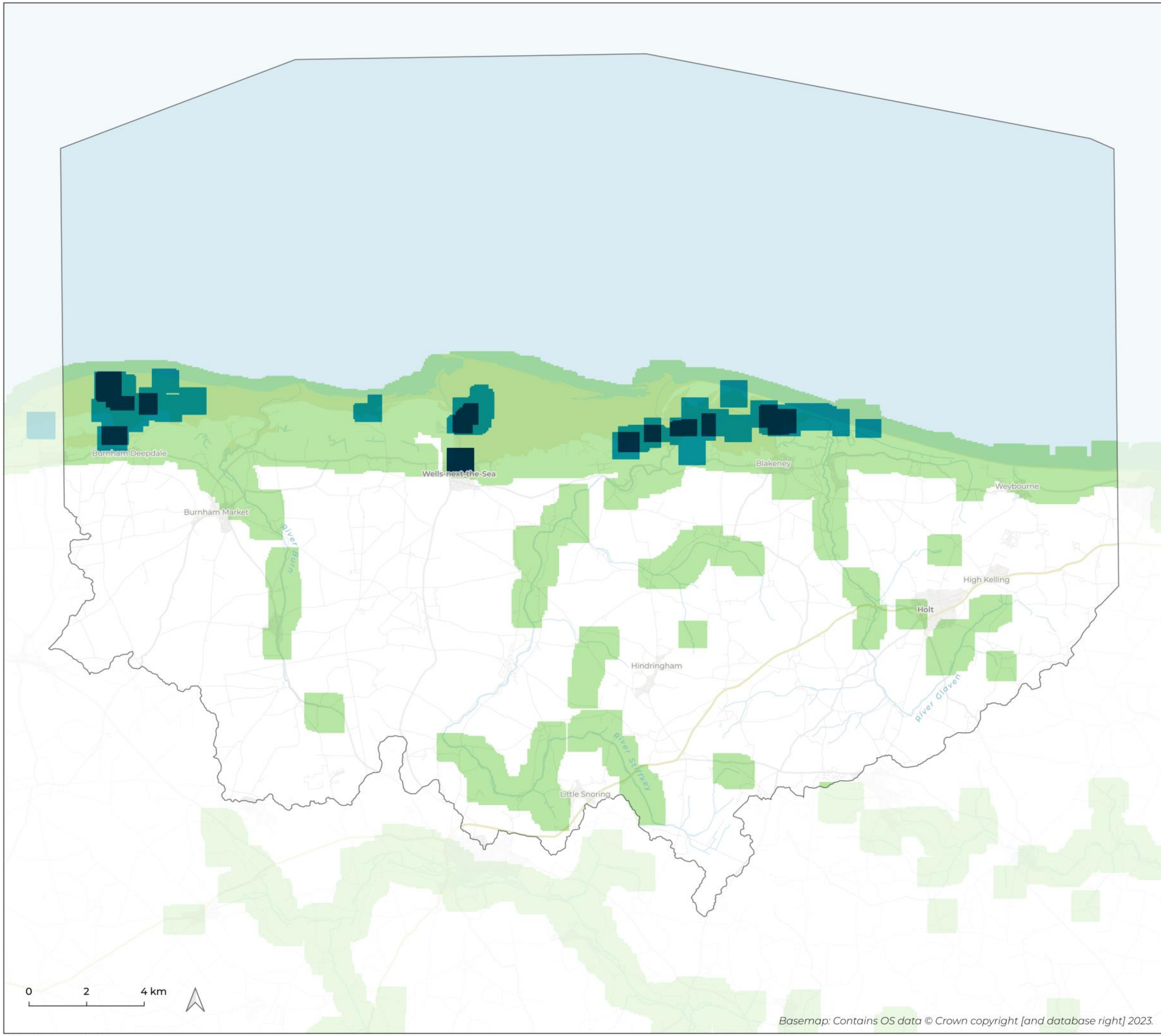

Key

Core habitat types present within 500m:

- 2
- 3
- 4

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Client: WWF

Project: North Norfolk Coastal Restoration Feasibility

Title: RPA Land Ownership Data

Output 1.3

July 2023

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Feasibility of multi-habitat coastal restoration in north Norfolk.

RQ2: What are the key pressures within North Norfolk that may impact restoration of coastal habitats?

Client: World Wide Fund for Nature
Reference: J006807

Company Registration Number: 3724176
VAT Number: 601216305

Issue:	Date:	Written by:	Reviewed by:	Approved by:
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Contents

1. Introduction

This report has been produced as part of a study into the feasibility of multi-habitat coastal restoration in North Norfolk. In particular, the project focuses on four key coastal habitats which have been shown to exhibit positive feedback mechanisms where each are present within the coastal system. This report relates to Research Question 2 (RQ2) of the project. This is a multi-stage research question which seeks to address the questions outlined below:

1. What are the key pressures within the area defined in Map 1, that may impact the coastal zone and coastal habitat restoration? What are the factors inhibiting natural expansion of coastal habitat types?
2. What is the current status of water quality in the coastal area? What parameters define the system and what are the primary limiting factors? I.e., chemical and nutrient inhibitors.
3. What is the current status of water quality in the rivers Burn, Stiffkey and Glaven? What parameters define the system and what are the primary limiting factors?
4. What are the sources of different pollutants within the system, where are they located, and what are their relative contributions?
5. To what degree does the relevant literature suggest that upstream river projects contribute to bioremediation of chemical and nutrient pollutants (e.g., wetland creation, sustainable agriculture, land-based habitat restoration, etc)?
6. Based on relevant literature, what levels of chemical and nutrient pollutants can exist within the coastal system, where coastal habitats can remain ecologically productive?

The aims of this report are as follows. First, to present a high-level overview of pressures faced by inland, transitional, and coastal waterbodies within the study area. Second, to explore water quality monitoring data further to develop a picture of the specific locations where environmental quality limits have been exceeded and the magnitude of these exceedances. Third, pollutants of concern situated within the local context through a review of potential sources within the study area. Fourth, approaches which may be undertaken to address these challenges through upstream remediation are explored. Fifth, pollutants of concern are reviewed against core coastal habitat types to assess their resilience to the levels of pollutants reported within the hydrology of the study area.

The study area of this report encompasses three river catchments in North Norfolk and the surrounding coastal zone (Figure 1).

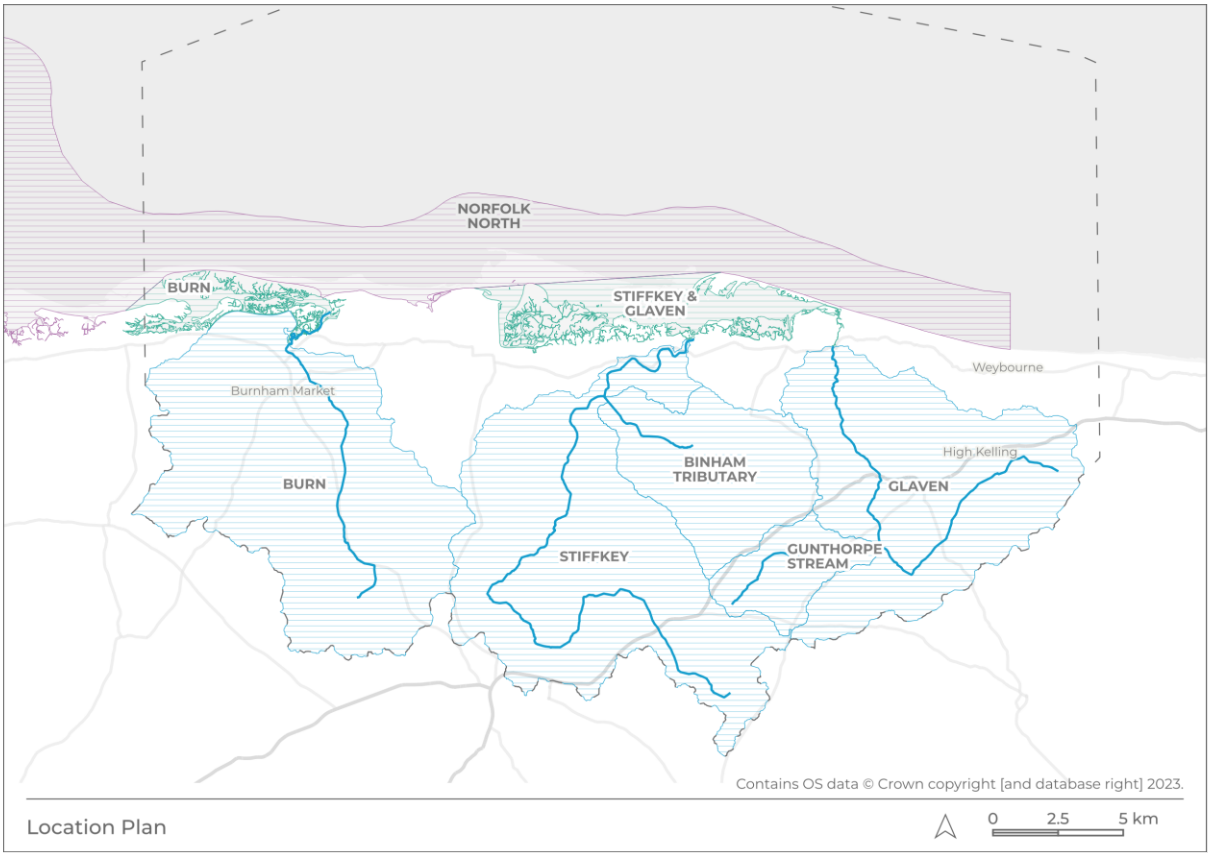

Figure 1: Location plan showing river basins, and transitional and coastal waters, within the study area, as monitored by the Environment Agency

2. Stakeholder Consultation

A number of different stakeholder organisations in the north Norfolk area were contacted (via email and phone) in order to obtain insights about what they feel to be the key threats and pressures to coastal landscape level habitat restoration work in the region. Questions were asked pertaining to the key threats or pressures impacting projects, stakeholder aspirations for coastal habitat restoration in the north Norfolk area, priority sites for restoration, and priority actions for mitigating key pressures. Feedback is likely to consist of a mixture of evidence-based impacts, and more anecdotal observations made by the various stakeholders.

The **Environment Agency** highlighted the dynamic nature of the coast due to being open and soft sediment based, with the geomorphology highly liable to shift over time. Coastal defences were mentioned in the context of climate change, and that any future projects should be embedding climate change adaptation and resilience into them and working with those natural processes to help manage and adapt to sea level rise, changes in geomorphological/hydrological processes, coastal squeeze, and any associated intertidal habitat loss.

Water quality issues were also mentioned, with this highlighted as a catchment wide diffuse pollution problem, primarily from agriculture and to a lesser degree urban impacts. Other pollution sources that were highlighted (following discussion with **Norfolk Rivers Trust**) were linked to tourism, recreational boating/water activities and road/car park runoff. The potential of a local campaign and citizen science initiatives to educate and reduce impacts by monitoring cleanup operations was mentioned (and the RYA 'Green Blue' campaign mentioned as a relevant example). The importance of better understanding previous trends through measurements across the north Norfolk catchments was highlighted as useful work when planning the next phase of ecological enhancement works. Other threats (as discussed during the stakeholder project meeting) were more generic or global (e.g. climate change linked to rising CO_2 levels), although it was highlighted that these were not necessarily relevant to the development or delivery of a project, beyond something on Ocean Literacy (where the importance of not making a project too large or overly complicated was emphasised, otherwise it risks scaring people off that you otherwise need to engage and bring with you). The importance of using appropriate language when communicating or writing up project work was highlighted when discussing ecological engineering or enhancement work, such as managed realignment as a means of creating intertidal habitat and alleviating pressure associated with sea level rise and coastal squeeze, this being a highly complex and emotive issue.

The **RSPB** view recreational disturbance (particularly from dog walkers, but also growing pressure from paddleboarders and low-flying aircraft) as primary issues to address, creating habitat disturbance that impacts north Norfolk's internationally important seabird populations. Such pressures are already impacting coastal ecosystems and the species they support (e.g. little terns, ringed plovers and oystercatchers). Water quality is another issue in the region, and measures will need to be taken to mitigate the negative impacts of pollution in order to ensure that new habitat and species projects can be delivered effectively, while helping prevent the deterioration of existing habitats. Ensuring that development in the region is appropriate for the area was also highlighted as being important, due to the additional recreational pressures, increased pressures on water resources and quality, and offshore impacts, with the potential for sediment pathway disruption which can alter the coast. The RSPB are also pushing back against a proposed barrage project in The Wash which would be highly detrimental to coastal ecosystem in the north Norfolk area.

Natural England feel that work on intertidal habitats and seagrass regeneration should be a priority at this time, but given the scope for a broad variety of ecological enhancement projects to be undertaken by a number of organisations, it was felt that a shared understanding and shared vision of what form this work needs to take and how it can be rolled out at scale was very important.

Anglian Water view phosphate pollution and water abstraction as being key issues impacting the river catchments in the region (with water abstraction potentially compounding the impact of nutrient pollution, through a lack of dilution of pollutants). It was also stated that each river catchment varies with regard to the pressures and threats that it faces. Diffuse pollution impact (particularly nitrates) was also highlighted as an important issue (likely stemming from agricultural runoff). In coastal habitats, the impact of dog fouling and combined sewer overflows (CSOs) was highlighted, with increased nutrient loads in the marine environment being linked to algal blooms. The potential of credit generation (e.g. nutrient neutrality, BNG, ELMS payments) to help fund or create revenue streams was of interest, coupled with regulations that require net zero carbon and reduced nutrient pollution levels entering watercourses by 2030. The water industry national environment programme (WINEP) is a programme of work that will ensure that water companies in England are required to fulfil their obligations arising from environmental legislation and UK government policy. It was stated this could provide potential means of facilitating ecological remediation to some of the pressures in the region, by providing funding and encouraging holistic collaboration between different organisations across the landscape. An interest in supporting the creation of carbon sequestering habitats such as saltmarsh and seagrass was mentioned. Anglian Water have also recently submitted an application for an advanced WINEP which encourages match funding for larger and more joined up and holistic programmes.

The Wash and North Norfolk Marine Partnership at Norfolk County Council highlighted a range of threats and pressures to coastal restoration work in the north Norfolk area. These included the impacts of climate change and rising sea levels exacerbating coastal erosion; recreational disturbance from tourism-related activities, marine recreation and dog walkers (including disturbance of birds); changes in the ranges and populations of species due to changing temperatures, phenolic impacts on the life cycles of organisms, growing numbers of invasive species, and atypical mortality of molluscs such as cockles due to greater disease susceptibility resulting from warmer waters. Highlighted human impacts include damage from boating, including anchoring in sensitive areas (with recreational boats considered the primary issue). Anchoring and fishing practices such as trawling were highlighted as a significant barrier to the restoration of marine habitats such as native oyster reefs. A lack of awareness and understanding among business in the region regarding their ecological impact was mentioned, and development pressure bringing an influx of people and offshore marine infrastructure construction (such as off-shore windfarms) was also mentioned. The importance of marine spatial plans for future work (including plans developed by the MMO to regulate marine activities) was highlighted as something helpful to inform future marine ecological enhancement work. The importance of balancing various activities undertaken by many different stakeholders in the region so that they can coexist while considering their cumulative impact on the environment was highlighted, and the issue of displacement effects was raised, such as a lack of or unclear communication leading to disruption in communities and ecosystems (e.g. Holkham's dog zoning needing dispersal rather than displacement). The importance of fostering unity and a collaborative approach among stakeholders was highlighted as key for developing effective disturbance mitigation strategies.

Rivers Ecology (formerly Norfolk Rivers Ecology) who have broad experience of undertaking habitat creation and ecological restoration work in the north Norfolk region highlighted that the primary issues or barriers were sociological rather than environmental or ecological. It should be noted that the feedback from Rivers Ecology is more directed at potential upstream ecological enhancement work which may mitigate pollution, rather than coastal/marine habitat restoration. Issues around uncertainty, a lack of clarity and short termism from the UK government were highlighted. Uncertainty around potential funding sources such as biodiversity net gain (BNG) and nutrient neutrality were mentioned, and a lack of certainty regarding long-term funding for undertaking ecological enhancement work underpinned hesitancy and a reluctancy to commit to such work. This in turn acted as a significant barrier to landowners when it came to their willingness to undertake such work. There are also issues around different priorities and interests pertaining to land use management in the region, such as from pheasant shooting interests. Shifting baseline syndrome, and the sense of familiarity people associate with otherwise degraded and biodiversity-depleted landscapes was also highlighted as a barrier for undertaking ecological enhancement work.

3. Water Quality Status

3.1. River Quality Status Overview

The quality of the rivers Burn, Stiffkey, and Glaven has been derived from Environment Agency Catchment Data Explorer data. The rivers Burn and Stiffkey are classified as '*heavily modified*' waterbodies, with the Glaven being classified as '*not designated artificial or heavily modified*'. Heavily modified waterbodies are those which have been physically modified by human activity to the point where the waterbody has substantially changed in character, with long-term changes made to the hydromorphology.

This data provides an overall status and a status pertaining to several components of condition. A breakdown of the components that comprise the overall river waterbody status are shown in Figure 2, below. The figure displays monitoring results as points, this highlights the reporting of results annually from 2013 to 2016, prior to this being adjusted to once every three years from 2016 onwards.

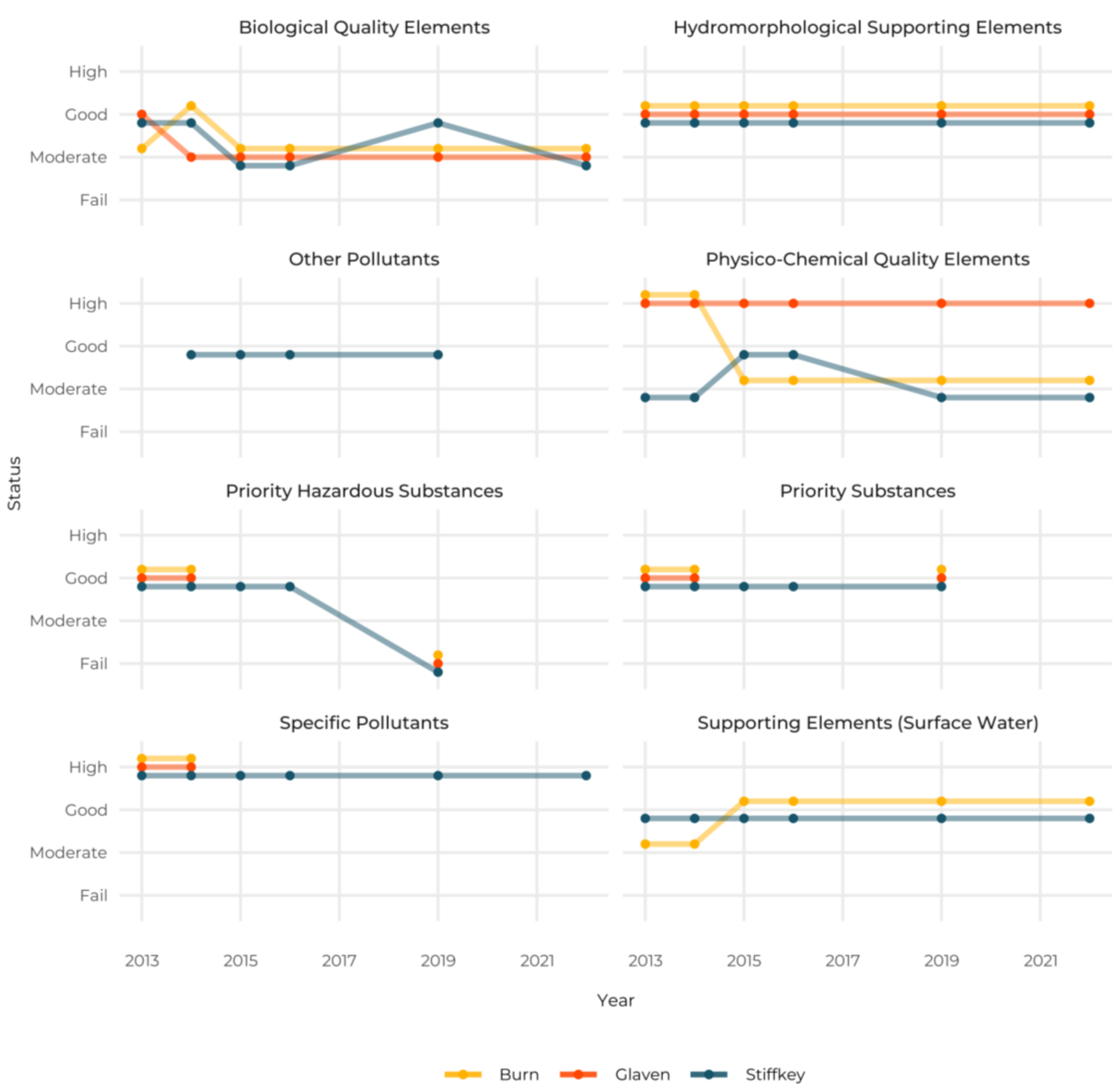

Figure 2: Waterbody status for key elements of water quality as presented on the Environment Agency Catchment Data Explorer (Environment Agency, 2023a–h)

This data highlights that 'Priority Hazardous Substances' have declined from 'Good' to 'Fail' status at all three rivers throughout the period 2014 to 2019. The drivers of these changes are revealed by the challenges faced by each waterbody, as reported by the Environment Agency. Several pollutants are highlighted here as being of concern within the rivers of the study area. Notably, polybrominated diphenyl ethers (PBDEs) and mercury and mercury compounds are listed as being a challenge faced by all three rivers. Evidence indicates that both PBDEs and mercury and mercury compounds impact coastal habitats. These are compounds which can bioaccumulate in coastal ecosystems. Mercury is known to act as a potent neurological poison in fish, wildlife, and humans, while it should be noted that the data on how PBDE's impact the marine system is currently limited. The data of the PBDEs in marine system are currently limited; thus, data gaps are identified as well. Further impacts of these compounds on coastal habitats are detailed in Section 8.

No specific activity is given for the presence of either (i) PBDE compounds and (ii) mercury and mercury compounds within the systems to the degree that water quality standards failed. Water quality objective data reports that the quality target for these rivers to attain 'Good' status is 2040 for mercury and 2063 for PBDE compounds. These dates reflect the anticipated recovery time for the substance to achieve compliance with respective EQS values. Though no specific source is given on the Catchment Data Explorer, these targets indicate that there is a reasonable confidence that inputs of both PBDE and mercury compounds into river systems are no longer active. Similarly, while the River Burn and Binham Tributary both record 'Fail' statuses for the concentrations of perfluorooctane sulphonate (PFOS) compounds, the sources of these compounds within the study area are currently not attributed.

Specific challenges faced by the key river waterbodies within the study area are also provided by the Environment Agency's Catchment Data Explorer. This data provides insight into the specific pressures and activities which produce these challenges. Review of activity data for the three main river waterbodies in the study area (Burn, Stiffkey, Glaven), indicates that nutrient management represents a challenge across all three waterbodies. Sewage discharge is identified as a pressure in the rivers Burn and Stiffkey.

Table 1: Descriptions for activities reported within Environment Agency water quality data.

Activity	Description
Barriers (ecological discontinuity)	Barriers which impact the dispersal of aquatic organisms through waterways.
Flood protection (water level management)	Pressure exerted via changes in water-level as part of flood protection activities.
Groundwater / surface water abstraction	Pressure exerted on waterbodies by the extraction of groundwater or surface water (e.g., for consumption or irrigation)
Land drainage	Pressure exerted on waterbodies by land drainage (e.g., for agriculture)
Poor livestock management	Livestock management practices which exert pressure on waterbodies (e.g., livestock being able to access waterbodies)
Poor nutrient management	Nutrient management practices which exert pressure on waterbodies (e.g., excess fertiliser application)
Poor soil management	Soil management practices which exert pressure on waterbodies (e.g., soils left exposed and vulnerable to erosion)
Reservoir / Impoundment (non-flow related)	Pressure exerted by water storage infrastructure which is disjoint from water channels and their flow regimes.
Septic tanks	Pressure exerted on waterbodies due to the presence of sceptic tanks within a catchment.

Activity	Description
Sewage discharge (continuous / intermittent)	Pressure exerted on waterbodies due to the presence of sewage outlets in continuous or intermittent use.
Track / rural road	Presence of a road / track which places pressure on waterbodies (e.g., via run-off)
Unknown	Activity classed as 'not applicable' by the Environment Agency
Unknown (pending investigation)	Activity currently unknown.

Table 2: Challenges in key river catchments within the study area, as reported by the Environment Agency (Environment Agency, 2023a, 2023b, 2023c, 2023d, 2023e)

Classification Element	Activity	Burn	Stiffkey	Glaven	Binham Tributary	Gunthorpe Str.
Benzo(g-h-i)perylene	Unknown (pending investigation)		Fail			
Fish	Flood protection - water level management	Moderate				
	Sewage discharge (intermittent)	Moderate				
	Barriers - ecological discontinuity	Moderate				Moderate
	Poor livestock management					Moderate
	Poor soil management					Moderate
Hydrological Regime	Groundwater abstraction		Supports Good			
	Surface water abstraction		Supports Good			
Macrophytes and Phytobenthos Combined	Sewage discharge (continuous)		High		Moderate	
	Poor nutrient management		High	Moderate	Moderate	
	Poor livestock management		High			
	Land drainage		High		Moderate	
	Poor soil management					Moderate
	Reservoir / Impoundment (non-flow related)					Moderate
Mercury and Its Compounds	Unknown	Fail	Fail	Fail	Fail	Fail
Perfluorooctane sulphonate (PFOS)	Unknown (pending investigation)	Fail			Fail	
Phosphate	Sewage discharge (continuous)	Moderate			Moderate	
	Poor nutrient management	Moderate			Moderate	
	Poor livestock management	Moderate			Moderate	
	Track / rural road				Moderate	
	Septic tanks				Moderate	
Polybrominated diphenyl ethers (PBDE)	Unknown	Fail	Fail	Fail	Fail	Fail

3.2. Coastal and Transitional Water Quality Status

Review of challenges reported within coastal and transitional waters within the study area highlights that these waters face a similar set of challenges to the area's riverine systems, notably, mercury (and mercury compounds) alongside PBDEs are highlighted as issues at each of the waterbodies for which data is provided. In addition, invertebrates and phytoplankton are stated as being issues for transitional waters, with dissolved inorganic nitrogen (e.g., nitrate) being given as a challenge faced by the Norfolk North coastal region.

The phytoplankton biological quality element is assessed in consideration of the abundance of composition of phytoplankton alongside nutrient ratios and planktonic bloom frequency and intensity (measured via chlorophyll biomass) (Water Framework Directive: UK Technical Advisory Group, 2012*a*). Normative reference descriptions for quality classes for each condition element are given in Annex V of the UK Water Framework Directive (WFD). Given descriptions range from '*High*' to '*Moderate*', however, with no description provide for '*Bad*' status. A '*Moderate*' status for phytoplankton in coastal waters is described as a waterbody where (i) there are moderate signs of disturbance in planktonic taxa composition and abundance, (ii) algal biomass lies substantially outside of the expected range for the waterbody to a degree which will impact other elements of biological quality, and (iii) there is a moderate increase in planktonic bloom frequency and intensity.

The invertebrate biological quality element is assessed in transitional and coastal waters using the Infaunal Quality Index (IQI) (Environment Agency, 2022). This index comprises three metrics selected to consider invertebrate abundance and diversity, alongside the presence and / or absence of taxa tolerant of pollution and sensitive to disturbance (Water Framework Directive: UK Technical Advisory Group, 2012*b*). Here, a '*Moderate*' status waterbody is one where (i) invertebrate taxa diversity and abundance are outside of the expected conditions by a moderate degree, (ii) there is presence of pollution-indicative taxa, and (iii) many pollution-sensitive taxa which would be expected to be present in the waterbody are absent (Water Framework Directive: UK Technical Advisory Group, 2012*b*).

Currently, no known activity is stated as being the key driver behind the challenges posed by both dissolved inorganic nitrogen and invertebrate status, with these issues pending further investigation. Further, no direct activity is attributed to any of the challenges faced by transitional or coastal waters within the study area. However, given the available information on river water quality status within the study area, it is likely that riverine inputs represent a key pressure on the coastal system. Several pressures are a common issue across riverine, transitional, and coastal waterbodies, including, mercury and PBDEs. Further, all other coastal and transitional pressures – invertebrates, phytoplankton, and dissolved inorganic nitrogen – are sensitive to the nutrient input of the riverine systems.

Table 3: Transitional and coastal water challenges, as reported by the Environment Agency (Environment Agency, 2023f, 2023g, 2023h)

Classification Element	Activity	Burn *(Transitional)*	Stiffkey and Glaven *(Transitional)*	North Norfolk *(Coastal)*
PBDE	Unknown	Fail	Fail	Fail
Mercury and Its Compounds	Unknown	Fail	Fail	Fail
Invertebrates	Unknown (pending investigation)		Moderate	
Phytoplankton	Unknown		Bad	
Dissolved Inorganic Nitrogen	Unknown (pending investigation)			Moderate

4. Pollutants of Concern

4.1. Overview

This section presents each of the pollutants of concern identified through a review of the Environment Agency's water quality monitoring in the region. Each pollutant is presented in turn with detail given on pollutant concentrations recorded under water quality monitoring programmes. This seeks to identify specific locations within waterbodies where respective EQS values have been found to have been exceeded. This is followed by a review of the potential sources of each pollutant which are then grounded within the context of the study area. Data was downloaded from the Environment Agency Water Quality Archive (Environment Agency, 2023i) programmatically, via a series of R scripts.

Finally, this section refers to a series of monitoring sites by their identifying codes. A map locating each of these sites within the study area to act as a reference is given in Annex 1.

4.2. Mercury and Mercury Compounds

Mercury and mercury-containing compounds are at elevated concentrations in each of the rivers Burn, Glaven, and Stiffkey. This is described by the EA's catchment data reported as being an issue for which measures have been taken to address elevated concentrations, for each of the rivers Burn, Glaven, and Stiffkey. Review of information available from the EA indicates that while the original source is unknown – with no specific activity or sector given as a source – mercury input to the system is no longer a concern, with the river systems being classed as awaiting recovery by the Environment Agency. Time periods given for this recovery are estimated based on the chemical status recovery time to natural conditions, defined by the EA as the "delay in the chemical substance meeting the required standard once the necessary measures to achieve compliance have been implemented" (Environment Agency, 2021c).

A study undertaken by the Environment Agency (2015) applied Source-Appointment GIS (SAGIS) to model the relative emissions of mercury from a variety of sources at a national level. highlights North Norfolk as a region where mercury concentrations in freshwater fish are between 1 and 5 times greater than the EQS (Environment Agency, 2015; Figure 4). Further, the report assessed national sources of anthropogenic mercury emissions. To provide background on the potential sources of mercury within the study area, national sources identified by the report are given in Table 4 below, in order of largest to smallest contribution:

Table 4: Total estimated urban area within each catchment, both as absolute area in hectares and as a proportion of the total catchment area.

Rank	Source	Emissions *(kg year $^{-1}$)*
1	Industrial discharges	128
2	Background / ambient	126
3	Urban run-off	66
4	Wastewater treatment works	40
5	Intermittent discharges	16
6	Atmospheric inputs	7
7	On-site waste water treatment works	1

Environmental quality standards for mercury set under the Water Framework Directive recommend threshold concentrations of mercury and its compounds of EQS of 20 μg kg^{-1} for prey tissue (wet weight), selected from an appropriate species. Recommended standards for water are 0.05 μg L^{-1} AA (annual average) and 0.07 μg L^{-1} MAC (maximum allowable concentration) for both inland and other surface waters (Environment Agency, 2019a).

To further shed light on mercury concentrations in the rivers within the study area, EA WIMS data was reviewed. Mercury measurements within the WIMS data are made in terms of dissolved mercury (measured in μg L^{-1}), dry weight mercury (measured in mg kg^{-1}), and wet weight mercury (measured in μg kg^{-1}). The results of these measurements throughout the period 2011 to 2021 are shown in Figure 3 and Figure 4 below.

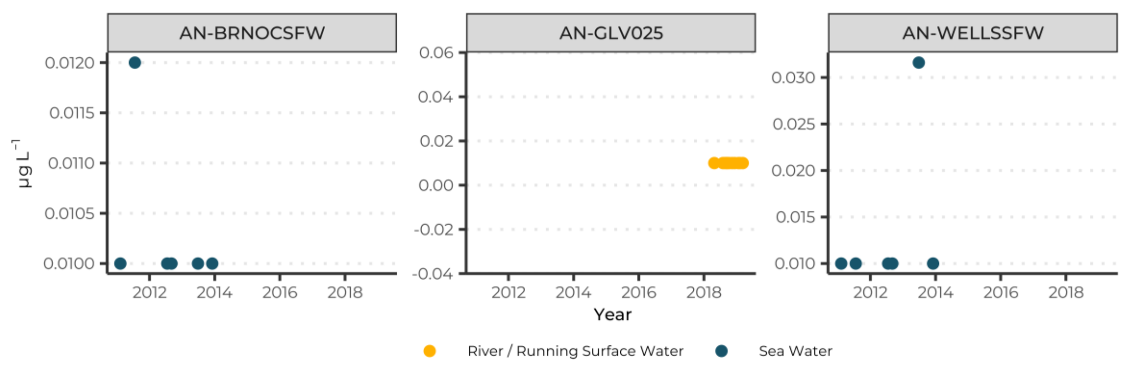

Figure 3: Measured dissolved mercury concentrations, as reported by EA WIMS data (Environment Agency, 2023i)

Values recorded for dissolved mercury concentrations in EA WIMS monitoring data indicate that all recorded values across three sites meet the EQS defined by (Environment Agency, 2019a) in terms of both annual average and maximum allowable concentration values.

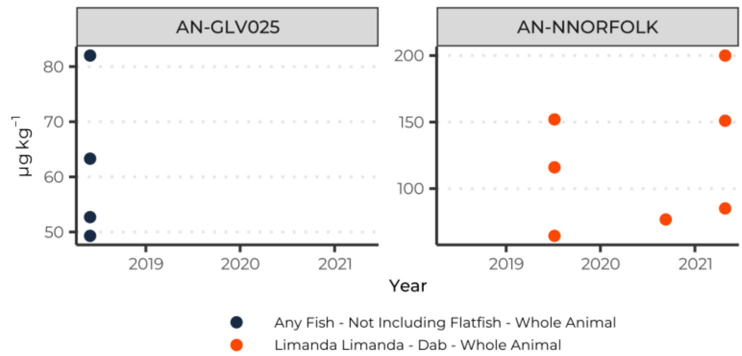

Figure 4: Measured wet weight mercury concentrations, as reported by EA WIMS data (Environment Agency, 2023i)

This data highlights that concentrations of mercury within sampled common dab (*Limanda limanda*) are consistently above EQS, with the lowest value recorded being 49.3 μg kg^{-1} (May 2018) and the greatest 200 μg kg^{-1} (April 2021). The mapped locations of these exceedances are displayed in Figure 5, which highlights the presence of elevated mercury levels within biota at both a riverine and coastal location within the study area.

Reasons for not achieving good status (RNAG) published by the Environment Agency for the River Glaven do not provide a specific activity or sector as the source of elevated mercury concentrations throughout the study area (Environment Agency, 2023c). Objectives set a target for good status to return by 2040, owing to the recovery time needed (Environment Agency, 2023c). This recovery time relates to the delay in the chemical status achieving compliance following implementation of appropriate measures.

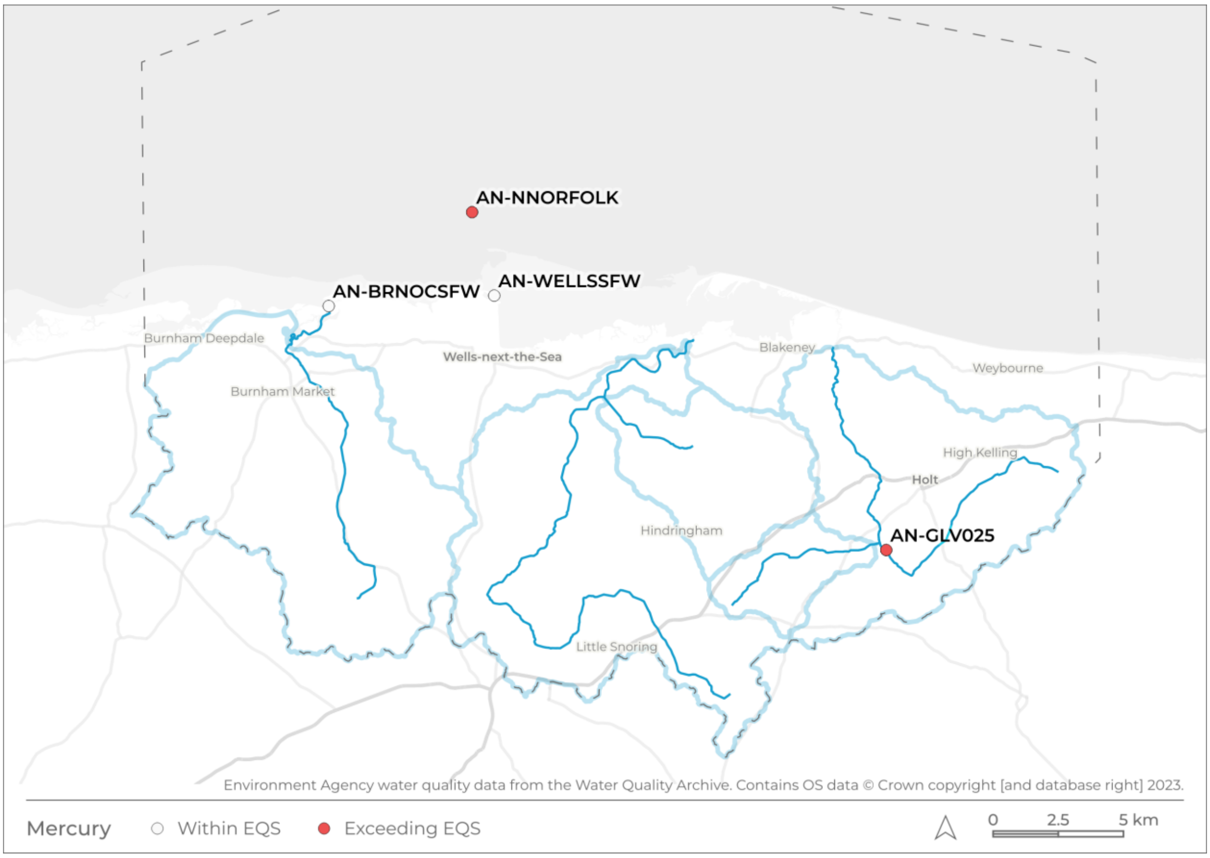

Figure 5: Locations of mercury EQS exceedances derived from EA WIMS data.

4.3. Polybrominated Diphenyl Ethers (PBDEs)

Polybrominated diphenyl ethers (PBDEs) are a class of compounds often used as flame retardants. They are persistent pollutants with potential to bioaccumulate in the environment (Costa and Giordano, 2014). Policy measures have been implemented to prevent the use of these compounds. PBDEs are – however – present in many old consumer products, including those used in homes and businesses (Environment Agency, 2019b). Consequently, wastewater treatment works (WWTWs) represent a key pathway of these pollutants into the wider environment. The resuspension of PBDE-contaminated sediment represents a further pathway by which PBDEs enter the wider environment.

Monitoring data extracted from the EA WIMS database is plotted in Figure 6 and Figure 7. This data covers measurements available for each PBDE compound, at each monitoring site. Samples have been further divided into dry weight measurements of coastal and/or marine sediment samples and wet weight measurements of whole animal samples of the common dab (*Limanda limanda*). The data is limited, particularly in regard to dry weight measurements, which return a single monitoring value per site, per PBDE compound.

Environmental quality standards for PBDEs are given in relation to the sum concentrations of 6 PBDE congeners. These are (i) PBDE-28, (ii) PBDE-47, (iii) PBDE-99, (iv) PBDE-100, (v) PBDE-153, and (vi) PBDE-154 (European Commission, 2013). The Water Framework Directive specifies a maximum allowable concentration EQS of 0.14 µg L^{-1} for inland surface waters and 0.014 µg L^{-1} for other (i.e., coastal, and estuarine) surface waters. And an EQS of 0.0085 µg kg^{-1} for total wet weight PBDE concentrations in fish (European Commission, 2013). It should be noted that the EQS for PBDE concentrations in fish is based on human receptors (as the most sensitive endpoint), rather than aquatic or other life (Environment Agency, 2019b). Monitoring values from sites within the study area – as reported in EA WIMS data (Environment Agency, 2023i) – are given in Figure 6, below.

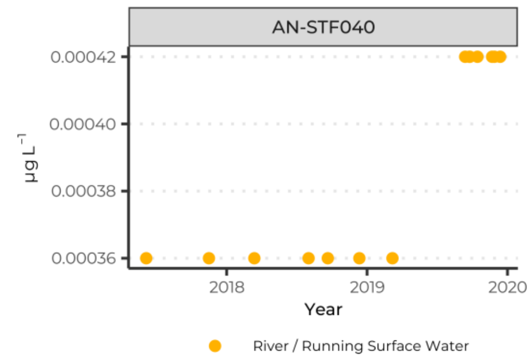

Figure 6: Measured total PBDE concentrations in waters, as reported by EA WIMS data (Environment Agency, 2023i)

Total PBDE concentrations within river and/or running surface waters – as included within EA WIMS data – highlight that reported PBDE concentrations within these waters are below the 0.14 µg L^{-1} EQS set within the Water Framework Directive. These concentrations remained relatively stable throughout the monitoring period, though, a slight increase in concentrations was noted between 2019 and 2020, the magnitude of this change (0.00006 µg L^{-1}) is small in relation to the EQS threshold value.

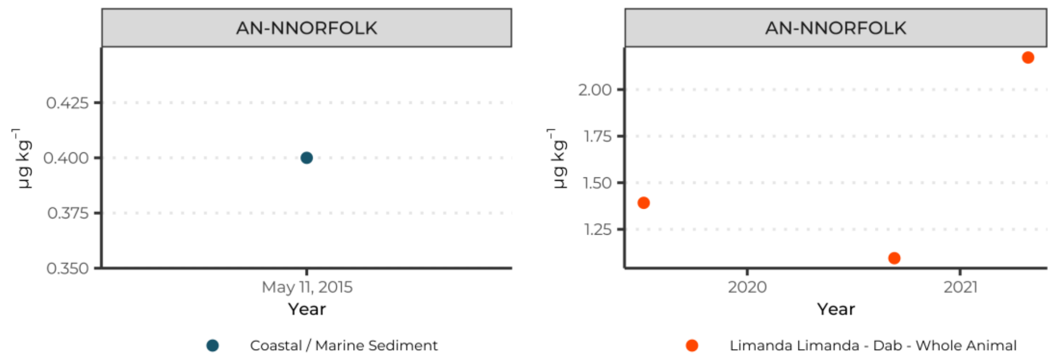

Figure 7: Measured total dry weight (*L)* and wet weight (*R*) PBDE concentrations, as reported by EA WIMS data (Environment Agency, 2023i)

Reported dry and wet weight PBDE concentrations in sediment and biota – as given within EA WIMS data – are plotted in Figure 7. Available data is highly limited here, with a single reported value given for dry weight PBDE concentrations in coastal / marine sediment., and three values given for wet weight PBDE concentrations in common dab (*Limanda limanda*) specimens. Reported concentrations within common dab (*L. limanda*) specimens range from 1.095 µg kg^{-1} to 2.172 µg kg^{-1}.

These values are in excess of the EQS by a range of 12,782.4 % to 25,452.9 %. The degree to which the EQS is exceeded reflects similar studies undertaken in the North Sea. For example, Gaion *et al.* (2021) sampled Atlantic herring (*Clupea harengus*) originating from the North Sea and found PBDE concentrations to be in excess of the EQS by 3276.47 % to 27241.18 %.

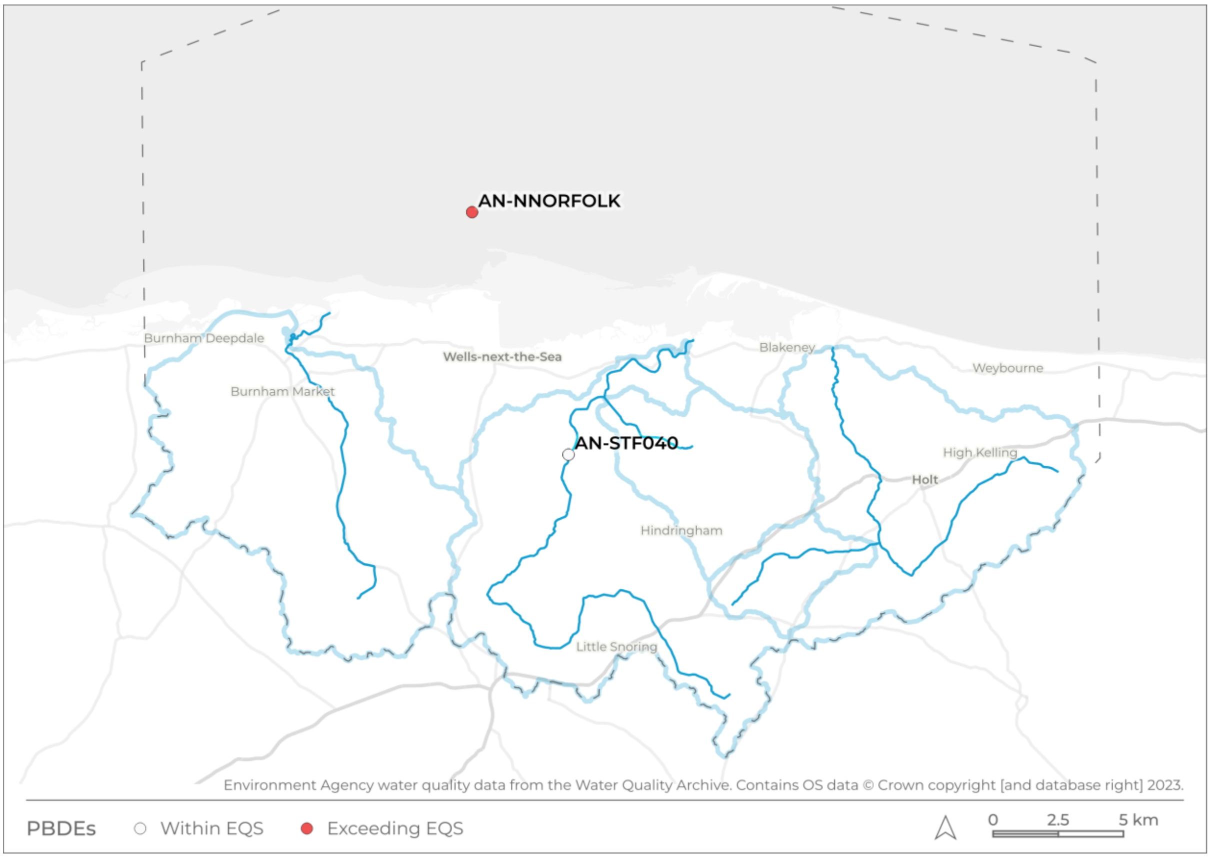

Figure 8: Locations of PBDE EQS exceedances derived from EA WIMS data.

4.4. Perfluorooctane Sulphonate (PFOS)

Perfluorooctane sulphonate (PFOS) are a category of substances belonging to a wider group of compounds known as perfluoroalkyl and polyfluoroalkyl substances (PFAS). These substances have been widely used in domestic consumer products due to their grease, stain, and water repellent nature (Environment Agency, 2019c). Moreover, PFAS have potential to break down into PFOS during water treatment or in the environment, presenting a complication for understanding pathways of PFOS into the environment (Environment Agency, 2019c).

In the environment, PFOS substances are highly stable, and present risk of significant health problems to birds and mammals (including humans) as well as exhibiting toxicity to aquatic organisms ranging from algae to invertebrates and fish (Environment Agency, 2019c). Key sources of PFOS substances into the environment are: (i) wastewater treatment works, (ii), industrial operations, (iii) urban run-off, (iv) atmospheric deposition, (v) leachate from landfill, and (vi) terrestrial sewage spreading (Environment Agency, 2021a).

Environmental quality standards produced for PFOS are defined in terms of concentrations in both water and biota. The given annual average EQS for inland surface waters is 0.00065 μg L^{-1} with a value of 0.00013 μg L^{-1} for coastal and estuarine waters (Environment Agency, 2019c). A threshold value of 9.1 μg kg^{-1} wet weight is given as the EQS for biota. As with PBDE compounds, biota EQS for PFOS are derived from human receptors, with humans being the most sensitive endpoint (Environment Agency, 2019c).

Monitoring data extracted from the EA WIMS database is plotted in Figure 9. This data contains samples extracted from two monitoring points within the study area, with samples extracted from (i) whole fish (excluding flatfish), (ii) common dab (*Limanda limanda*), and (iii) river or running surface water.

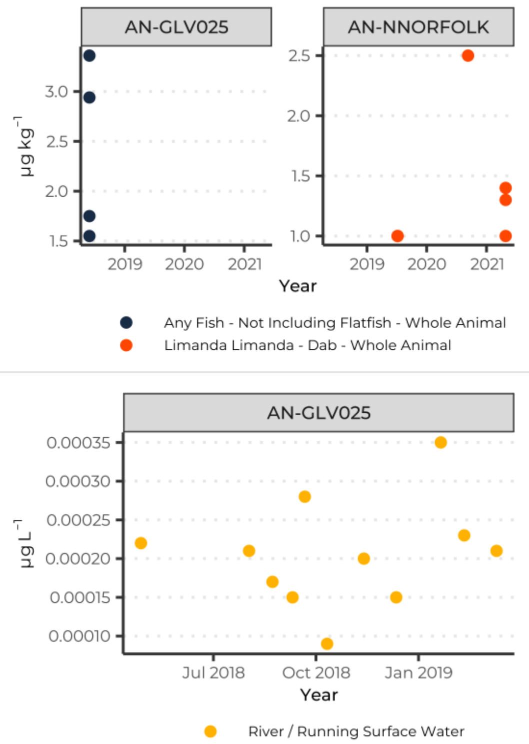

Figure 9: Recorded PFOS concentrations within the study area (Environment Agency, 2023i)

Comparison of PFOS concentrations retrieved from EA WIMS monitoring data indicates that returned samples where data is available are within EQS for both biota and inland surface waters. However, these samples cover only a small portion of the study area – a single point on the River Glaven and a single offshore location. The annual average (AA) EQS for inland surface waters is 0.00065µg/l and the AA EQS for other surface waters is 0.00013µg/l. The biota EQS is 9.1µg/kg wet weight. This suggests that PFOS have been at the upper limit of EQS in the past (see Figure 10).

In certain pH conditions, PFOS may be present as the perfluorooctanoate anion (see Environment Agency, 2019c, for further information). Reported concentrations of the perfluorooctanoate anion from EA WIMS data are given in Figure 10, below.

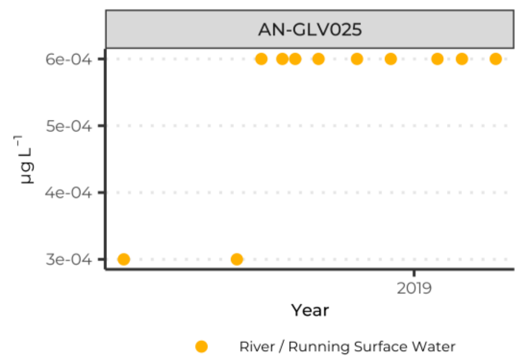

Figure 10: Recorded perfluorooctanoate anion concentrations within the study area (Environment Agency, 2023i)

4.5. Benzo(g-h-i)perylene

Monitoring data for benzo(g-h-i)perylene is present for a single monitoring location within the River Stiffkey, spanning a period from the 6th June 2017 to the 13th February 2020. The results of this monitoring are presented in Figure 11, below. These samples were all extracted from flowing river water. Recommended threshold concentrations of benzo(g-h-i)perylene within the WFD EQS are defined in terms of the sum of benzo(g-h-i)perylene and ideno(1,2,3-cd)perylene. The value set is a concentration of the combined compounds of no more than 0.002 µg L^{-1} (UK Government, 2015).

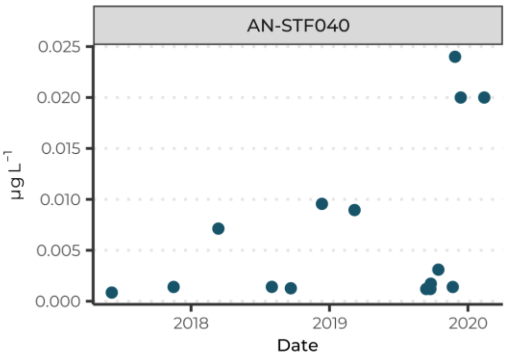

Figure 11: Recorded benzo(g-h-i)perylene concentrations in the River Stiffkey (Environment Agency, 2023i)

Monitoring data highlights that these concentrations have been exceeded when considering benzo(g-h-i)perylene alone, with all values recorded post-2019 being approximately an order of magnitude greater than the WFD EQS threshold value.

The location of the monitoring location on the River Stiffkey where these EQS exceedances were recorded is shown in Figure 12, below.

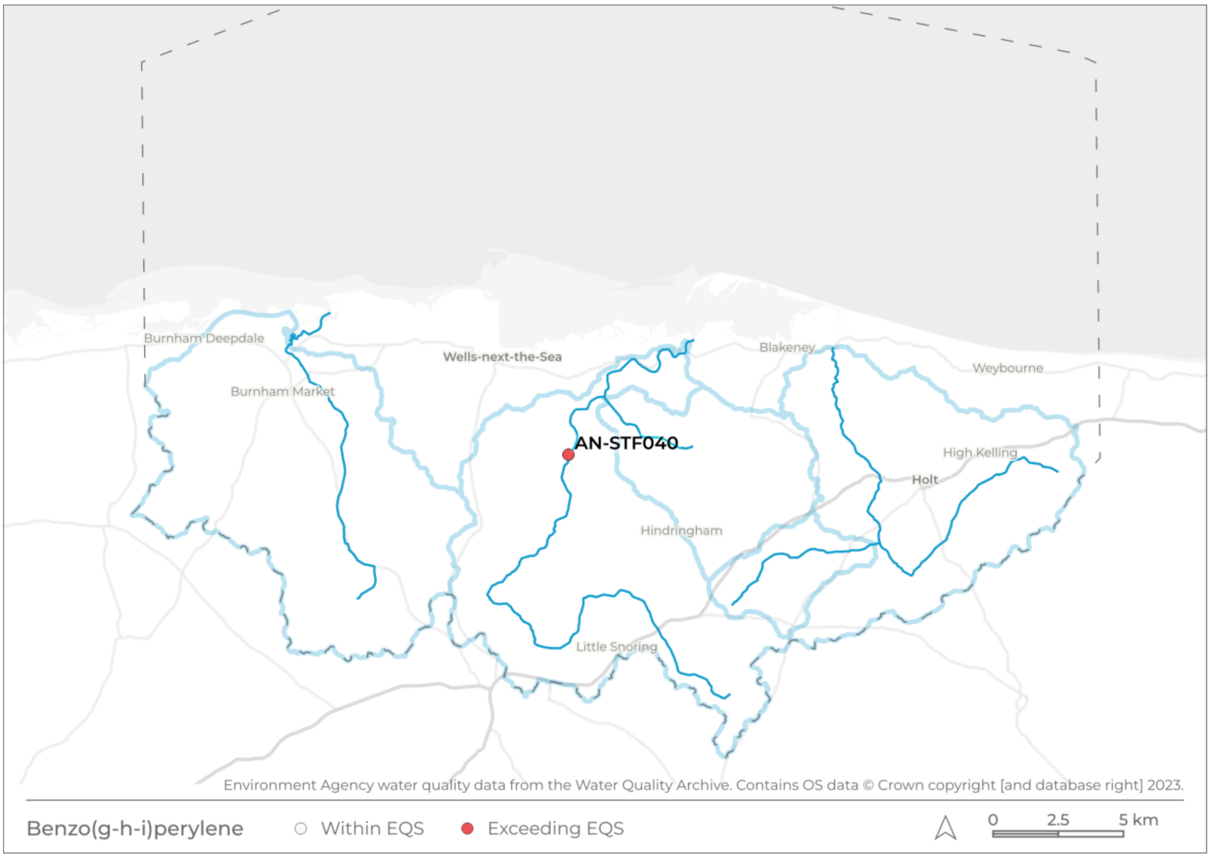

Figure 12: Locations of benzo(g-h-i)perylene EQS exceedances derived from EA WIMS data.

4.6. Phosphates

Phosphorus standards are variable depending on other water quality parameters. A predictor tool to calculate these has been published by the UK Technical Advisory Group (UKTAG) (2014). This tool takes two predictor variables (i) altitude and (ii) mean observed alkalinity (expressed as mg $CaCO_3$ L^{-1}). To retrieve elevation data for the sampling points where phosphorus data is available, GIS tools were applied. Mean alkalinity measurements reported in the EA WIMS data (2012-2021) (Environment Agency, 2023i) were used as inputs for mean observed alkalinity. Alkalinity measurements were unavailable for two monitoring locations (AN-BRN005 and AN-GLV005). In these instances, the alkalinity measurements from the nearest available downstream location were used as an alternative.

The standards produced by this approach are plotted, alongside calculated phosphorus concentrations, in Figure 13, below.

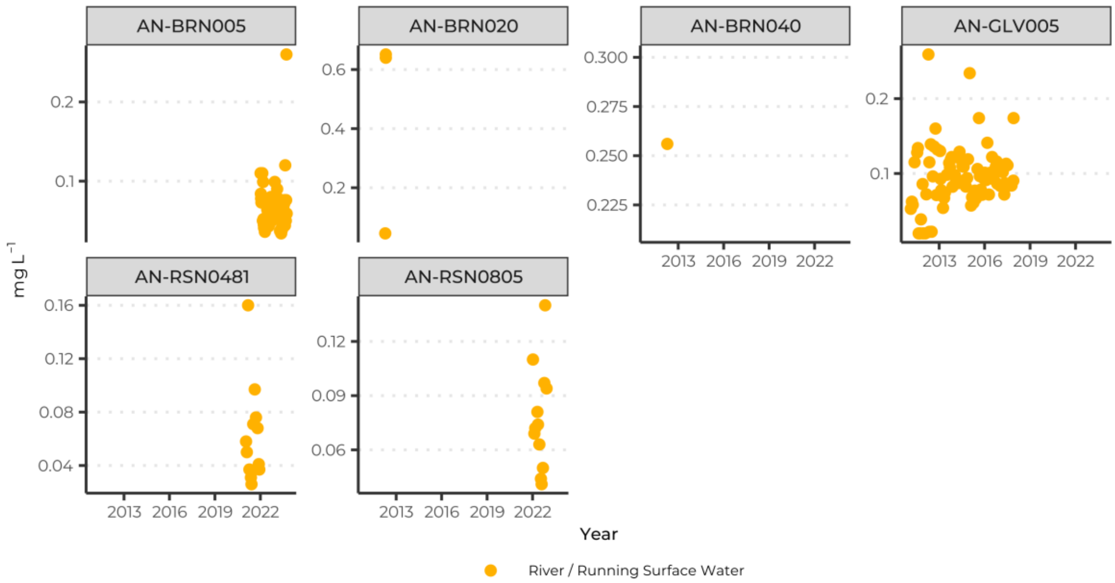

Figure 13: Phosphorus concentrations (as total P) as reported by EA WIMS data (Environment Agency, 2023i)

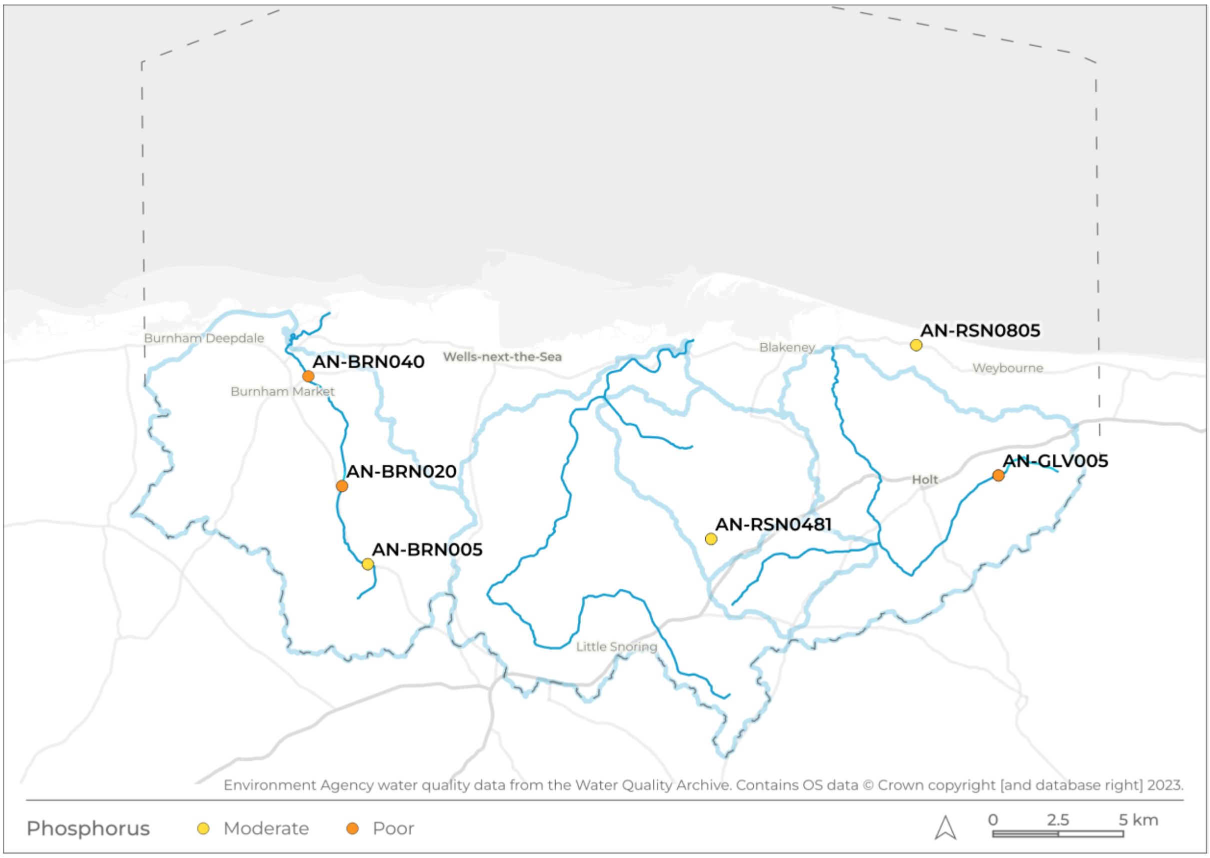

Figure 14: Locations of phosphorus (as total P) condition values derived from EA WIMS data.

Comparison of measured values for total phosphorus with calculated environmental quality standards highlights that both the Rivers Burn and Glaven recorded a status of 'poor' as assessed against standards calculated from the UK TAG predictor tool. No results were returned for the River Stiffkey. Applying the results plotted in Figure 13 (above), with the map presented in Figure 14, highlights that total phosphorus concentrations in running surface waters are highest at AN-BRN020, located approximately mid-way along the course of the River Burn.

To seek to address the gap in available data for the River Stiffkey, additional measures of phosphorus content were calculated. These were total inorganic phosphate and leachable orthophosphate. Retrieving measures of total inorganic phosphates does not provide any additional data in relation to the River Stiffkey, rather additional data relating to the three monitoring points along the River Burn, for which phosphorus (as total P) data has been retrieved. Indeed, total inorganic phosphate concentration shows a similar pattern to total P concentration.

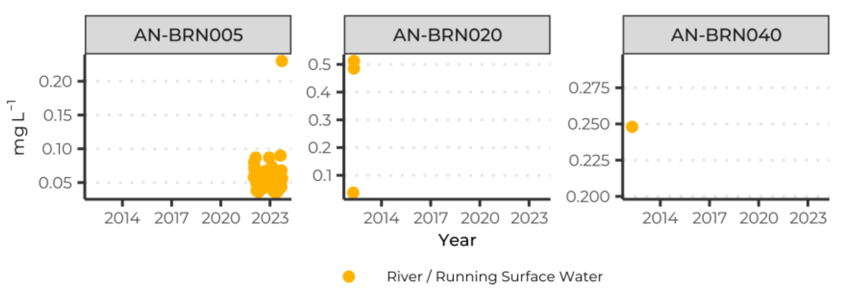

Figure 15: Total inorganic phosphate concentrations as reported by EA WIMS data (Environment Agency, 2023i)

4.7. Nitrogen

Water quality status data highlights nutrient management as a key challenge to water quality in the study area, in particular issues relating to macrophytes and phytobenthos. Measures relating to nitrogen are further explored here.

Nitrogen is plotted as Ammoniacal Nitrogen as N, and Nitrate as N. Ammonia within waterbodies undergoes nitrification, through which it is oxidised to form nitrite and nitrate. Nitrate and ammonia data contains a much greater depth of records than many other contaminants explored here, with the data spanning a range of approximately 20 years.

4.7.1. Nitrates

Sources of nitrates within England are estimated by the Environment Agency (2021b) at approximately 70% agriculture and 25% - 30% sewage effluent, with nitrate issues typically most pronounced in southern and eastern England. Elevated nitrate concentrations within waterbodies presents risk of eutrophication to lowland surface waters, with additional risks of acidification posed to upland surface waters (Environment Agency, 2019d).

Nitrate Vulnerable Zones (NVZs) are designated areas comprising land which drains into nitrate-polluted or -threatened waters (Environment Agency, 2021b). These are mapped in Figure 16, below, alongside the primary reason for classification. Here, terrestrial areas within the study area are entirely classed as NVZs for groundwater, with several areas of surface waters also receiving the NVZ designation. Areas of surface waters classified as NVZs are: (i) the majority of the River Burn catchment, (ii) the Binham Tributary catchment, and (iii) the River Glaven upstream of the river's confluence with Gunthorpe Stream. In addition, the Bure Broads eutrophic lake NVZ is located immediately east of the study area.

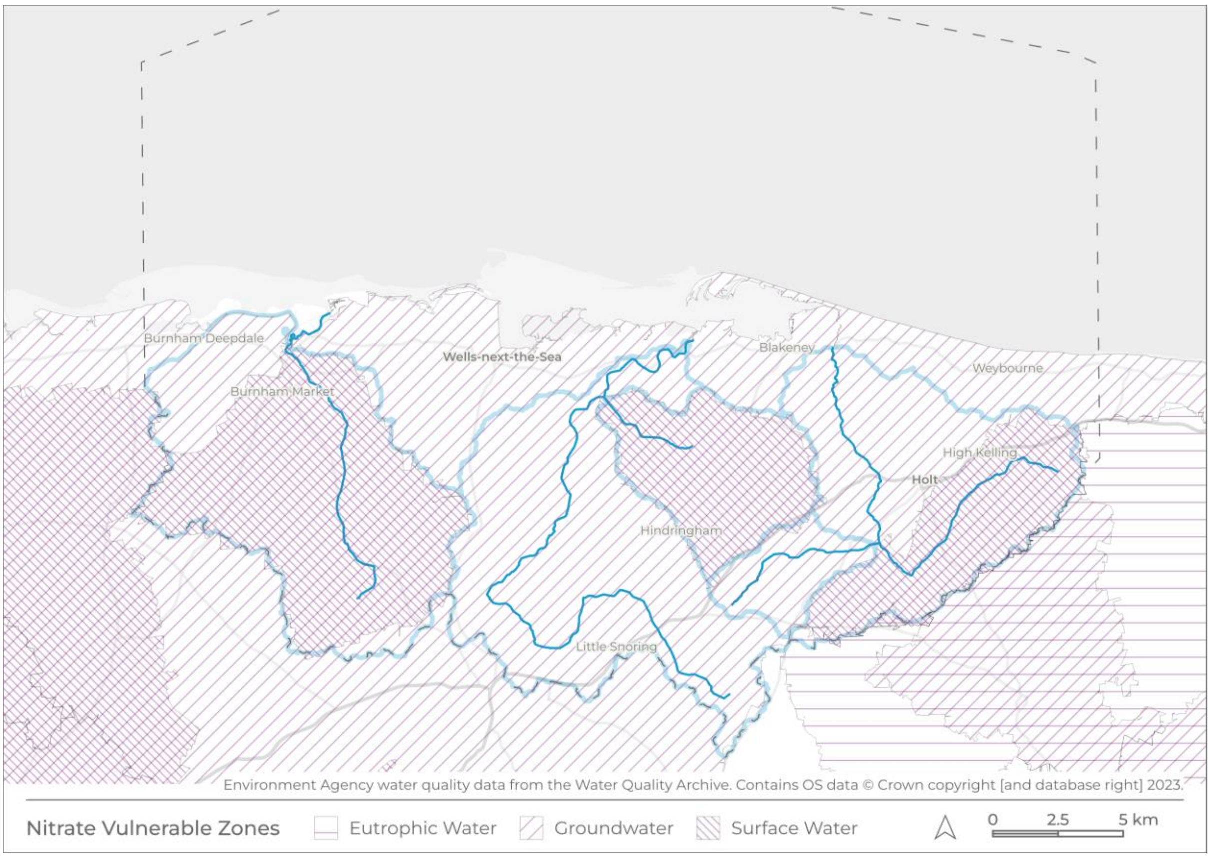

Figure 16: Nitrate Vulnerable Zones within the study area

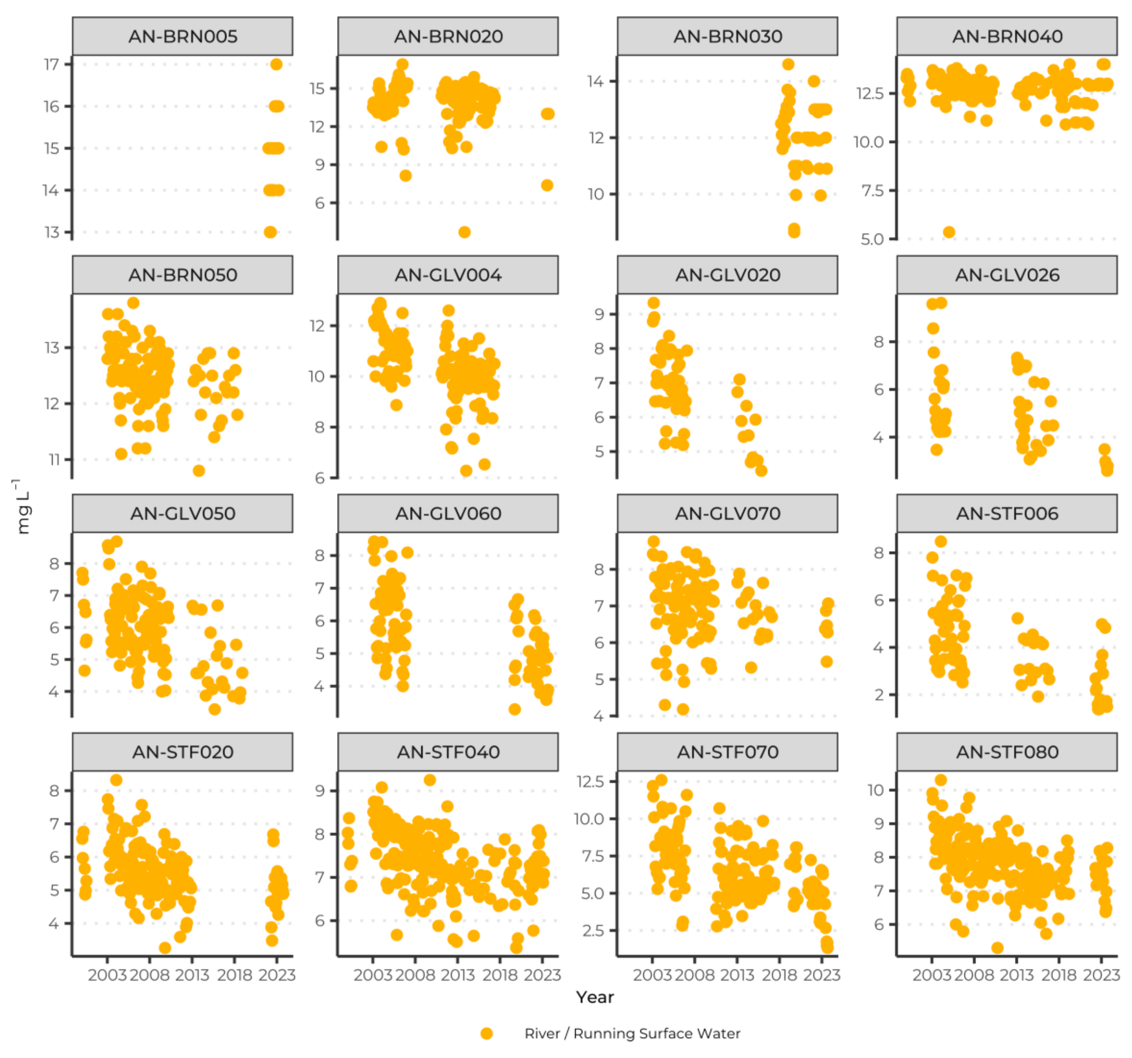

Figure 17: Nitrate concentrations as reported in rivers and running surface waters by EA WIMS data (Environment Agency, 2023i)

Reviewing concentrations recorded within the study area highlights that all monitoring points along the River Burn record values within the 10 to 25 mg L^{-1} range. This range is the most frequently occurring value nationally. The monitoring points along the River Glaven each recorded values within the 2 to 10 mg L^{-1} range, with the exception of the furthest upstream monitoring point (GLV004) which records values within the 10 to 25 mg L^{-1} range. This correlates with NVZ data, with this point located in the River Glaven NVZ. Finally, the River Stiffkey records nitrate levels within the 2 to 10 mg L^{-1} range upstream, with recorded values increasing into the 10 to 25 mg L^{-1} range further downstream.

Analysis of groundwater monitoring data [Annex 2] displays recorded nitrate groundwater concentrations as being highest in the upper reaches of the River Burn and the River Glaven, where values near the upper limits of the <25 mg L^{-1} range. All recorded concentrations are within the < 25 mg L^{-1} range, with an estimated 59 % of monitoring points being within this range across England.

Table 5: Mean nitrate concentrations in (i) rivers and lakes, and (ii) groundwaters, 2012-2015 (UK Parliament, 2018)

Waterbody	Monitoring Points in Range (%)					
	0 to 2 mg L^{-1}	>2 to 10 mg L^{-1}	>10 to 25 mg L^{-1}	>25 to 40 mg L^{-1}	>40 to 50 mg L^{-1}	>50 mg L^{-1}
Rivers and Lakes	6 %	22 %	36 %	24 %	6 %	6 %
Groundwater	59 %			19 %	8 %	14 %

4.7.2. Ammonia

Ammonia environmental quality standards within riverine systems are variable with the altitude and alkalinity of the monitoring location (UK Government, 2015). Here, altitude was calculated with GIS tools and alkalinity using long-term monitoring data retrieved from the EA WIMS data archive (Environment Agency, 2023i). This returned the same standards for each monitoring location, a factor of the low-lying landscape and their geographic proximity. Standard threshold concentrations are then based on the 90th percentile (UK Government, 2015). This gives the following lower limits for standards at each site: High status = 0.3 mg L^{-1}, Good status = 0.6 mg L^{-1}, Moderate status = 1.1 mg L^{-1}, Poor status = 2.5 mg L^{-1}. These standards reflect the alkalinity of river waterbodies within the study area.

Due to the number of monitoring sites and sampled materials where ammonia content is measured, nitrogen inputs are plotted as groups. Sites where river and running surface water is sampled are plotted (Figure 18).

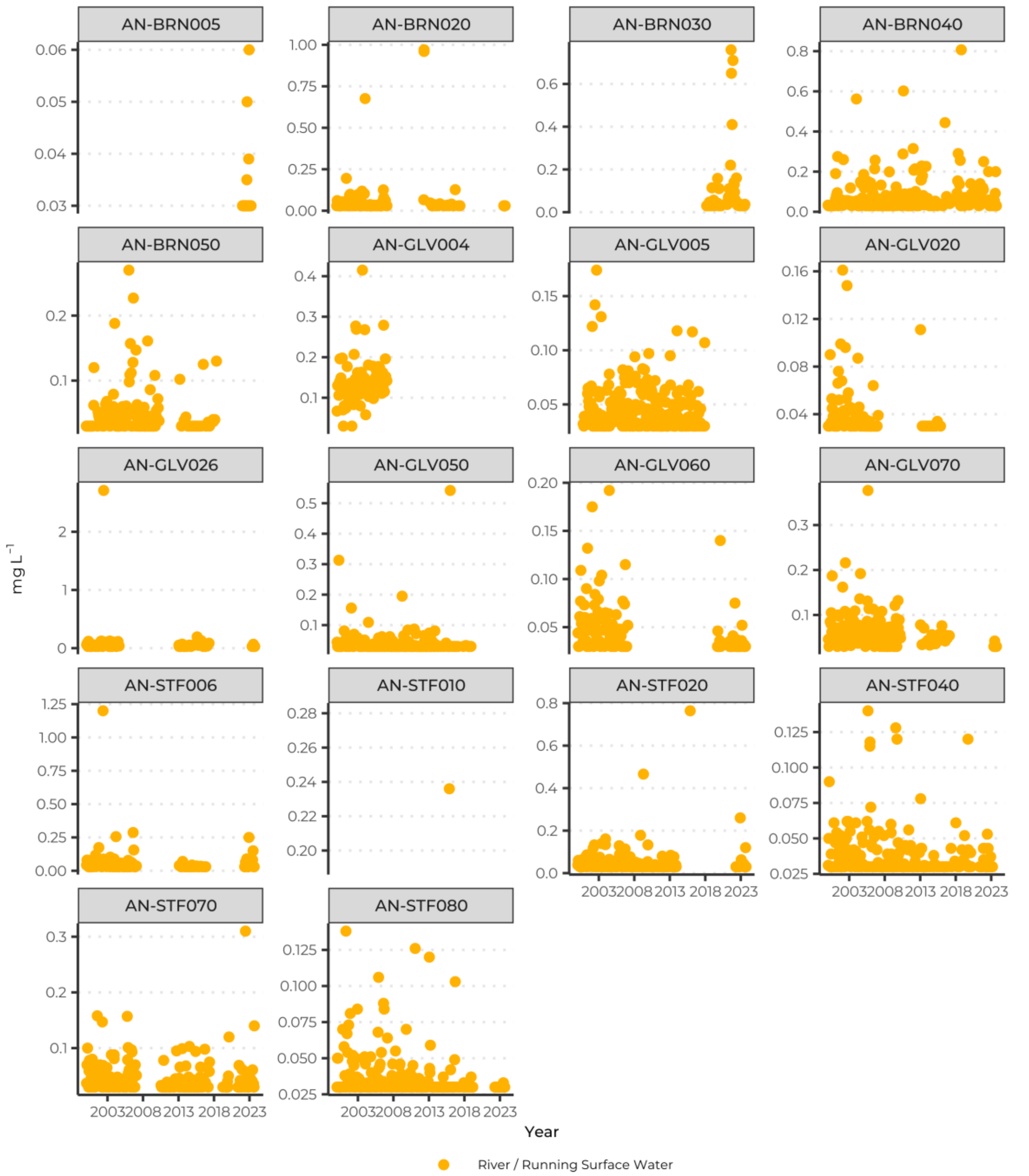

Figure 18: Ammonia (as N) concentrations as reported in rivers and running surface waters by EA WIMS data (Environment Agency, 2023i)

Maximum values reported in EA WIMS data (Figure 18) range from between approximately 0.13 mg L^{1} to approximately 2.75 mg L^{-1}. This data highlights values recorded within some river catchments which fall within the 'Poor' water quality status, however, when considering the mean of 90^{th} percentile values, the lowest water quality status recorded is 'Moderate'.

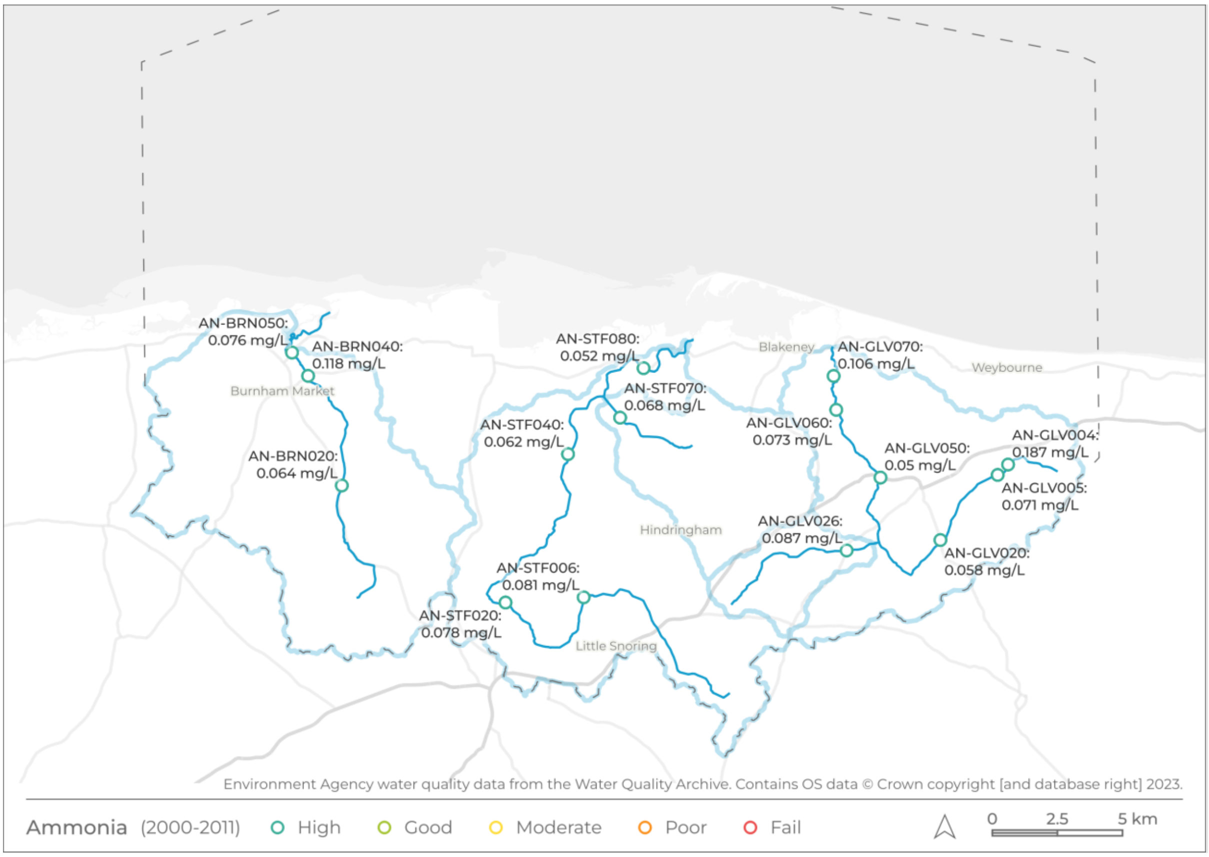

Figure 19: Ammonia (as N) concentrations as reported in rivers and running surface waters by EA WIMS data, values shown are the mean of the reported 90th percentile value throughout the period 2012 to 2023 (Environment Agency, 2023i)

This data highlights the calculated water quality status – based on monitoring data available through the EA WIMS database. This suggests two trends in the data; (i) that the River Burn exhibited most occurrences of ammonia water quality status being below 'Good', and (ii) that these areas of below 'Good' status are typically located midway along the river's route.

5. Drivers of Pressures

5.1. Overview

Here, we look to wider datasets to explore activities being undertaken within the study area which may contribute to the chemical and nutrient pressures identified by the review of Environment Agency monitoring data. These activities include wastewater processing and discharge, agriculture, industry, landfill and waste management, urban development, and shipping.

5.2. Wastewater

Wastewater has been identified as a key source of the pollutants of concern identified through review of water quality monitoring data. These pollutants include the nitrogenic compounds, phosphate, and both PBDEs and PFOS. There are a number of combined sewer overflows (CSOs) and active wastewater treatment works (WWTW) within the study area.

5.2.1. Combined Sewer Overflows

Locations of combined sewer overflows (CSOs) and discharge event duration monitoring data are published annually by the Environment Agency (2023j). These annual returns present discharge events in terms of total duration in hours and in terms of the 12/24-hour counting method. Under this method, spills in the first 12-hour block following discharge are counted as one spill, with spills in each subsequent 24-hour block counted as one spill per block (Environment Agency, 2023j). This data highlights the presence of CSOs at both inland and offshore locations. Spills published in annual returns for 2022 for CSOs in the study area are shown in Figure 20, below. Each CSO is represented by a point, with colouration representing the number of recorded spills in 2022, as measured using the 12/24-hour counting method. This is to highlight the relative discharges of CSOs within and around the study area.

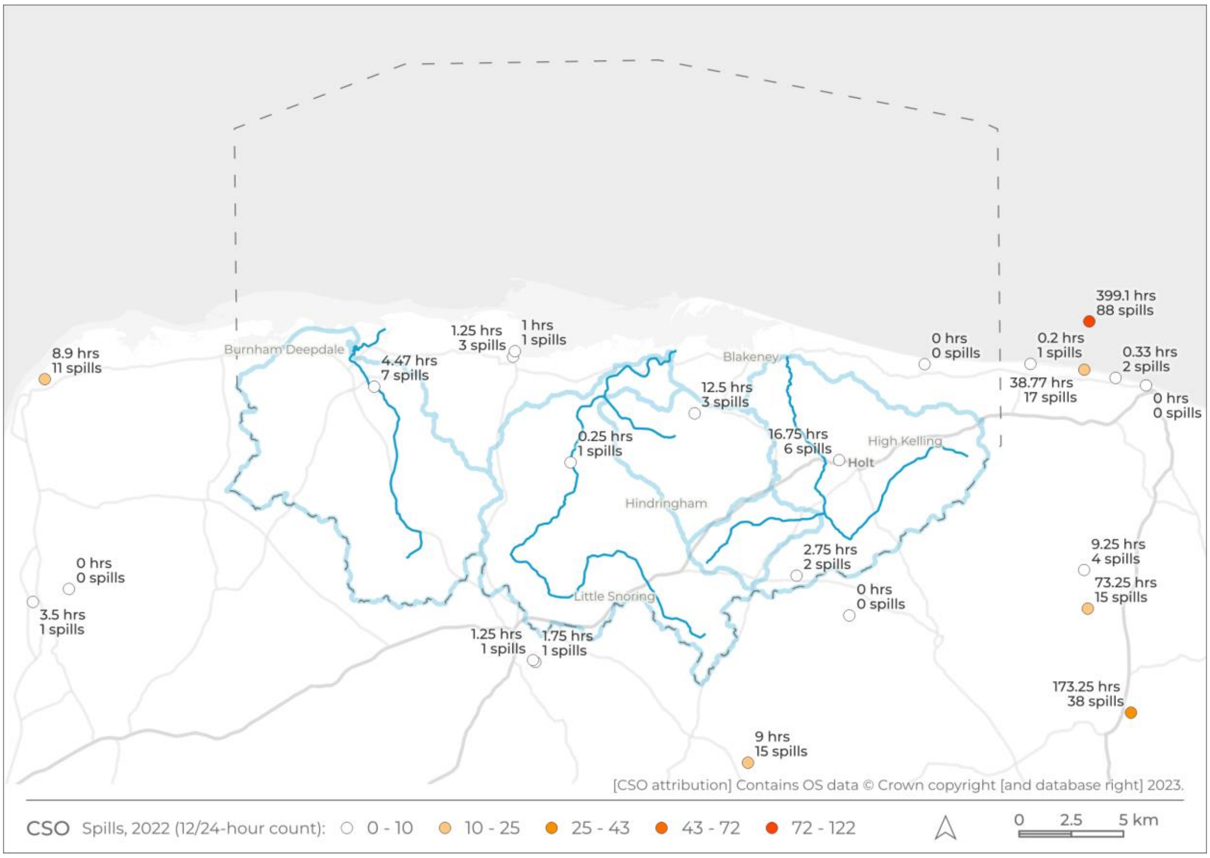

Figure 20: CSO spills published in annual returns for 2022, spills are shown with both total spill duration (in hours) and the number of spills calculated as per the 12/24-hour counting method.

This data highlights the presence of CSO within each of the main three river catchments (Burn, Stiffkey, and Glaven) which comprise the study area. These CSO reported between 1 and 7 spills (totalling between 0.25 and 16.75 hours) in 2022. The wider area, particularly to the east of the study, displays a much greater prevalence of discharge events, most notably a discharge point located offshore of Sheringham. This discharge point is an inlet storm overflow and is part of Cromer Sewage Treatment Works. A total of 88 spills were recorded from the overflow in 2022, totalling 399 hours in duration.

Table 6: Total spill duration and spill count by river basin.

Basin	**Total Spill Duration** *(hours)*	**Spill Count** *(12/24-hour counting method)*
Burn	4.47	7
Glaven	19.50	8
Stiffkey	0.25	1
Binham Tributary	12.50	3
Gunthorpe Stream	0	0
Burn (Transitional)	0	0
Stiffkey & Glaven (Transitional)	2.25	4
North Norfolk (Coastal)	0	0

5.2.2. Final Effluent Monitoring

Discharges of wastewater effluent are monitored for a range of contaminants at key discharge points by the Environment Agency. This provides insight into the composition of post-treatment wastewater being discharged within the study area, and therefore the degree to which these activities contribute to the chemical and nutrient pressures reported within the study area.

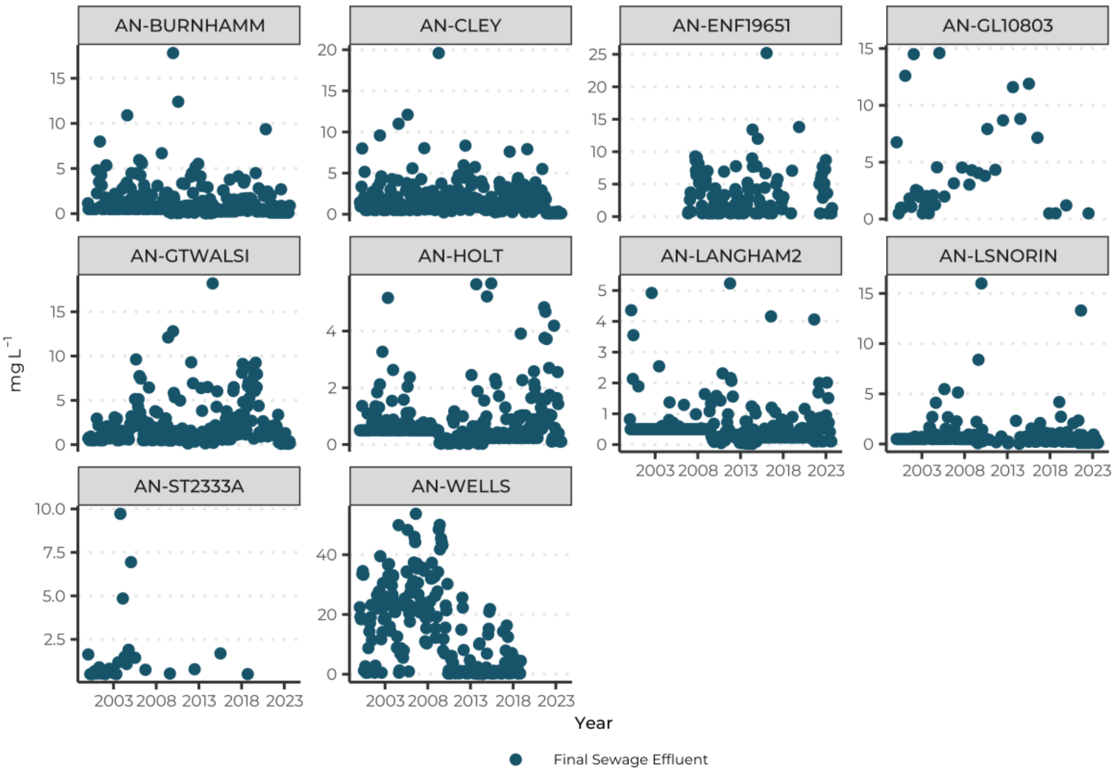

Figure 21: Ammonia (as N) concentrations as reported in final sewage effluent by EA WIMS data (Environment Agency, 2023i)

The data presented in Figure 21 shows that monitored final sewage effluents within the study area typically range from containing maximum ammonia (as N) concentrations ranging from approximately 5 mg L^{-1} (AN-LANGHAM2) to approximately 60 mg L^{-1} (AN-WELLS). This data has been summarised by the count of discharge points within each river basin within the study area, and the mean concentrations recorded over the period 2012-2023.

Table 7: Monitored final sewage effluent discharge point count and mean ammonia concentration by river basin.

Basin	Discharge Point Count	Mean Ammonia Concentration *(mg L^{-1})*
Burn	1	1.195
Glaven	2	1.327
Stiffkey	3	1.912
Binham Tributary	1	0.447
Gunthorpe Stream	1	5.649
Burn (Transitional)	0	0
Stiffkey & Glaven (Transitional)	2	3.741
North Norfolk (Coastal)	0	0

5.3. Industry

Limited information is available on aquatic industrial emissions. A review of the Environment Agency's Pollution Inventory dataset (Environment Agency, 2023i) for discharges via wastewater and controlled waters identified a single potential emission source within the study area.

This is Edgefield Landfill Site, located within the catchment of the River Glaven. The landfill site stopped receiving new waste in 2014 and is categorised within the Pollution Inventory as being a non-hazardous landfill site. Landfill sites may represent a source of a wide range of pollutants, including mercury, PBDEs, and PFOS. No discharges of these substances – or any other monitored substances - via controlled or wastewaters above the reporting threshold have been reported throughout the period 2013-2021. This reporting threshold

Expanding this search to include atmospheric emissions (alongside controlled waters and wastewater) identified a wider set of industries. These industries – as reported in the 2021 data include (i) an intensive (>2,000 animal) pig farm in the Burn catchment, (ii) a food processing centre in the Stiffkey catchment, (iii) two intensive (>40,000 animal) poultry farms – both within the Stiffkey catchment, (iv) an additional intensive (>40,000 animal) poultry farm near the outlet of the River Stiffkey. Each of these industries is required to report emissions for a set of substances, should these emissions exceed a threshold value. These substances include methane and ammonia for the intensive pig farm, ammonia and PM10 (particulate matter with a diameter of 10 microns or smaller) for the intensive poultry farms, and carbon dioxide and total particulate matter for the food processing facility.

These sites, along with Edgefield Landfill site, are plotted in Figure 22, below.

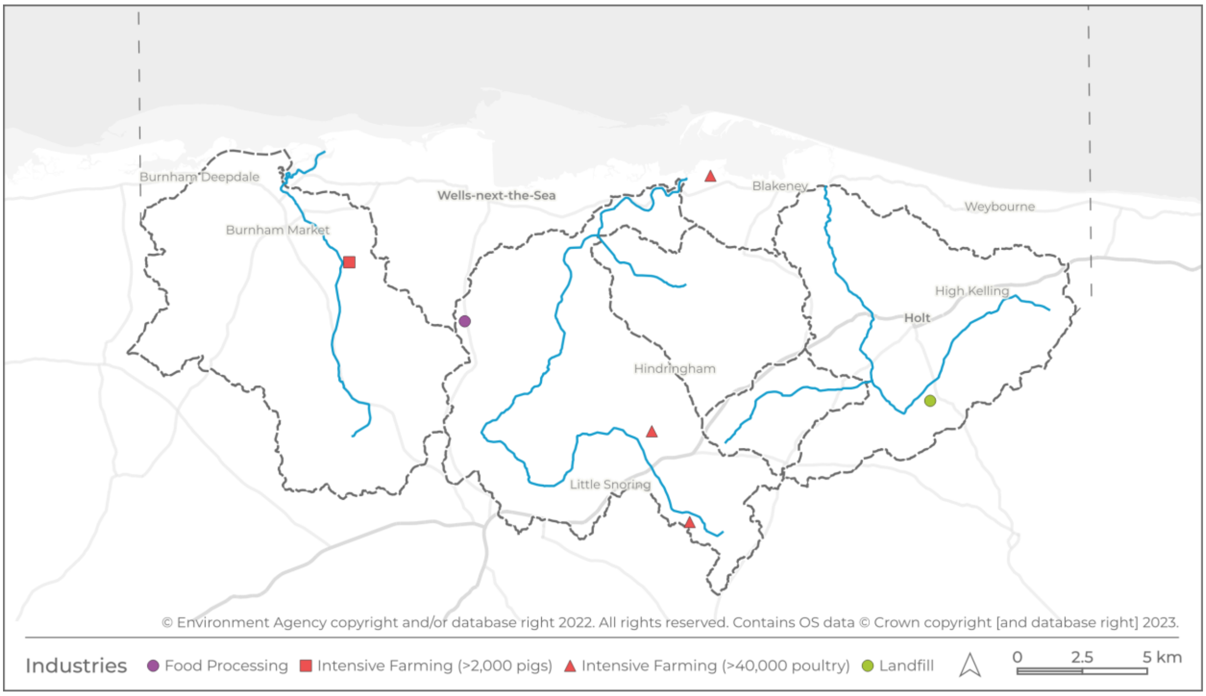

Figure 22: Locations of key industries within the study area, as reported in EA Pollutant Inventory data Environment Agency, 2023i.

Reviewing this data highlights the concentration of industrial activity within the study area to the agriculture and food industry, with ammonia emissions reported at four of the five identified sites.

It is worth noting that this data does not contain any records of sensitivity either commercially or to national security are not included within this data.

5.4. Agriculture

5.4.1. Livestock Inputs

Livestock management has been identified as a contributing factor to multiple pressures throughout the study areas.

Information relating to cattle population density is published annually by the UK Animal Plant & Health Agency [APHA] and produced by Livestock Demographic Data Groups, established in 2014. This data includes livestock populations aggregated to the local authority level. These are given in Table 8 for each of the two local authorities present within the study area, namely "*King's Lynn and West Norfolk*" and "*North Norfolk*". These give counts for four major groups of livestock (Table 8), with values for cattle obtained from APHA Cattle Tracing System (CTS) data.

Table 8: Livestock populations (2013-2021) on commercial holdings per Local Authority as reported by Defra (2023)

Local Authority	Year	Cattle & Calves	Sheep & Lambs	Pigs	Poultry
King's Lynn and West Norfolk	2021	9,520 (+8.0%)	30,806 (+19.7%)	159,462 (+48.8%)	1,149,413 (+134%)
	2016	8,811 (-4.1%)	25,720 (+20.3%)	107,194 (-3.2%)	491 018 (+13.5%)
	2013	9,187	21,378	110,788	432,503
North Norfolk	2021	9,178 (-14.1%)	23,527 (+31.9%)	99,944 (+55.6%)	2,919,712 (+74.9%)
	2016	10,685 (-8.5%)	17,837 (+4.1%)	64,222 (-10.2%)	1,669,571 (-13.1%)
	2013	11,677	17,133	71,502	1,921,740

This data indicates that cattle and calve populations have remained stable within the study area between 2013 and 2021. In contrast, sheep and lamb, pig, and poultry populations across both local authorities have increased over the same period.

This may reflect a potential intensification of livestock farming within the study area, though consideration needs to be given to the fact that these values represent an area (Local Authorities) wider than the study area. This produces uncertainty in the extent to which these changes are produced by changes in livestock populations within the study area specifically. However, as identified through review of EA Pollutant Inventory data, there are two intensive poultry farms containing > 40,000 animals and one intensive pig farm containing > 2,000 animals within the study area (Figure 22).

To further indicate livestock activity within the study area, a review of aerial imagery has been undertaken to digitise areas of livestock activity. Areas identified by this review are shown in Figure 23, below.

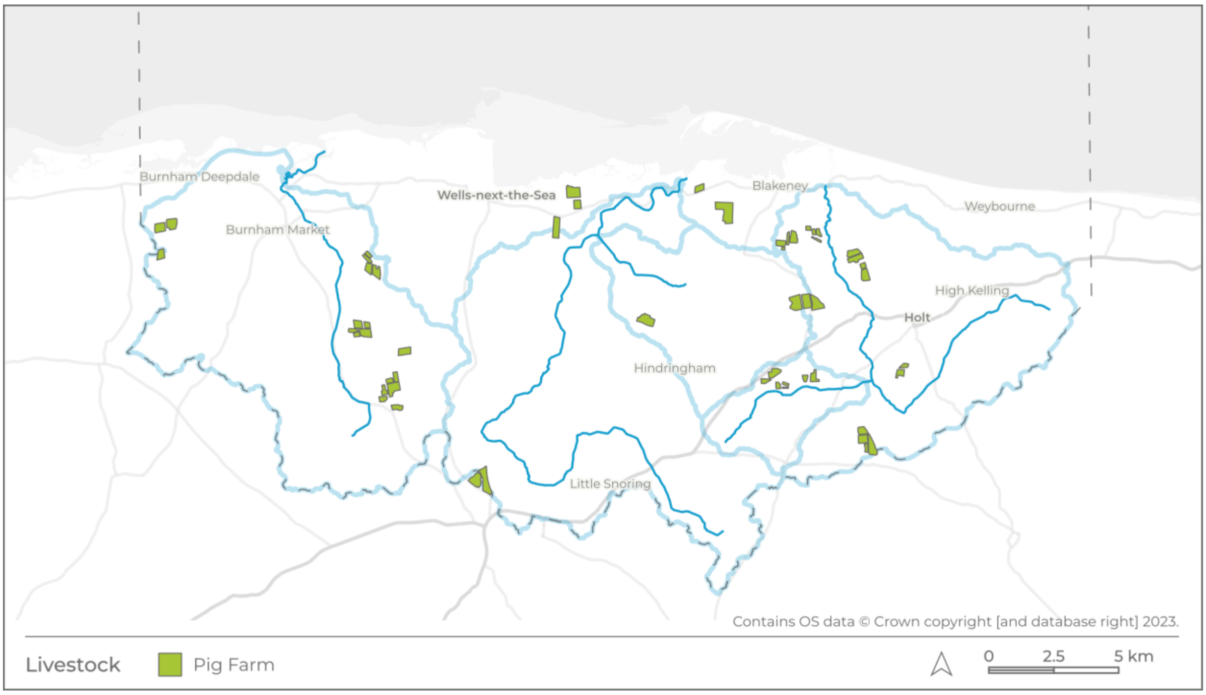

Figure 23: Locations of pig farming within the study area, digitised from aerial imagery.

As pig farming is typically undertaken under rotation, these values are representative of a snapshot in time. Therefore, the value given for total farming area is given to provide a more general indication of the degree to which pig farming is undertaken within the study area.

Table 9: Total area of pig farming within the study area

Basin	Catchment Area *(ha)*	Total Area of Pig Farming *(ha)*	Area of Pig Farming *(as % of total)*
Burn	10120.30	159.2	1.57
Glaven	7681.95	155.1	2.02
Stiffkey	9899.35	30.15	0.30
Binham Tributary	3680.24	48.63	1.32
Gunthorpe Stream	1499.00	37.38	2.49
TOTAL	**32880.84**	**430.46**	**1.31**

Nutrient pollution has been identified by the Environment Agency as a challenge in both coastal and terrestrial waterbodies throughout the study area, with livestock management identified as a challenge in each of the five terrestrial catchments. The increase in livestock numbers - particularly poultry - within the Local Authority areas intersecting the study area, within the period 2013-2021, highlights a potential area of concern. However no clear evidence of a direct impact of these livestock numbers on water quality within the study area has been identified through review of Environment Agency data. This may be a result of the Local Authority increases in livestock numbers being disproportionately located outside of the study area or limitations with the Environment Agency monitoring data.

5.4.2. Fertiliser Application

To indicate potential nutrient inputs from fertilised land, Defra's 2021 Survey of Fertiliser Practice (Defra, 2022) was applied with Crop Map of England (CROME), with data published by the Rural Payments Agency (Rural Payments Agency, 2023). These data sets have been used to map crops in the study area using the overall application rates for England and Wales published in the Survey of Fertiliser Practice

(Defra, 2022). It should be noted that application rate values are calculated as an average for England and Wales, and therefore, there may be a high degree of variation within the mapped data. There is also likely to be variation in the pathways taken by applied fertilisers due to the range of mitigation measures which may be in place at any given location. These application rates as applied here have been given in Table 10, below. The crop codes as given in CROME data have also been provided.

Table 10: Overall application rates of nitrogen (N), phosphate (P_2O_5), and potassium oxide (K_2O) for key crops as reported in Defra (2022), mapped to CROME crop classes (Rural Payments Agency, 2023.)

Crop Class	Crop Code(s)	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Spring Wheat	AC32	139	12	13
Winter Wheat	AC66	188	19	23
Spring Barley	AC01	101	18	20
Winter Barley	AC63	141	23	29
Winter and Spring Oats	AC19, AC65	104	15	15
Winter Rye	AC68	115	13	17
Potatoes	AC44	116	83	140
Sugar Beet	AC03	67	19	44
Winter Oilseed	AC67	170	21	23
Linseed	AC16	90	10	11
Maize	AC17	57	38	21
Peas	LG07	-	-	6
Spring and Winter Field Beans	LG03, LG20	1	9	13
Spring Cabbage	AC34	-	31	84

This data is mapped for total nitrogen (N) in Figure 24 (below). This highlights the relatively high density of total nitrogen intensive crops within the Burn and Stiffkey catchments, while these are predominantly restricted to the upper reaches of the Glaven catchment.

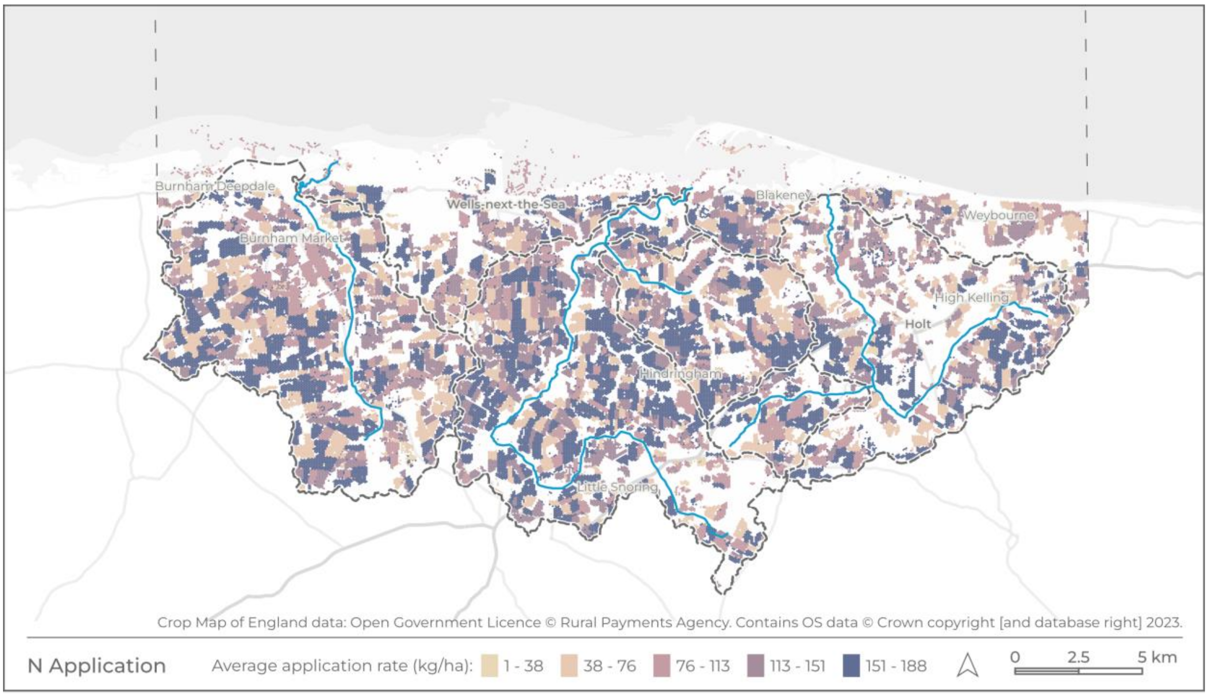

Figure 24: Estimated total nitrogen application within the study area.

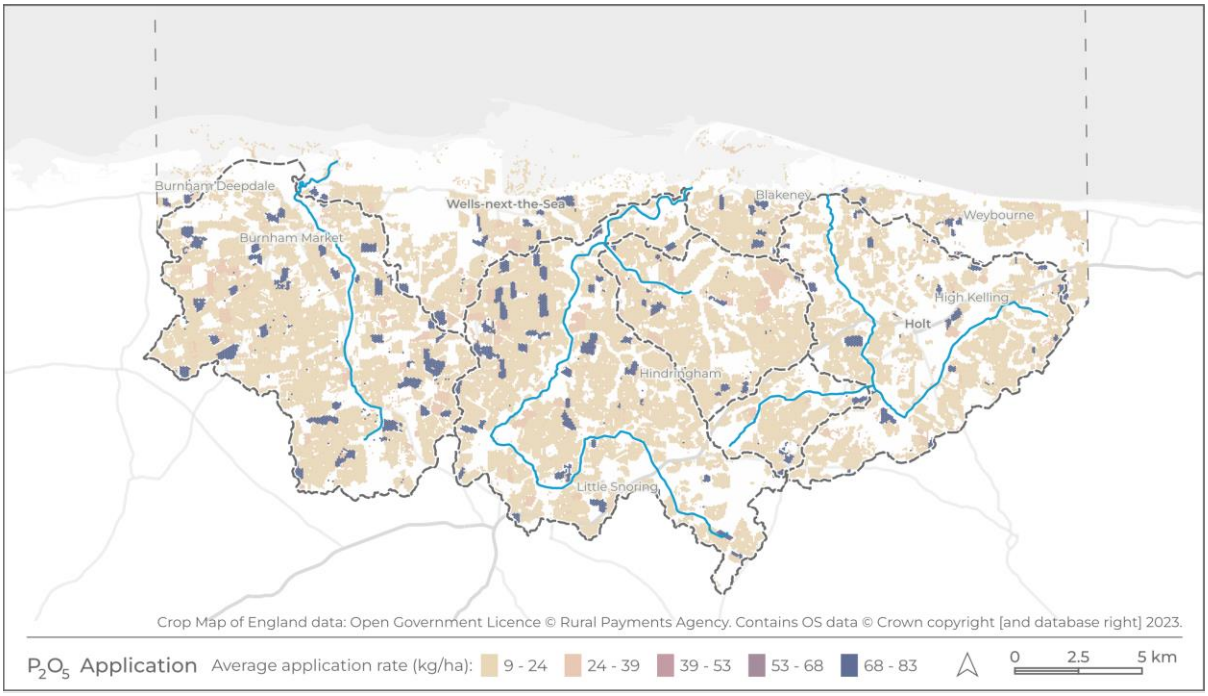

Figure 25: Estimated phosphate application within the study area.

Results for phosphate [P_2O_5) are given in Figure 25, above. Areas highlighted as being likely to comprise crop types which have high application rates for phosphates are here, represented by potato crops as detailed in the values derived from the Survey of Fertiliser Practice (Defra, 2022). Mapping these areas highlights the general concentration of predicted high-phosphorus input cropland within the River Burn and River Stiffkey catchments.

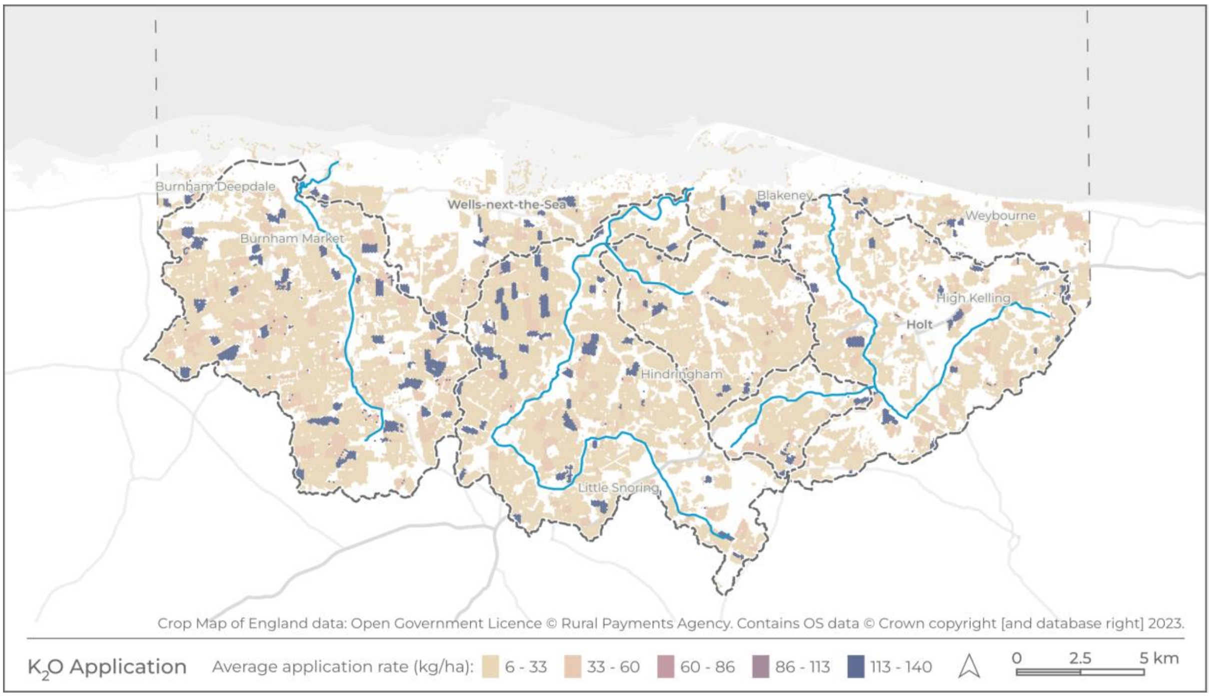

Figure 26: Estimated potassium oxide application within the study area.

Mapped values for total nitrogen, phosphate, and potassium oxide, as aggregated by river basin are shown in Table 11, below.

Table 11: Estimated mean nitrogen (N), phosphate (P_2O_5), and potassium oxide (K_2O) inputs for each basin within the study area.

Basin	Mean N	Mean P_2O_5	Mean K_2O
Burn	78.9712	16.56	22.89
Glaven	60.532	11.60	15.75
Stiffkey	81.908	15.87	21.37
Binham Tributary	90.691	16.34	20.31
Gunthorpe Stream	69.023	12.48	17.11

Through this analysis the Glaven appears to be the river basin with the lowest estimated inputs for each of nitrogen, phosphate, and potassium oxide. This is consistent with observed trends in the reporting of ammonia concentrations against environmental quality standards, where concentrations were estimated to be at the 'good' level or higher. This is in contrast to the Stiffkey and Burn where the lowest recorded ammonia concentrations within each were estimated to be at the 'moderate' level.

There are several key limitations on the data shown here. First, fertiliser application rates are not necessarily directly proportional to the losses of these nutrients into waterways. Second, there is a high variation in fertiliser application rates throughout England. Each of these factors this being influenced by a range of conditions, including soil type, climate conditions, and farming practices (Gish et al., 2011). An additional factor that may have a particular influence in Norfolk is that nutrients are often the limiting factor to crop yields due to the favourable climatic, drainage, and irrigation conditions within the region.

Landcover data was applied here to map urban and built areas. The Living England Habitat Map (Natural England, 2022) was applied here to understand the extent to which urban land cover is present within each catchment area, highlighting north Norfolk's low cover of urban area compared to the national average.

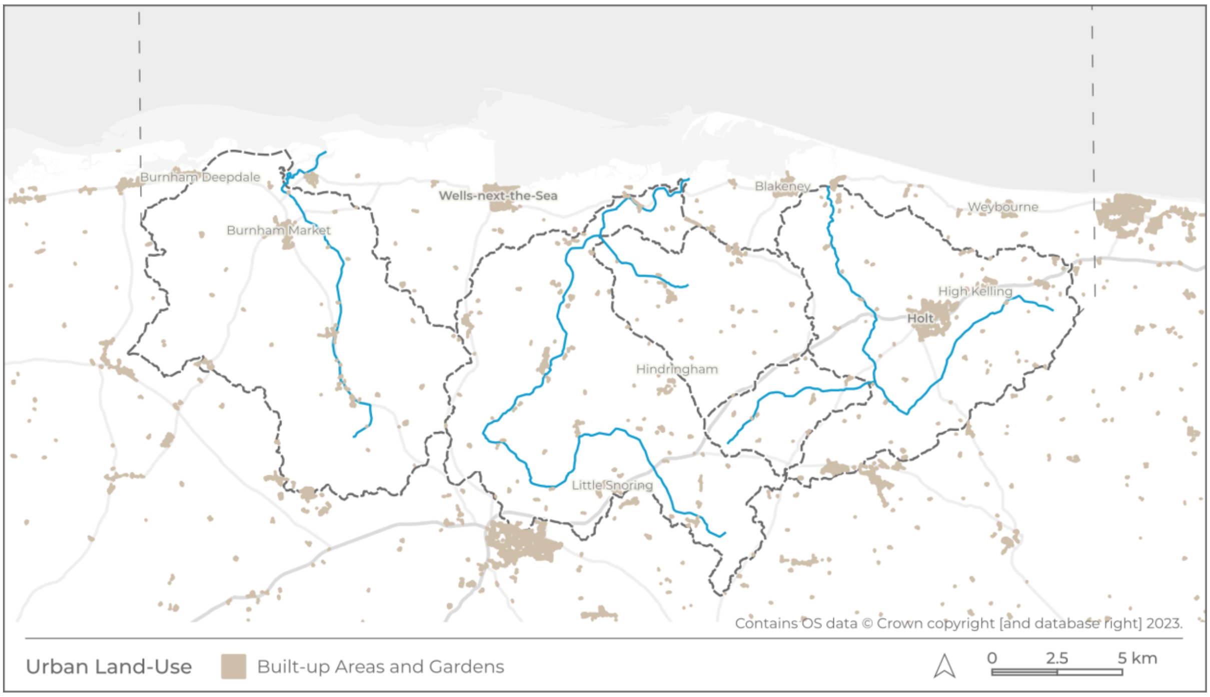

Figure 27: Areas of built and urban land use within the study area

In urban areas, a range of pressures are exerted on waterbodies, both riverine and coastal. A key manifestation of these pressures is through urban run-off. Vehicles for example, produce particulate pollution which may be mobilised from road surfaces from vehicle emissions and tyre erosion (Tan *et al.,* 2023).

Further, sealed surfaces increase the rate of flow of surface waters through catchment systems. This increases the potential of surface water flows to erode land surfaces (e.g., soils) and transport sediments, in turn mobilising pollutants held within the transported substrates (Herrero *et al*., 2018). These pollutants are often mobilised to coastal waters – whether directly or indirectly (e.g., via rivers).

There are no major areas of urban land cover within the study area, the largest being the town of Wells-next-the-Sea, with a population of 2,165 (as of the 2011 Census) (Office for National Statistics, no date supplied). The recorded population of the town was 2,555 in 1891, and 2,245 in 1971 (University of Portsmouth, no date supplied), indicating that the population has remained relatively stable throughout recent history. However, public transport connections within the region are known to be poor, with tourism also being a significant industry locally. These factors are both likely to increase car use per person within the study area, in contrast to regions better integrated with public transport networks. The specific activities identified by the EA (Environment Agency, 2023d) identify rural roads and tracks as an activity exerting pressure (through phosphates) in the Binham Tributary catchment. Indeed, studies have linked phosphate pollution to vehicular emissions (Indris *et al*., 2020).

It is important to note here that the major settlement in the study area (Wells-next-the-Sea), falls outside of the terrestrial catchments, as defined by the Environment Agency (Figure 1). This is significant as this is likely to be the urban settlement which has the greatest impact on coastal water quality in the study area. A factor of both its size and proximity to key coastal habitats, including a large area of saltmarsh. This in combination with the relatively heavy shipping traffic into Wells-next-the-Sea.

Table 12: Total estimated urban area within each catchment, both as absolute area in hectares and as a proportion of the total catchment area.

Basin	Catchment Area *(ha)*	Urban Area *(ha)*	Urban Area *(% of total)*
Burn	10120.30	91.1	0.900
Glaven	7681.95	190.25	2.480
Stiffkey	9899.35	123.81	1.251
Binham Tributary	3680.24	30.21	0.821
Gunthorpe Stream	1499.00	8.94	0.596

5.5. Shipping

Shipping exerts several pressures on coastal habitats. The physical impacts of shipping on key coastal habitats are well documented. Many of these impacts are associated with anchoring. For example, anchored ships can be 'swung' by wind and tidal currents, causing the anchor to 'scour' the seabed (Byrnes & Dunn, 2020). This physical action causes damages to seafloor habitats, in particular seagrass meadows (Byrnes & Dunn, 2020) and may result in the resuspension of sediments (Herbert *et al.,* 2009).

Anchoring from shipping can result in extensive and persistent damage, having the potential to abrade, penetrate and change seabed features. Anchoring poses a particular threat to seagrass beds and oyster reefs. Anchoring (and mooring) have the potential of causing direct damage to the seafloor while also increasing suspended sediments from disturbance of the seabed. Furthermore, shipping also presents a mechanism for the introduction of invasive species through both ballast water carried by ships and hull fouling (Costello *et al*., 2022).

Shipping density transit lines produced as part of a 2015 study into shipping density and routes (Marine Management Organisation, 2014), are published online (Marine Management Organisation, 2017). These transit lines are derived from automatic identification system (AIS) data supplied to the Marine Management Organisation (MMO) by the Maritime and Coastguard Agency. This data describes the size of vessel associated with each transit line feature, as well as classifying the vessel using the ship type group (STG) typology. Transit lines represent ship and boat movements undertaken throughout the year 2015. Transit line data has been overlaid in Figure 28, below.

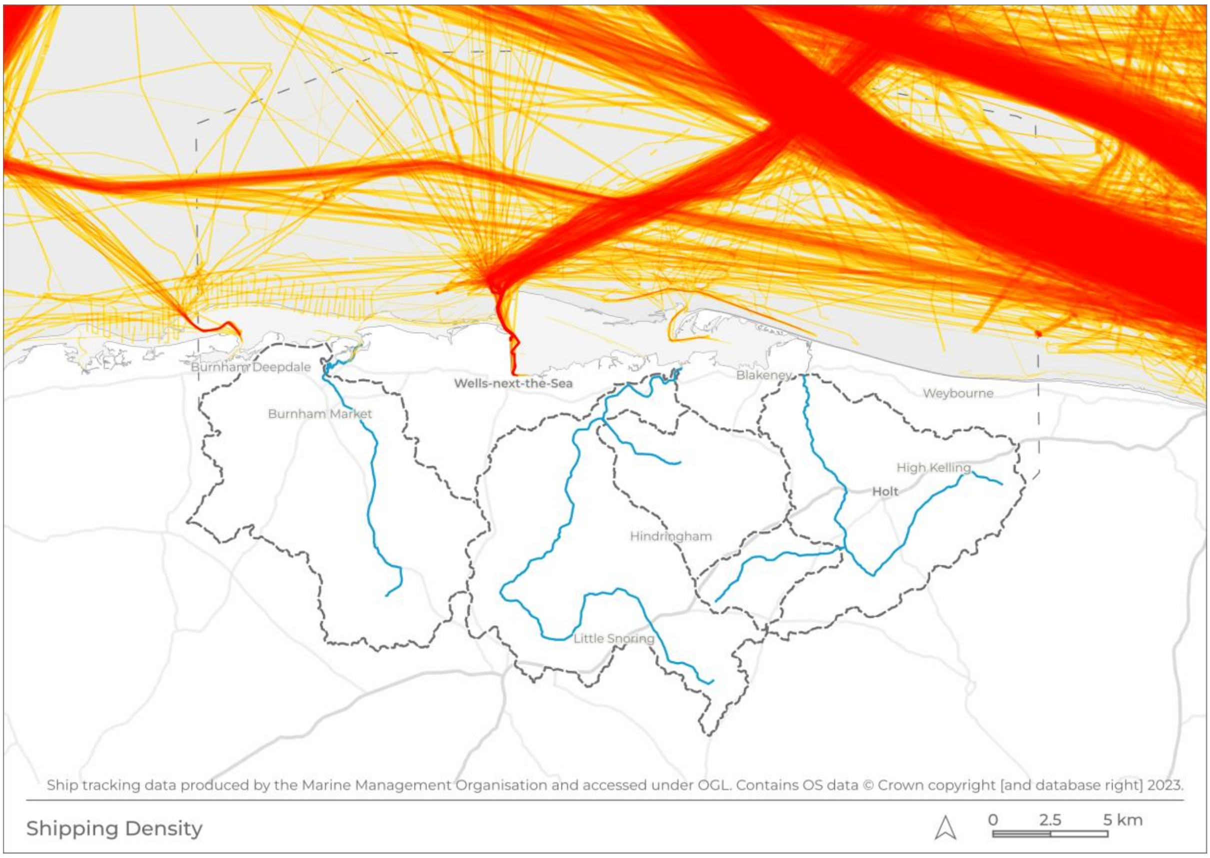

Figure 28: Shipping density (2015) across the study area for all classes of vessels, as reported by the Marine Management Organisation (2017).

Plotting this data shows that the channel into the port of Wells-next-the-Sea represents the area of highest shipping density along the coastline of the study area. There is a moderate level of shipping activity into Burnham Deepdale, and a lower-level of activity in Blakeney Harbour. To investigate the type of shipping operations undertaken in the area, transit lines are plotted by ship type group in Figure 29 and Figure 30, below.

Tracking data representing port service craft, dredging and underwater operations, high-speed craft, military and law enforcement, and passenger vessels are shown in Figure 29.

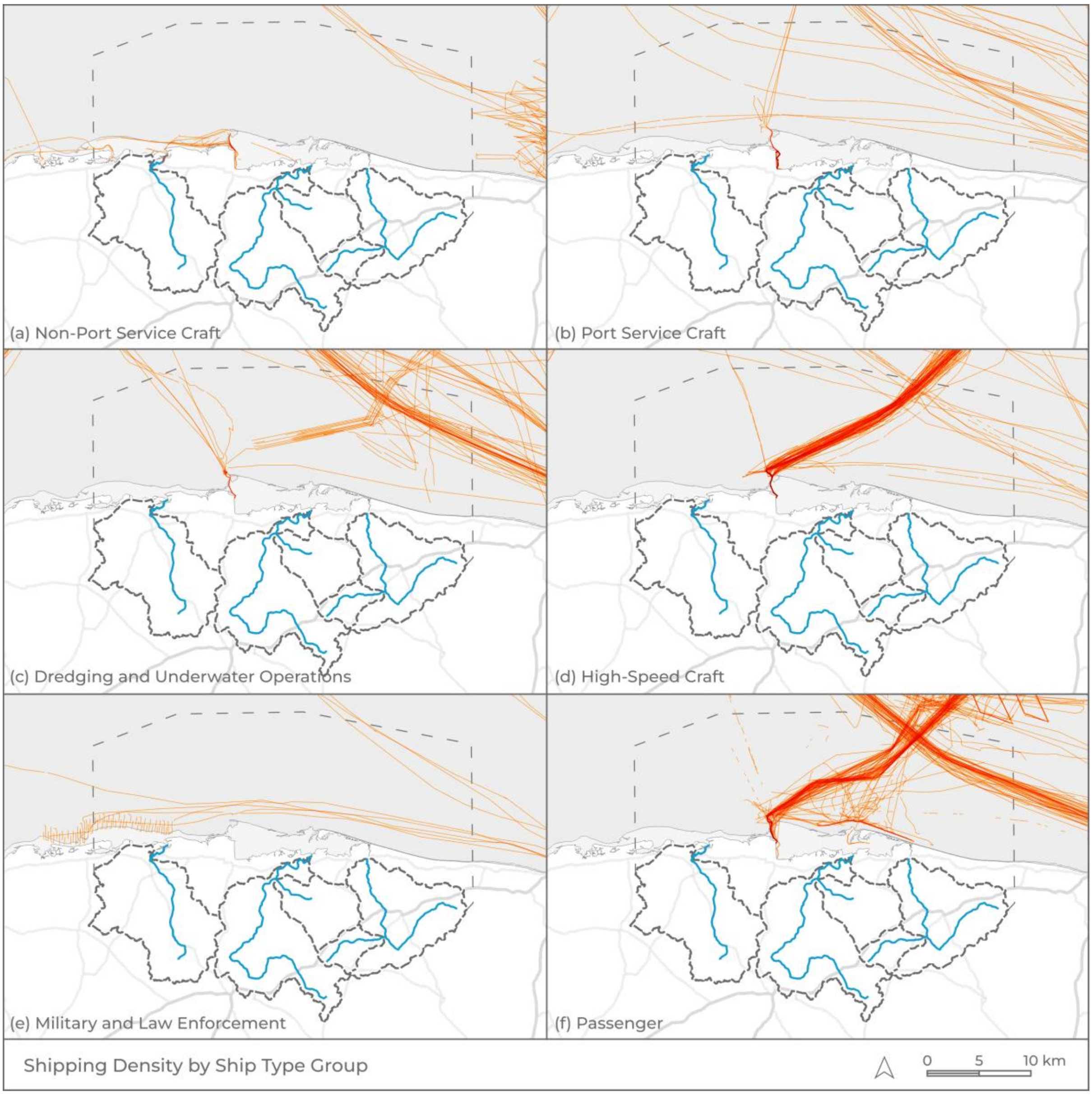

Figure 29: Shipping density (2015) across the study area plotted by vessel type, as reported by the Marine Management Organisation (2017).

This data highlights a concentration of shipping activity along the channel into Wells-next-the-Sea for all vessel types with the exception of '*military and law enforcement*'. Traffic along this channel is heaviest from '*high-speed craft*' and '*passenger vessels*'.

Non-Port Service Craft exhibit a limited level of activity near the intertidal zone to the west of Wells -next-the-Sea. Vessels classed as military and law enforcement show activity along the coastline, including a transect within the west of the study area. Inspection of the data confirms that the majority of this activity is from a single day, rather than recurring or prolonged activity.

Tracking data representing fishing, cargo, tanker, recreational, and unclassified vessels are shown in Figure 29.

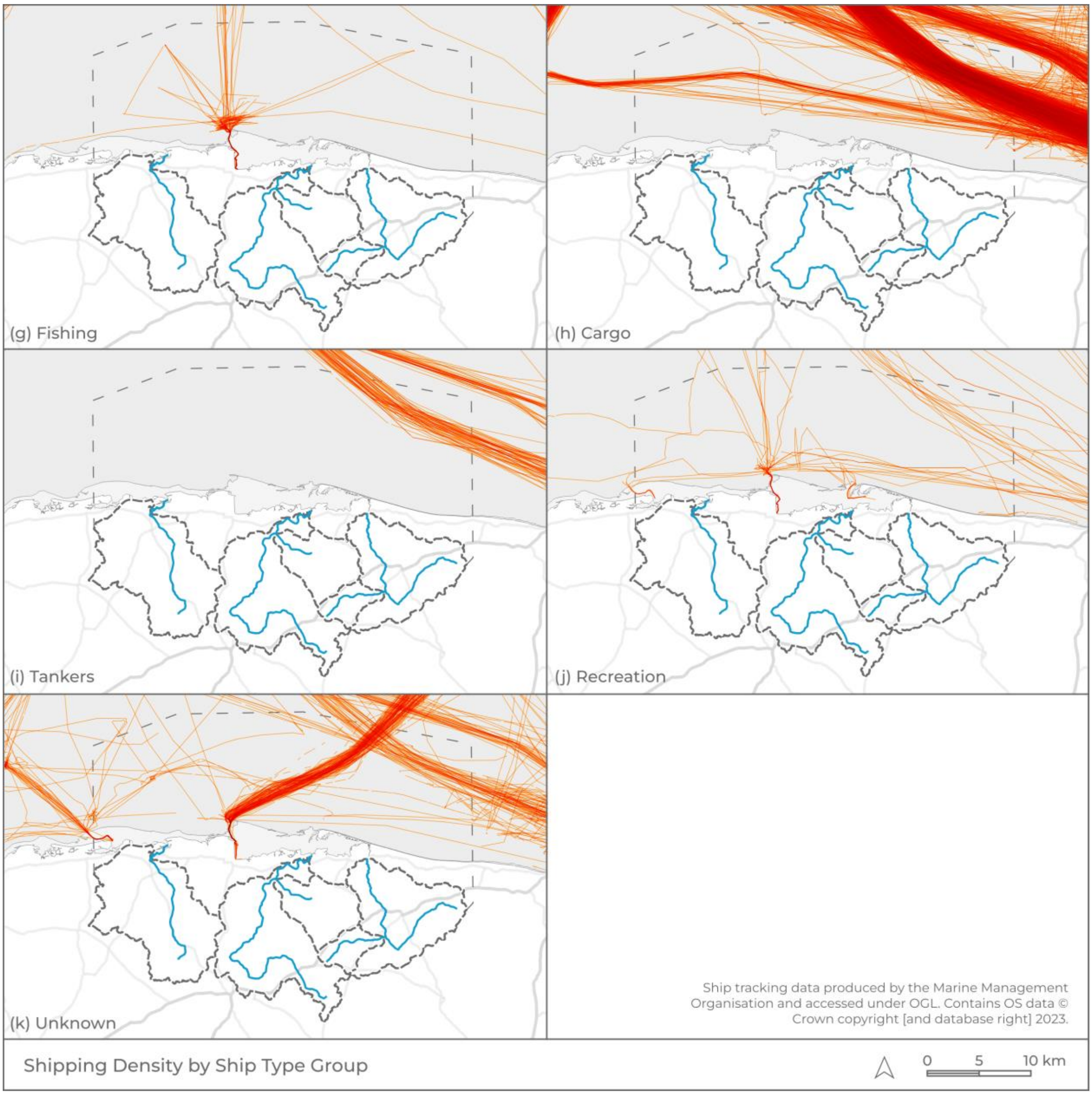

Figure 30: Shipping density (2015) across the study area plotted by vessel type, as reported by the Marine Management Organisation (2017).

Fishing vessel activity highlights the role of Wells-next-the-Sea as a hub for fishing vessels within the study area, with relatively heavy activity along the channel into the harbour as well as the open waters immediately adjacent to the harbour.

As may be expected, both cargo and tanker vessels show activity mainly confined to shipping channels which run from east to west across the study area. The data shown in both Figure 29 and Figure 30, highlights that the activity within Blakeney Harbour comprises almost entirely of passenger and recreational vessels. These vessels – and the majority of traffic which passes through the harbours within the study area – predominantly travel to an area approximately 25 km from shore, near Sheringham Shoal Offshore Windfarm. The relatively short distance of travel, with these vessels not tending to travel to other ports indicates that this traffic is unlikely to exert a major pressure on coastal habitats within the study area with regard to the introduction of invasive species. It should be noted that the MMO data applied here is now relatively old, though it is considered to represent the best available data for this report.

6. Source-Contribution Matrix

The pollutant-source matrix shown below has been developed from a review of key literature in relation to each of the key pollutants identified within this review. Where possible, relative contributions have been given. These contributions are based on England-wide pollutant sources. Where relative contributions have not been available, sources have been assessed qualitatively using the information compiled in Sections 3, 4, and 5 of this report.

Table 13: Sources of key pollutants identified in the main river systems within the study area (Environment Agency, 2019a; 2019b; 2019c; 2019e; 2021b)

Source	Mercury	PBDE	PFOS	Benzo(ghi) perylene	Phosphates	Ammonia	Nitrate
Wastewater (treated)	Moderate	Yes	Yes	Yes	Moderate	Yes	Moderate
Wastewater (untreated CSO)	Moderate	Yes	Yes	Yes	Low	Yes	Moderate
Agriculture (fertiliser)	-	Yes (sludge)	Yes (sludge)	Yes (sludge)	High	Yes	High
Agriculture (livestock)	-	-	-	-	High	Yes	High
Industry	High	-	Yes	Yes	-	-	Low
Urban Run-Off	Moderate	-	Yes	Yes	Low	-	-
Background / Ambient	High	-	-	-	Low	-	-

Pressures on key river basins are given in Table 14, below. This provides a qualitative assessment for the extent of pressures exerted in each river basin. This assessment is based on Environment Agency condition data, and data retrieved from the Environment Agency Water Quality Archive. Where a water quality element, or key contributing factor to that element, has been identified as being of '*Moderate*' status or lower condition within the Environment Agency classification, the pressure severity has been scored as high in Table 14. Pressures identified within Environment Agency status classification of higher condition that '*Moderate*' have been scored as a moderate pressure severity. In some circumstances, pressure severity has been updated following review of Environment Agency Water Quality Archive data.

Table 14: Extent of pressures exerted by key pollutants within the key study area water systems.

Waterbody	Mercury	PBDE	PFOS	Benzo(g-h-i) perylene	Phosphates	Ammonia	Nitrate
Burn (River)	High	High	High	-	High	High*	High*
Stiffkey (River)	High	High	-	High	-	Moderate	Moderate
Glaven (River)	High	High	-	-	High	High	High
Burn (Transitional)	High	High	-	-	-	Low	Low
Stiffkey & Glaven (Transitional)	High	High	-	-	-	High*	High*
North Norfolk (Coastal)	High	High	-	-	-	Moderate*	Moderate*

**No pressure reported in EA classification data, but elevated levels reported in EA WIMS data or mapped potential pollutant sources.*

The degree to which major sources of each contaminant are present in each river basin is given in Table 15, below. This is based on the mapped pollution sources presented in Section 4. Assessed sources for transitional waterbodies have been produced through review of mapped pressure sources and pressure sources from input river systems.

Table 15: Assessment of key pressure sources within the key study area water systems

Waterbody	Wastewater (treated)	Wastewater (CSO)	Agriculture (fertiliser)	Agriculture (livestock)	Urban Run-Off	Riverine Inputs (Coastal and Transitional only)	Shipping
Burn (River and Transitional)	Moderate	High	High	Moderate	Low	-	-
Stiffkey (River)	High	Low	High	Low	Moderate	-	-
Glaven (River)	High	High	Moderate	High	Moderate	-	-
Stiffkey & Glaven (Transitional)	High*	Moderate*	High*	Moderate*	Low*	High*	-
North Norfolk (Coastal)	High*	High*	Moderate*	Moderate*	Low*	High*	Low*

**No pressure reported in EA classification data, but elevated levels reported in EA WIMS data or mapped potential pollutant sources.*

A separate source-contribution matrix is provided overleaf for both river and transitional and coastal waterbodies. Each matrix details (i) the extent of each pressure within each waterbody, and (ii) the presence of key drivers of the pressure within each waterbody. These values are each scored from 1 to 3 where 1 is low and 3 is high. A final risk score is then allocated as the product of these values for each waterbody, pressure, and source combination, creating a final risk value with a range of 1 to 9.

Due to the limitations of currently available information in relation to mercury sources, and indications in EA reporting and WIMS data that there are no significant active mercury inputs into the study area catchments and coastal region, the greatest contribution of mercury is categorised as 'background / ambient' in each of the below risk matrices. Other mercury sources are assessed as per national data (Table 13). Similarly, in the coastal matrix, phosphates are given a pressure extent score, this is due to their anticipated presence in coastal waterbodies, but the absence of evidence to directly verify this or otherwise.

Table 16: Pressure risk matrix for river waterbodies within the study area (*p = pressure extent, s = source extent, r = risk*).

Mercury

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	2	3	**6**	2	3	**6**	2	3	**6**
WASTEWATER (CSO)	2	3	**6**	2	3	**6**	2	3	**6**
AGRICULTURE (FERTILISER)	-	-	-	-	-	-	-	-	-
AGRICULTURE (LIVESTOCK)	-	-	-	-	-	-	-	-	-
URBAN RUN-OFF	3	1	**3**	3	2	**6**	3	2	**6**
BACKGROUND / AMBIENT	3	3	**9**	3	3	**9**	3	3	**9**

PBDE

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	3	2	**6**	3	3	**9**	3	3	**9**
WASTEWATER (CSO)	3	3	**9**	3	3	**9**	3	3	**9**
AGRICULTURE (FERTILISER)	3	3	**9**	3	3	**9**	3	2	**6**
AGRICULTURE (LIVESTOCK)	-	-	-	-	-	-	-	-	-
URBAN RUN-OFF	-	-	-	-	-	-	-	-	-
BACKGROUND / AMBIENT	-	-	-	-	-	-	-	-	-

PFOS

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	3	2	**6**	-	-	-	-	-	-
WASTEWATER (CSO)	3	3	**9**	-	-	-	-	-	-
AGRICULTURE (FERTILISER)	3	3	**9**	-	-	-	-	-	-
AGRICULTURE (LIVESTOCK)	-	-	-	-	-	-	-	-	-
URBAN RUN-OFF	3	1	**3**	-	-	-	-	-	-
BACKGROUND / AMBIENT	-	-	-	-	-	-	-	-	-

Benzo(g-h-i) perylene

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	-	-	-	3	2	**6**	-	-	-
WASTEWATER (CSO)	-	-	-	3	3	**9**	-	-	-
AGRICULTURE (FERTILISER)	-	-	-	3	3	**9**	-	-	-
AGRICULTURE (LIVESTOCK)	-	-	-	-	-	-	-	-	-
URBAN RUN-OFF	-	-	-	3	3	**9**	-	-	-
BACKGROUND / AMBIENT	-	-	-	-	-	-	-	-	-

Phosphates

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	2	2	**4**	-	-	-	2	3	**6**
WASTEWATER (CSO)	2	3	**6**	-	-	-	2	3	**6**
AGRICULTURE (FERTILISER)	2	3	**6**	-	-	-	2	2	**4**
AGRICULTURE (LIVESTOCK)	2	2	**4**	-	-	-	2	3	**6**
URBAN RUN-OFF	2	1	**3**	-	-	-	2	2	**4**
BACKGROUND / AMBIENT	-	-	-	-	-	-	-	-	-

Ammonia

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	3	2	**6**	2	3	**6**	3	3	**9**
WASTEWATER (CSO)	3	3	**9**	2	1	**2**	3	2	**6**
AGRICULTURE (FERTILISER)	3	3	**9**	2	3	**6**	3	2	**6**
AGRICULTURE (LIVESTOCK)	3	2	**6**	2	1	**2**	3	3	**9**
URBAN RUN-OFF	-	-	-	-	-	-	-	-	-
BACKGROUND / AMBIENT	-	-	-	-	-	-	-	-	-

Nitrate

	BRN			STF			GLV		
	P	S	R	P	S	R	P	S	R
WASTEWATER (TREATED)	3	2	**6**	2	3	**6**	3	3	**9**
WASTEWATER (CSO)	3	3	**9**	2	1	**3**	3	2	**6**
AGRICULTURE (FERTILISER)	3	3	**9**	2	3	**6**	3	2	**6**
AGRICULTURE (LIVESTOCK)	3	2	**6**	2	1	**3**	3	3	**9**
URBAN RUN-OFF	-	-	-	-	-	-	-	-	-
BACKGROUND / AMBIENT	-	-	-	-	-	-	-	-	-

Table 17: Pressure risk matrix for transitional and estuarine waterbodies within the study area (*p = pressure extent, s = source extent, r = risk*).

	Mercury						PBDE						Phosphates						Ammonia						Nitrate						Physical Disturbance					
	ST/GL			**NNFLK**			**ST/GL**			**NNFLK**			**ST/GL**			**NNFLK**			**ST/GL**			**NNFLK**			**ST/GL**			**NNFLK**			**ST/GL**			**NNFLK**		
	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**	P	S	**R**
WASTEWATER (TREATED)	3	3	**9**	3	3	**9**	3	3	**9**	3	3	**9**	1	3	**3**	1	3	**3**	3	3	**9**	2	3	**6**	3	3	**9**	2	3	**6**	-	-	-	-	-	-
WASTEWATER (CSO)	3	2	**6**	3	3	**9**	3	2	**6**	3	3	**9**	1	2	**2**	1	3	**3**	3	2	**6**	2	3	**6**	3	2	**6**	2	3	**6**	-	-	-	-	-	-
AGRICULTURE (FERTILISER)	-	-	-	-	-	-	3	3	**9**	3	2	**6**	1	3	**3**	1	2	**2**	3	3	**9**	2	2	**4**	3	3	**9**	2	2	**4**	-	-	-	-	-	-
AGRICULTURE (LIVESTOCK)	-	-	-	-	-	-	-	-	-	-	-	-	1	2	**2**	1	2	**2**	3	2	**6**	2	2	**4**	3	2	**6**	2	2	**4**	-	-	-	-	-	-
URBAN RUN-OFF	3	1	**3**	3	1	**3**	3	1	**3**	3	1	**3**	1	1	**1**	1	1	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BACKGROUND / AMBIENT	3	2	**6**	3	2	**6**	3	2	**6**	3	2	**6**	1	2	**2**	1	2	**2**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RIVERINE INPUTS	3	2	**6**	3	2	**6**	3	2	**6**	3	2	**6**	1	2	**2**	1	2	**2**	3	2	**6**	2	2	**4**	3	2	**6**	2	2	**4**	-	-	-	-	-	-
SHIPPING	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	1	**2**	2	2	**4**

7. Sensitivity of Coastal Habitats

It should be noted that a range of different coastal habitats were considered, with seagrass, saltmarsh and oysters being prioritised. This is due to their relevance to the north Norfolk region, with areas of such habitats or species already present in some areas. This stands in contrast to kelp. While sugar kelp (*Laminaria saccharina*) is being commercially grown in Blakeney Harbour by Norfolk Seaweed, this is on rope, as north Norfolk lacks the rocky substrate on which kelp depends, and pre-existing records for kelp along the north Norfolk coast are lacking. It should be noted that there are seagrass beds and Atlantic oysters present (being grown for commercial use) in Blakeney Harbour, close to the mouths of the Rivers Stiffkey and Glaven. Saltmarsh habitat is also present around Blakeney Harbour and the wider north Norfolk coastal region. This suggests that the water quality in the area (and the influx of riverine pollutants) does not present a significant enough issue to impede the creation or restoration of these marine habitats. Liminal, transitional coastal marine habitats were also prioritised over strictly terrestrial coastal habitats such as sand dunes which are more cut off from both riverine and marine influence than these habitat types. It should also be noted that while there was data for levels of pollutants in the rivers in the study areas, considerably less data was found on levels of pollutants in the marine environment.

7.1. Seagrass

7.1.1. Nutrients

Nutrient inputs can impact seagrass via the growth of algal blooms or phytoplankton reducing the light available to seagrass plants (Fraser & Kendrick, 2017). Seagrasses can be especially susceptible to nutrient enrichment due to their preference for low energy regions within coastal systems (e.g., estuaries, lagoons) where tidal flushing is limited and nutrient loads are thus frequent and concentrated (d'Avack *et al.*, 2023). This impact can be further pronounced as seagrasses are species which typically require high concentrations of light (Fraser & Kendrick, 2017).

Seagrass losses were observed at Cockburn Sound in Australia which experienced a loss of 2169 ha of seagrass (75% of the total) throughout the 1960s, 1970s, and 1980s, owing to a decline in water quality (Fraser & Kendrick, 2017). The study also observed that although water quality had improved, seagrasses continued to decline, suggesting additional drivers of seagrass decline beyond poor water quality (Fraser & Kendrick, 2017). Sulphide intrusion from sediments was identified as a key driver of the decline (Fraser & Kendrick, 2017).

Using the Water Framework Directive (WFD) 'Good' status as a benchmark, d'Avack *et al.* (2022) assessed seagrass as being of 'medium' resistance, resilience, and sensitivity. It is important to note however, that WFD 'Good' status allows for a 30% loss of intertidal seagrasses (d'Avack *et al.*, 2022). It is likely, therefore, that these values are an underestimate of the 'true' sensitivity of seagrasses to nutrient enrichment. The report produced by d'Avack *et al.* (2022) states that seagrasses are commonly regarded as being of low resistance to nutrient enrichment.

Seagrass meadows (including native species *Zostera marina*, and *Z. noltei*) can benefit from moderate anthropogenic addition of **nitrogen** and **phosphorus**, with some *Z. noltei* meadows in Portugal noted for being in great health while receiving effluents from wastewater treatment plants and a food factory (Vieira et al., 2022).

An important determinant of the health of *Z. noltei* seems to be ammonium concentrations, which impeded growth when levels were too low, and was toxic to the seagrass when levels were too high, particularly in the absence of phosphorus, with levels of 200 to 663 μm ammonium ($NH^+{}_4$) / dissolved inorganic nitrogen (DIN) found to be toxic (Hernández *et al.* 1997, Cabaço, 2007, Cabaço *et al.*. 2007). The increased vulnerability to ammonium and the light environment under phosphate deficiency had already been reported for *Z. noltei* in the Bay of Cadiz, Spain (Brun *et al.*, 2008). The monitoring of *Z.*

marina in the British Isles as part of this study indicated that the meadows in better conditions (as indicated by the greater density of seagrass plants in the beds) were found in locations subject to mild or moderate nutrient additions to the natural background (Vieira *et al*., 2022). Phosphorus concentrations (as total P) tend to be below 0.2 ml L^{-1}, while total inorganic phosphate concentrations vary widely from 0.05 to 0.5 ml L^{-1} across sampling locations. Levels of nitrogen in river water samples tended to fall within the 10 to 25 mg L^{-1} range (around the natural average), while maximum levels of ammonia reported in EA WIMS data range from between approximately 0.13 mg L^{1} to approximately 2.75 mg L-1. It should be noted that despite a lack of marine water quality data, levels of all of these pollutants are likely to be significantly diluted in the marine environment. While anthropogenic nutrient inputs into seagrass beds can result in epiphytic algae growth on seagrass fronds which can reduce its ability to photosynthesise, resulting in decline, such impacts associated with minor to moderate nutrient pollution events may be offset by the herbivores grazing on these algae (McSkimming *et al*., 2015). It is unlikely that phosphorus levels in the marine environment will impede seagrass restoration.

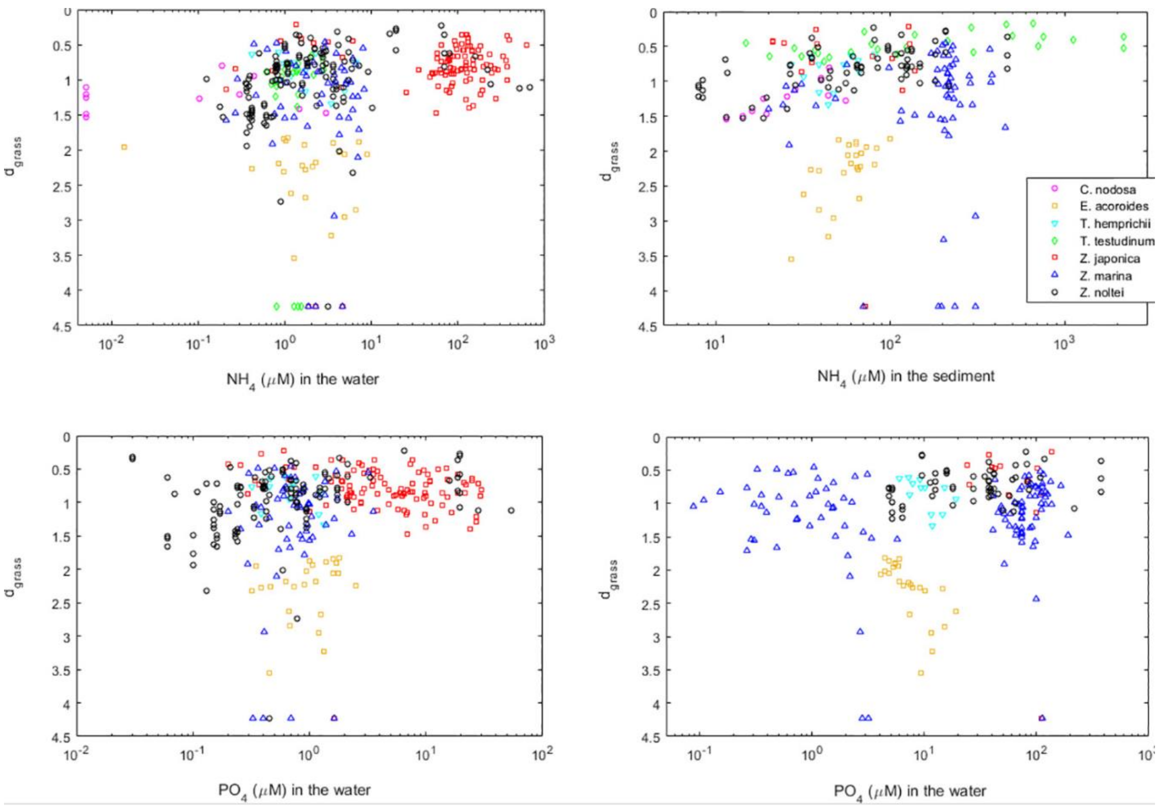

Figure 31: Health of seagrasses worldwide and their relation with the concentrations of ammonium and phosphate in water and sediments. Seagrass health is indicated by their distance (^{d}grass) to the seagrass IBL (i.e., their efficiency of space occupation). Source: Vieira *et al.,* 2022.

7.1.2. Persistent Organic Pollutants

A review conducted by d'Avack *et al.* (2022) identified limited evidence on the effects of synthetic compound contamination on seagrasses. As such the review focused on herbicides and pesticides. Values given for herbicides and pesticides are 'high' confidence, with overall values being of 'medium' confidence due to limitations in the data available for other synthetic compounds (d'Avack et al., 2022). These limitations highlight a data gap of currently limited understanding of the impacts of persistent organic pollutants on seagrass species. While there are high levels of PBDE's in the transitional and estuarine waterbodies within the north Norfolk study area (including the rivers Stiffkey and Glaven), these do not exceed the 0.14 µg L^{-1} EQS set within the Water Framework Directive for coastal, and estuarine surface waters (the pose more of an issue bioaccumulating in marine fauna). In light of existing evidence, it is highly unlikely PBDE levels will impede seagrass restoration efforts in the study area.

Physical Disturbance

Seagrass beds are particularly vulnerable to physical disturbance from shipping, including anchoring and mooring, in addition to fishing activities such as bottom trawling and dredging, and such activities must be considered if seeking to restore seagrass. Dredging may be particularly destructive to seagrass, which is sensitive to the increased water turbidity, sedimentation and removal and burial of vegetation associated with this fishing practice. In light of this, any level of dredging activities should be considered incompatible with seagrass restoration activities (for a review, see Erftemeijer & Lewis, 2006).

7.2. Saltmarsh

7.2.1. Nutrients

Alldred *et al*. (2017) highlighted a relationship of decreasing below ground biomass in saltmarsh species with eutrophication due to nitrogen loading, with this loss of biomass reducing the stability of the marsh. This study measured nitrate and ammonium content and reported the values combined as dissolved organic nitrogen. The Joint Nature Conservation Committee (JNCC) has produced a report detailing the conservation status of Atlantic salt meadows (habitat code H1330) within the England (JNCC, 2018). This report describes 'agricultural activities generating diffuse pollution to surface or ground waters' as a medium threat and pressure to the Atlantic salt meadow habitat. The review undertaken by Tyler-Walters *et al*. (2001) for MarLIN classed saltmarsh habitats as being of 'intermediate' intolerance, 'high' recoverability, and 'low' sensitivity to changes in nutrient levels (*note: not just enrichment*). These class values were assigned with a confidence of 'very low' (Tyler-Walters *et al.,* 2001). However, excessive nutrient inputs in the form of N and P may reduce the overall species diversity of saltmarsh habitats (Crain, 2007). In addition to the above, overgrazing may result in a reduction of species diversity which could decrease the overall resilience of the saltmarsh ecosystem to environmental stressors, including nutrient pollution. It should be noted though from available evidence that the levels of nutrient pollutants in the marine environment in the area including riverine inputs are not likely to impede saltmarsh regeneration, even if there is a risk of impacts to the saltmarsh plant community.

7.2.2. Mercury and Mercury Compounds

Saltmarsh plants such as sea rush (*Juncus maritimus*) and saltmarsh bulrush (*Scirpus maritimus*) also have the capacity to sequester **mercury**, but this varies significantly with plant species. The greater belowground biomass of *J. maritimus* means its capacity for sequestering mercury is up to 4-5 times higher than *S. maritimus*, with mercury sequestered via phytostabilization in the rhizosediment and phytoaccumulation in the belowground biomass (Marques *et al.,* 2011). However, sand dune ecosystems may be more sensitive to the effects of nutrient (mineral nitrogen) deposition, which can result in acidification and shifts in the plant community, reducing ecological integrity of dune habitats (Aggenbach *et al.,* 2017).

7.2.3. Persistent Organic Pollutants

The review undertaken by Tyler-Walters *et al*. (2001) for MarLIN classed saltmarsh habitats as being of 'high' intolerance, 'high' recoverability, and 'moderate' sensitivity to synthetic compound contamination. These class values were assigned with a confidence of 'low' (Tyler-Walters *et al.,* 2001). As indicated by the age of referenced papers, there is a literature gap in relation to the impacts of the persistent organic pollutants identified as potential pressures of concern here on saltmarsh habitats, in particular within the North Norfolk, and more broadly, UK locale. However, it should be considered that levels of persistent organic pollutants such as PBDE's in the study area are unlikely to impede saltmarsh regeneration.

7.2.4. Physical Disturbance

Saltmarshes are subject to processes of physical disturbance, this may be direct disturbance (e.g., wave energy produced by ship traffic, storm events) or indirect disturbance (e.g., increased wave energy due to channel dredging) (Wolters *et al.*, 2005; Spencer & Harvey, 2012).

Saltmarshes may also migrate inland under coastal erosion, this likely being particularly relevant on the dynamic North Norfolk coast. In areas where sediment and space for saltmarshes to migrate inland are limited, physical disturbance via coastal erosion is likely to present a greater risk to saltmarsh extents though 'squeezing' the space available for saltmarsh habitats (Office for National Statistics, 2022; Möller *et al.,* 2014).

7.3. Native Oyster

[ContaminantPressureSensitvity-Oysters-Rpt-30May2023.pdf (marlin.ac.uk)]

7.3.1. Nutrients

Nutrient enrichment – i.e., elevated concentrations of nitrogen (N), phosphorus (P), and silicon (Si) – has varying impacts on *Ostrea edulis*. Moderate enrichment, in particular via organic particulates and dissolved organic material, may benefit *Ostrea edulis* through increased food availability (Perry *et al*., 2023). Eutrophic conditions and long-term nutrient enrichment may have negative effects, including increased turbidity, increased suspended sediment, increased risk of deoxygenation, and algal bloom risk (Perry *et al*., 2023). As it is not anticipated that nutrient concentrations in compliance with Water Framework Directive (WFD) 'good' status will have a negative impact on the species, *Ostrea edulis* is classed as being of high resistance, high resilience, and not sensitive to nutrient enrichment by Perry *et al*. (2023). Moderate levels of nutrient enrichment in the form of organic particulates and dissolved organic material may increase food availability for suspension feeders such as oysters. However, long-term or high levels of nutrient enrichment may result in eutrophication and have indirect adverse effects, such as increased turbidity, increased suspended sediment, increased risk of deoxygenation and the risk of algal blooms (Perry & Jackson, 2017). In the marine environment of the study area, it is highly unlikely that nutrient pollution (N, P and Si) levels in the marine environment will pose a threat to the survival of oysters in the area.

Oyster beds can facilitate nutrient uptake and the assimilation of organic nitrogen into inorganic nitrogen gas is a process that is elevated with increased numbers of filter feeding bivalves (Newell *et al*., 2005; Piehler & Smyth, 2011; Smyth *et al*., 2013) in addition to assimilating from the water column and sequestering it in their shell and tissue. In addition to these effects on nitrogen, oyster reefs can also sequester phosphorus (Dame *et al*., 1989). A single oyster can filter up to 240 L of water a day (equivalent to 11 and a half full bathtubs) – resulting in increased water quality and clarity, which can benefit nearby habitats.

7.3.2. Mercury and Mercury Compounds

The effects of mercury on the Atlantic oyster (*Ostrea edulis*) has not been well studied, although an LC50 of 4200 μg/L was established for adults and an LC50 between 1 and 3.3 μg/L for larvae following 48 hour exposure (Connor, 1972). Another study reported a 48-hour LC50 for Hg of 1-3.3 ppb in *Ostrea edulis* larvae compared with a 48- hour LC50 for Hg of 4200 ppb in adults (Bryan, 1984). This highlights the much greater sensitivity of oyster larvae to mercury relative to adult oysters. A study on the effect of varying mercury levels on the Pacific oyster (*Magallana gigas*, or *Crassostrea gigas* according to some scientists) on embryogenesis, survival, growth, and metamorphosis of oyster larvae reported that embryogenesis was abnormal in 50% of individuals at 11 μg L^{-1}. While a distinct species to the native

Atlantic oyster (*Ostrea edulis*) it occupies a very similar ecological niche, and without more species specific data, for the Atlantic oyster, the mercury levels affecting the growth and development of the Pacific oyster should be considered as possibly impacting the growth and development of the Atlantic oyster The LD-50 for D-shaped, umbonate and pediveliger larvae was 33, 115 and 200 µg L^{-1}, respectively. Growth rates were more sensitively impacted by mercury levels, negatively impacted at 4 µg L^{-1}. Metamorphosis rates of pediveliger larvae were significantly negatively impacted when exposed at mercury levels of 64 µg L^{-1} for 48 hours (Beiras & His, 1994). While mercury pollution was a highlighted issue in the study area (with wastewater sources highlighted as being important sources), detected levels in water were consistently below the recommended standards for water, rarely above 0.03 µg L^{-1} AA, with 0.05 µg L^{-1} the annual average and 0.07 µg L^{-1} the MAC (maximum allowable concentration) for both inland and other surface waters (Environment Agency, 2019a). Thus mercury levels (likely be lower in the marine water environment than riverine water) are unlikely to impede the growth, development or survival of Atlantic oysters, although given the high levels reported in fish in the area (with mercury levels within sampled common dab (*Limanda limanda*) consistently falling above EQS, with the lowest value recorded being 49.3 µg kg-1 (May 2018) and the greatest 200 µg kg-1 (April 2021), it is likely that mercury will bioaccumulate in oysters over time to some degree. This could potentially be assessed through future sampling.

7.3.3. Persistent Organic Pollutants

The review conducted by Perry *et al*. (2023) identified *Ostrea edulis* as being of low overall resistance and resilience and high sensitivity to synthetic compound contamination. There is some variation between contaminants in this class, in particular PCBs and PFAs, to which *Ostrea edulis* are of high resistance and resilience and are not sensitive to respectively. The full data is given below (adapted from Perry *et al*. [2023]). These pollutants have been known to bioaccumulate in shellfish, including oysters. One study assessing samples of Scottish Atlantic oysters reported very low levels of polybrominated biphenyls (PBBs) and low levels of brominated dioxins (PBDD/Fs), although elevated levels of 237-TriBDD (up to 14.5 ng kg^{-1}) were detected (Fernandes *et al*., 2009). While high levels of persistent organic pollutants such as PBDE's have been detected in the study area, PBDE concentrations within these waters are below the 0.14 µg L^{-1} EQS set within the Water Framework Directive. It is difficult to draw firm conclusions on how this may impact Atlantic oyster populations inferring from existing data, although they do exhibit higher resilience and resistance to other brominated organic compounds such as PCBs and PFAs.

7.3.4. Physical Disturbance

Oyster reefs are vulnerable to physical disturbance from shipping, including anchoring and mooring, in addition to fishing activities such as bottom trawling and dredging. Dredging can result in sedimentation of oyster reefs which can cause oyster mortality, as well as degrading the overall quality of the oyster reef habitat to other wildlife. Such activities must be considered if seeking to restore seagrass or oyster reefs.

8. Remediation Potential

There are a number of potential upstream river projects that might contribute to bioremediation of chemical and nutrient pollutants. In addition to providing the means to reduce pollution levels, each of these initiatives can provide important habitat and support biodiversity. Such approaches can reduce pollution levels at source (such as a shift to sustainable/regenerative agricultural practices), while others (such as buffer strips, whether established around fields or alongside rivers) can mitigate pollution close to source, filtering and capturing it before it enters waterways. Other approaches such as strategic construction and placement of ICWs (such as when linked to wastewater treatment works) and free-living beaver reintroduction (with their associated dam building and eco-engineering) can mitigate pollution downstream of source Of these, approaches that mitigate pollution at, or close to source (including shifts in agricultural practices and establishment of buffer strips in the upstream stretches of rivers) are likely to be the most cost effective. Coastal marine habitats such as saltmarsh, seagrass meadows, oyster beds and kelp also have some inherent resilience and capacity to handle and process nutrient pollution.

8.1. Shift to Sustainable / Regenerative Agricultural Practices

Switching to more sustainable agricultural practices such as crop diversification, use of cover cropping and use of legumes in crop rotations can lead to a substantial reduction in nitrogen entering watercourses (Chatterjee, 2009), while also reducing pesticide usage. No-till farming practices can reduce soil erosion and sediment runoff, but may necessitate greater use of herbicides. However, it may be possible to reduce herbicide use under no-till crop production by using an integrated approach such as crop competitive enhancement, seed bank reduction technologies, crop rotation and biological control (Kumar & Aloke, 2020; Swanton & Weise, 1991; Summers *et al*., 2021). No-till farming practices are also likely to synergise with implementation of field-edge or riparian buffer strips (Aguiar Jr. *et al*., 2015). A switch to regenerative agricultural practices could be partly supported by environmental land management schemes (ELMS), which are due to be implemented this year. There are already examples of multi-landowner collaborative regenerative agriculture initiatives being undertaken in the Norfolk area which could make a useful reference for further projects, including the Wendling Beck Environmental Project headed by Dillington Hall Estate, landscape recovery of the Upper Wensum river catchment area headed by Wensum Farmers, and the Broads Authority ELMS test and trial.

8.2. Buffer Strips

Riparian buffer strips are vegetated areas that run alongside streams, rivers and other water bodies. They can play an important role in buffering aquatic habitats from pollution resulting from land-based activities such as intensive agriculture by trapping sediment and filtering runoff. Restoration of riparian zones does require knowledge of an area's hydrology and ecology, but restoring them for water quality improvement may yield greater economic benefits than allocating the same land area to crops (Fennessey & Cronk, 1997). The vegetation that makes up buffer strips is effective at trapping and retaining sediment (often a key pollutant in many waterways), and plants can uptake and store nutrients in the form of nitrogen and phosphorus. The roots of vegetation that comprise buffer strips can also help stabilise banks, therefore reducing soil erosion. Buffer strips are effective at reducing levels of nutrient pollutants such as nitrogen and phosphorus-based substances entering waterways (Weissteiner *et al*., 2013), even when input concentrations are high (Mander et al. 1997). One meta-analysis reported the overall mean of phosphorus removal efficacy pooled across 35 studies was 54.5% (Tsai et al., 2022). One meta-analysis of nitrogen retention by buffer strips assessed 123 studies, and of these reporting buffer strips of 10-15m width, the average nitrogen reduction in surface runoff and underground water reached approximately 79% and 59%, respectively (Lyu et al., 2021). Buffer strips may be particularly effective if implemented in the upstream parts of stream and river networks (Feld *et al*., 2018), with this also applying to riparian tree planting (Parkyn *et al*., 2005). Establishing riparian buffer strips alongside the rivers in the region could help reduce pollution entering the rivers and the coastal environment, while also providing important benefits to biodiversity. Buffer strips can also be potentially established around the edges of agricultural fields, and so help filter pollutants closer to source. There is likely to be funding opportunities available to support the establishment of riparian buffers strips through ELMS payments, with the government just having announced that Sustainable Farming Incentive (SFI) payments will cover creation of riparian buffer strips alongside rivers.

Figure 32: Example riparian buffer strip. Source: USDA.

Buffer strip width and the vegetation types that comprise them are important determinants of their capacity to filter and sequester nutrient pollution (Castelle *et al*., 1994; Hu *et al*., 2023). One study reported that buffer strips of 60m width composed of woody soils were more effective in phosphorus (99.9%) and nitrogen (99.9%) removal when compared to areas of shrub (66.4% and 83.9%, respectively) or grass vegetation (52.9% and 61.6%, respectively) (Aguiar Jr. *et al*., 2015). However, buffer strips half this width have been found to be effective in trapping sediment, and a review of buffer strip performance found that buffer strips of 15m width were necessary to protect wetlands and streams under most conditions (Castelle *et al*., 1994), and even buffer strips of much more modest width can be effective (Borin *et al*., 2010). Research suggests that buffer strips harbouring a range of vegetation types (comprising grasses and woody vegetation) may be more effective at removing sediment and sediment-bound nutrients (Lowrance & Sheridan, 2005; Lee *at al*., 2003). Further research found that plants with higher biomass and more developed rooting systems are more effective at reducing levels of a range of pollutants including levels of total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH_3-N), and chemical oxygen demand (COD) (Hu *et al*., 2023). Edge-of-field buffer strips could also be considered, as these may be more effective at reducing pesticide runoff and agricultural erosion inputs from fields (Reichenberger *et al*., 2007).

Longer term studies of buffer strip performance have highlighted the need for wider strips, in part due to a drop off in phosphorus retaining performance due to soil saturation over time. Buffer strips can also help reduce levels of pesticides entering waterways. One study found that buffer strips were able to reduce runoff events by 63-83%, with substantial reductions in levels of various herbicides entering waterways. It was concluded that buffer strips are a very effective means of reducing surface water pollution by herbicides, even in agronomic situations that promote runoff (Carretta *et al*., 2017). One study reported a 60-90% reduction in herbicides, although this will vary with the particular herbicide and time since application (Borin *et al*., 2010). Buffer strips can also support biodiversity, providing important habitats and wildlife corridors (including space for beavers, with buffer strips having been found to drastically reduce human-beaver conflicts in Bavaria). Buffer strips harbouring trees and larger woody vegetation have the potential to reduce water temperature due to shading which may help buffer against the effects of climate change, aiding in climate change adaptation (Wu *et al*., 2023). In addition, organic matter inputs in the form of leaf litter entering waterways can also be beneficial for aquatic ecosystems, benefitting a range of species and the food webs associated with these habitats.

8.3. Integrated Constructed Wetlands (ICWs)

Integrated Constructed Wetlands (ICWs) seek to holistically emulate the capacity of natural wetlands to facilitate the removal, recycling, transformation or immobilisation of nutrients and sediments, with wastewater being treated through various physical, chemical and biological processes. The concept is based upon the free surface-flow of water through a series of sequential linked shallow ponds or wetland cells vegetated with a range of native emergent plant species, with these acting as biofilters, absorbing excess nutrients and reducing water velocity to encourage sedimentation of particulate material (Almuktar *et al*., 2018; Cooper *et al*., 2019). Wetland vegetation, microorganisms, water, soil and sunlight all contribute to water treatment in the wetlands (Kadlec & Knight, 1996; Scholz *et al*., 2007; Mitsch & Gosselink, 2007). ICWs provide a multifunctional and multi-benefit approach centred on managing water quality and quantity, enhancing biodiversity while possessing the design flexibility to fit into whatever landscapes they are needed (Harrington & McInnes 2009; Everard *et al*. 2012). Of all the constructed wetland types, ICWs are the most supportive of wetland biodiversity. Examples of ICWs in the north Norfolk region include Frogshall ICW alongside the River Mun, Ingoldisthorpe ICW alongside the River Ingol and the recently constructed Stiffkey Integrated Constructed Wetland near Langham, all of which process effluent from adjacent wastewater treatment works. For effective pollution mitigation, ICWs could most efficiently be implemented to intercept and process the effluent from wastewater treatment works prior to it entering the rivers in the area (as is the case with the aforementioned examples).

Research on ICWs in different water treatment contexts (including domestic wastewater and agricultural point source pollution) has indicated their capacity to reduce water nutrient concentrations sustainably (Doody *et al*., 2009; Mustafa *et al*., 2009; Dong *et al*., 2011). In addition, well designed ICWs may be the most effective form of constructed wetland for wastewater treatment when it comes to reducing nutrient concentrations (Hickey *et al*., 2018). While the overall nutrient (especially phosphorus) removal efficiency of ICWs may decrease with age (Kayranli *et al*., 2010), one study assessing the long-term water purification potential of an ICW found that the average removal rates of TN and TP were maintained at 53.6% and 67.3% over 10 years, respectively (Zhu *et al*., 2021).

One study assessed the nutrient removal efficiency of two ICWs of differing ages (1 and 5 years old, respectively) installed at wastewater treatment plants in Norfolk. At the 1-year-old ICW, mean nitrate and phosphate concentrations were reduced by 30% while nutrient loadings were reduced by 70%. At the 5-year-old ICW, mean nitrate and phosphate concentrations were reduced by 63%, while nutrient loadings were reduced by 57%. In economic terms, the total capital cost of both ICWs was comparable to £31-39 per person served. ICWs were found to significantly reduce eutrophication risk of wastewater plant discharges while providing a cost-effective alternative to conventional tertiary wastewater treatment, while being suitable for smaller wastewater treatment works that currently lack legal obligations to minimise nutrient concentrations through conventional treatment (Cooper *et al.*, 2020).

Figure 33: ICW located within the River Stiffkey basin (Source: Ecosulis)

One study assessed an ICW in Norfolk which was receiving treated effluent from a small sewage treatment works to address the degradation of a receiving stream and lake. Nutrient concentrations of the ICW influent and effluent were compared, and the percentage reductions were as follows: total phosphorus (TP): 78%, orthophosphate: 80%, nitrate: 65%, nitrite: 67%, ammoniacal nitrogen: 62%, total oxidised nitrogen (TON): 65% and mean dissolved oxygen concentrations increased (influent mean: 6.4 ± 1.4 mg L^{-1} effluent mean: 17.8 ± 3.3 mg L^{-1}). Nutrient concentrations were found to be reduced progressively through the sequential treatment train of ICW cells, with the greatest reductions taking place in the 1st cell (which comprised 54% of total ICW area). The ICW was not sufficient to reduce stream and lake phosphorus levels below suggested target thresholds and it was estimated that the ICW would need to be 3.6 times larger (1.1 ha in size) to meet those standards (van Biervliet *et al*., 2020). One study monitoring 12 ICW systems in Ireland over an 8-year period found that while they received influent of variable nutrient and organic loadings, there was a mean reduction of Total P and soluble phosphorus (MRP) exceeding 95% with a reduction in nitrogen compounds (principally ammonium-N, exceeding 98%) due to interception and processing by the ICW systems (Harrington & McInnes, 2009).

ICWs have been found to reduce levels of other pollutants including pharmaceuticals (Li *et al*., 2014; Yan et al., 2016), steroid hormones and biocides (Chen *et al*., 2019), organophosphate pesticides (Chen *et al*., 2022a, 2022b; for a review see Vymazal & Březinová, 2015), petroleum hydrocarbon derivatives (Knight *et al*., 1999; McLaughlin *et al*., 2021), persistent organic pollutants including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Wojciechowska, 2013) and heavy metals (Khan *et al*., 2009; Lesage *et al*., 2007). Relevant to the study area, bacterial activity has been found to degrade PBDEs in the anaerobic conditions of wetland sediments (Wang et al., 2021). ICWs are effective at removing microplastics although these will persist in the initial part of an ICW treatment train (predominantly near the inlet area) (Chen *et al*., 2021; Lu *et al*., 2022). Antibiotics are also broken down in ICWs (Shan *et al*., 2020), with one study reporting that antibiotics and antibiotic resistance genes (ARGs) were removed at rates of 78-100 % and >99 %, respectively (Chen *et al*., 2015). ICWs also have the capacity to reduce levels of faecal coliforms (the most commonly used indicator bacteria to quantify health risks from waters) (Smith *et al*., 2005) and pathogenic bacteria including *E. coli*, *Salmonella* and *Enterococcus*, with levels of bacteria diminishing over sequential ICW cells (McCarthy *et al*., 2011; Scholz *et al*., 2007). Further work is warranted to assess the effects of ICWs on other pollutants (van Biervliet *et al*., 2020).

8.4. Beavers

Through their eco-engineering activities, beavers can reduce levels of nutrient pollutants in waterways, with their dams acting as sediment traps and filters. There have already been a number of beaver reintroductions in the north Norfolk area, such as on the source of the River Glaven by Norfolk Rivers Trust, on Wild Ken Hill estate and at Sculthorpe Moor Nature Reserve. The eco-engineering effects of beavers such as damming are more substantial on smaller lotic water bodies, so their impact on water pollution through dam construction is likely to be greater in the headwaters of the rivers in the region.

Figure 34: Beaver-engineered stream and dam (Source: Scottish Wild Beaver Group).

One study assessing the ecological impact of a pair of beavers found that 13 dams they constructed trapped large quantities of sediment (of which 70% was soil from adjacent fields), in addition to significantly reducing levels of nitrogen and phosphorus (Puttock *et al*., 2017). Vegetation can then capture these nutrients in the beaver ponds. Further research has reported that beaver dam and pond creation can reduce levels of nitrates downstream of dams (Devito *et al*., 1989; Dewey *et al*., 2022). As a result of such findings, it has been suggested that in agriculturally dominated catchments where diffuse pollution rates are high, beaver ponds may be an effective means of mitigating diffuse nitrogen pollution issues from intensive agriculture upstream (Lazar *et al*., 2015), which can in turn enhance habitat for pollution-sensitive species downstream (Rosell *et al*., 2005; Strzelec *et al*., 2018). Further research has corroborated this capacity of beaver dams to filter nitrogen and phosphorus from river water, with a study conducted on beaver dams in Lithuania reporting similar reductions in nitrogen and phosphorus levels through sediment deposition, although it should be noted that mercury was also sequestered in the beaver pond sediments (Čiuldienė *et al*., 2020). Mercury can be transformed into hazardous and neurotoxic methylmercury (MeHg) in beaver ponds by biological process in the anaerobic conditions of the pond sediment. However, on balance, if scaled up to catchment level, wider reintroductions of free-living beavers to the upper stretches of rivers in the catchment area would likely have significant benefits to the rivers and coastal areas they flow into in the area. In addition to mitigating against the impacts of nutrient pollution, beaver eco-engineering can also enhance biodiversity at landscape scale (for a review, see Brazier *et al*., 2020).

9. Conclusion

There are a number of threats and pressures imposing on ecological enhancement work in coastal and marine environments in the north Norfolk area. These may include recreational disturbance (such as through marine recreation and dog walkers), destructive fishing practices such as bottom trawling and dredging, habitat loss through development, water quality issues, invasive species, sociological issues (e.g. uncertainty over funding and governmental short termism) and more generic or global threats such as climate change and associated sea level rise, coastal erosion and squeeze, and temperature change. Of these issues, the majority of stakeholders had a shared view of water quality as being a major issue in the region, with pollution being a diffuse catchment wide problem. Pollution is also a notable issue in that as well as being a pervasive, catchment wide issue that can negatively impact coastal ecosystems in a variety of ways, it can also be mitigated in a number of ways, both at its source and further downstream, hence it warranting a central focus in this report. Special attention should also be given to destructive fishing practices such as dredging, which should not be considered as being compatible with areas undergoing marine habitat restoration work (such as seagrass meadow and oyster reef restoration). It should be noted that there are data gaps, such as the effects of certain pollutants on the marine environment, and a better understanding of previous trends across the north Norfolk catchments may be useful when planning the next phase of ecological restoration works. Furthermore, the importance of maintaining appropriate and consistent language when communicating ecological enhancement work (aligning with the community's understanding, incorporating relevant financial and business terminology) was also deemed important, along with the need of balancing various activities undertaken by many different stakeholders in the region so that they can coexist while considering their cumulative impact on the environment.

Given that water pollution is an issue of central importance, its mitigation warrants particular consideration. These take the form of a range of pollutants entering rivers in the region, primarily as a result of intensive agricultural practices, with some lesser input from urban sources and industry. Further pollution inputs come from shipping in coastal waters, with the added pressure of physical disturbance resulting from this (primarily from recreational shipping). It should be noted that assessments of pollution levels in the marine environment of the north Norfolk coast are constrained by a limited number of sampling points. However, it should be noted that there a number of potential options for mitigating these issues, and these marine and coastal ecosystems also come with varying levels of resilience to the impacts of pollution and disturbance, and some of them can also play a role in reducing levels of nutrient pollution in the marine environment as long as pollution levels do not exceed their tolerance. There are a number of potential mitigation approaches, some of which may reduce pollution at source (or close to it), while other approaches may help reduce pollution downstream of source, and so help buffer the coastal environment. A notable benefit is that all outlined approaches to pollution mitigation will also benefit biodiversity where implemented. Adoption of sustainable and regenerative agricultural practices may be able to reduce pollution at source, and the establishment of field margin or riparian buffer strips can filter and capture pollutants close to source before they enter waterways, and with this the marine environment. Both approaches may be more cost effective than larger heavy engineering solutions such as ICW construction, and they will likely be eligible for funding through environmental land management schemes (ELMS) and Sustainable Farming Incentive (SFI) payments which will be introduced this year. An ELMS pilot trial is already being undertaken by Norfolk Rivers Trust to assess the effects of riparian buffer strips in the region on nutrient pollution mitigation. Beaver reintroduction to river headwaters could provide a cost-effective means of mitigating pollution, but wild release of free-living beavers is not currently permitted in England.

A number of coastal areas in the north Norfolk region have been highlighted for potential multi-habitat ecological enhancement work. Among these, Blakeney Harbour is notable in that there are already existing seagrass beds there, highlighting the value of the habitat, with the possibility of transplanting from stock present there to aid in restoration work. In addition, Norfolk Seaweed are commercially producing both native oysters (*Ostrea edulis*) and sugar kelp (*Laminaria saccharina*) in Blakeney Harbour, highlighting that conditions and water quality in the area do not impede multiple forms of marine habitat restoration or creation. Blakeney (freshmarsh) also offers the opportunity of habitat enhancement work further inland. Brancaster harbour was also highlighted as a promising site for ecological enhancement work, and Salthouse freshmarsh also offers opportunity for coastal habitat creation, particularly when considering the issues of sea level rise and coastal squeeze. Consideration should be given to long-term projects spanning decades, and looking ahead, a holistic and joined up approach emphasising a shared, collective effort, using clear and consistent communication between different stakeholders will be important for ensuring broad benefits to the environment and community.

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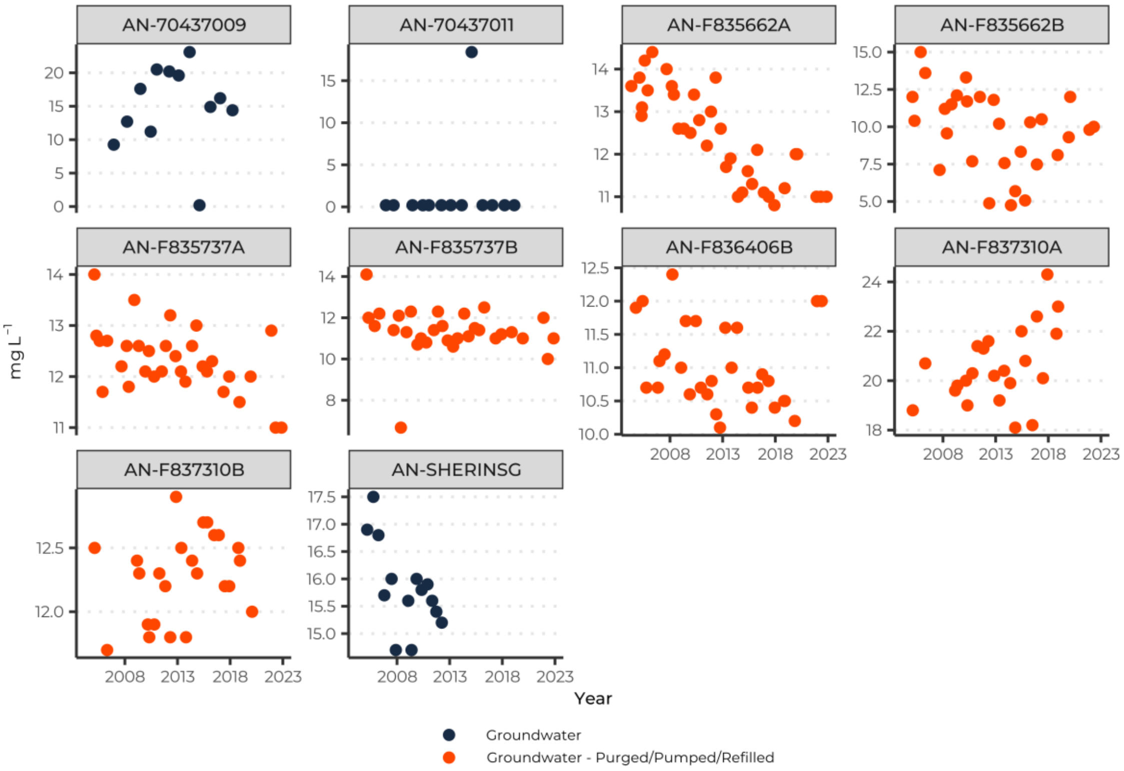
Annex 1: Sample Points Map

Annex 2: Nitrates in Groundwater



Feasibility of multi-habitat coastal restoration in north Norfolk.

RQ3: What indicators can be used to assess connectivity and restoration success?

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Contents

1. Executive Summary

Coastal habitats, such as saltmarshes and seagrass meadows are among the most valuable ecosystems in the world. WWF-UK's Wholescape Programme aims to develop an integrated approach to the management of the UK's land, rivers, and seas. In alignment with the wholescape approach, this research employs a literature review to identify potential ecosystem indicators of restoration success and determine effects of functional connectivity between multiple coastal habitat types. The primary focus is on developing a framework that includes a suite of indicators; both overarching and species-specific indicators applicable to multiple coastal habitats.

The key findings from the literature are as follows:

1. Overarching Indicators:
   - Drawing on the Society of Ecological Restoration's attributes, the research evaluates the success of restoration in terms of three major ecosystem attributes; biodiversity, structural characteristics, and ecological processes.
   - Emphasising the importance of a multi-ecosystem wholescape approach for coastal restoration acknowledges positive interactions between habitats.
2. Species-specific indicators
   - Identifying easily monitored species and suites of species across multiple coastal habitats, especially those that require multiple coastal habitats to complete key life stages.
   - Considering the population and conservation status of species enhances the assessment of habitat condition and interconnectedness.

2. Introduction

Coastal ecosystems, with their intricate interplay of diverse habitats, are dynamic and invaluable components of our natural environment. In North Norfolk, these ecosystems encompass a mosaic of habitats, from salt marshes to seagrass beds, each playing a unique role in sustaining the region's rich biodiversity. This report forms part of a larger study examining the feasibility of multi-habitat coastal restoration in North Norfolk.

This report aims to address Research Question 3 of the project:

'What are key ecosystem indicators of restoration success, common to and applicable across multiple coastal habitats in North Norfolk?'

The aim of RQ3 is to first identify and define the primary ecosystem indicators most applicable to monitor restoration success across multiple coastal habitats, through a literature review. Second, to evaluate the existing data, collection frequency and custodians of these data to inform future monitoring frameworks. We have split the research into two key areas; (i) overarching indicators of restoration success and connectivity (ii) species- specific indicators of improved coastal habitat condition and of interconnectedness between coastal habitats.

Ecological restoration, as defined by the Society of Ecological Restoration (SER. 2004), is the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed. The overarching objective of restoration is to create a self-supporting ecosystem that is capable of withstanding disturbances without requiring further assistance.

The Society of Ecological Restoration international has issued a primer illustrating nine ecosystem attributes that should be taken into account and adopted when assessing the success of ecological restoration. These are (1) similar diversity and community structure in comparison with reference sites; (2) presence of indigenous species; (3) presence of functional groups necessary for long-term stability; (4) capacity of the physical environment to sustain reproducing populations; (5) normal functioning; (6) integration with the landscape; (7) elimination of potential threats; (8) resilience to natural disturbances; and (9) self-sustainability. Monitoring all of these attributes would provide an excellent assessment of restoration success, but would demand significant financial and time investments. In practise, most studies have assessed measures that can be categorised into three major ecosystem attributes. These are (1) biodiversity, (2) structural characteristics (such as vegetation structure), and (3) ecological processes (such as carbon sequestration) (Ruiz-Jaen and Aide, 2005). Both diversity and abundance are most commonly used in restoration success assessment, and it is also important to consider an assessment of social and cultural values of coastal restoration in the determination of the success if restoration projects (Wortley et al., 2013).

Restoration practice has been dominated by single-habitat approaches, potentially limiting the range of benefits that restoration can provide. For ecosystem restoration to meet its full potential in delivering socio-ecological benefits that are resilient to environmental change, restoration practises should plan beyond single-species and single-habitats to a multi-ecosystem wholescape approach. Where multiple habitats are co-restored, their positive interactions mutually benefit each other to stabilise and even accelerate ecosystem recovery (McAfee et al., 2022). However, assessing the success of multi-habitat coastal restoration becomes challenging due to the complex interactions and dynamic nature of interconnected ecosystems, and traditional indicators that are designed for singular habitats.

To determine the level of restoration success, there is a need to provide a target for the outcomes of ecosystem recovery and indicators can be used to benchmark a site against the target. This target is often determined by comparing ecosystem attributes with reference sites (Ruiz-Jaen & Aide, 2005). Functional success of restoration can be ecologically evaluated through comparisons of ecosystem functions indicators in restored with those in reference sites. However, defining measurable targets for success and establishing reference sites for comparison is challenging due to ‘shifting baseline syndrome’ (Pauly, 1995). Shifting baselines is characterised by the gradual acceptance of degraded environmental conditions as normal and the dynamic nature of degraded ecosystems further complicates the establishment of fixed restoration success goals. Due to the effects of climate change, many prominent ecologists have recognised the need to broaden the meaning of ecological restoration to include “hybrid” or “novel” ecosystems (Hobbs & Cramer, 2008). These ideas have helped broaden the goal of restoration to include states other than historic baselines or analogues. For example, by conceptualising “Anthropocene baselines,” it may be possible to triage historic remnant ecosystems, while at the same time recognising the reality of irreversible ecological change in highly altered and human-dominated ecosystems.

A restoration project could reach success if the ecosystem has been restored to a more natural or functional state. Success encompasses the recovery of key ecological components, including positive impacts on biodiversity and improved ecosystem services. However, there is also a need for a more flexible and open-ended approach to goal-setting in restoration initiatives. Rather than fixating on predefined benchmarks that may inadvertently underestimate the potential of degraded nature, it is recommended to adopt adaptive and context-specific targets and levels of success. This approach allows for a more nuanced understanding of ecosystem dynamics, considering the historical context, and enables restoration initiatives to become dynamic processes capable of eliciting transformative change.

Indicators are monitoring metrics that assess ecosystem attributes and can be linked to restoration goals and objectives and the overall success of a project (SER, 2004; Waltham et al., 2020). Indicators need to be responsive to spatial and temporal change and able to differentiate between natural and anthropogenic drivers. Ideally, the success indicators should be comprehensive, broadly applicable, and not overly labour-intensive. Recognising and understanding effective ecosystem indicators is fundamental to assessing coastal habitat restoration. Key to this understanding are the behavioural adaptations of selected indicator species. Indicator species, or suites of species, should be easily monitored, sensitive to environmental change and their presence/absence, abundance and distribution should reflect or predict the condition(s) of the environment in which they are found. For the research specifically, we are interested in species that are common to and applicable across multiple coastal habitats across North Norfolk and therefore can act as indicators of multi-habitat restoration success. Examining population and distribution trends of these species refines our understanding of restoration success and associated ecological recovery. Natural population fluctuations, migration patterns, and external influences beyond habitat conditions are also considered. By addressing these complexities, we ensure a comprehensive assessment, to inform an indicator framework for assessing multi-habitat coastal restoration success in North Norfolk. The framework enables quantitative assessment and comparison against reference sites and flexible, ambitious forecasted targets.

3. Ecosystem Indicators Overview

Table 1. A proposed success indicator system for multi-habitat coastal ecosystem restoration based on key attributes of a functioning ecosystem. Each indicator is specified according to the key ecosystem attribute it measures, metric(s) that can be used to measure the indicator and exisiting measuring methods. The rationale behind each indicator is summarised with additional details available in section 5. Data sources, custodians, and exisiting data collection frequencies are identified, as well as suggestion monitoring period.

Ecosystem Attribute	Indicator	Metric(s)	Measuring methods	Rationale	Data sources	Data Custodians	Data collection frequency	Recommended monitoring period
Ecosystem Function: Species Dispersal	Landscape Connectivity	Fragmentation status / Effective Mesh Size	Mapping nature networks and landscape barriers	Lead indicator, increased land-scape scale connectivity is essential for species dispersal and key ecosystem processes.	Mapped nature networks and key coastal habitat types (Priority Habitats Inventory) Mapped landscape barriers	Natural England, Environment Agency, Marine Management Organisation, CEFAS, NBN Atlas, National Trust	Every 3-5 years	Throughout the year
Species Composition	Wetland and Coastal Birds	Diversity, population abundance and distribution	Point Count/ Transect Surveys. BTO monitoring scheme, Bioacoustics monitoring	Responsive to environmental changes, have important ecological functions (such as seed dispersal), easy to survey, resonance with the public	Breeding bird survey. Wetland bird survey.	BTO/JNCC/RSPB, NBN Atlas	Annually	Nov-Feb (wintering) & March-July (breeding bird season)
Species Composition	Benthic Macrioinvertebrates	Diversity, population abundance, distribution and biomass	Transect surveys, Quadrats, net collecting,	Easy to monitor, reflect aquatic habitat health, limited mobility & sensitive to pollution.	Marine Mollusc Recording Scheme	Conchological Society, Seasearch	Throughout the year	Throughout the year, summer months best
Species Composition & Structural Diversity	Diadromous and Coastal Fish	Diversity, population abundance and distribution, typical length/age	Electrofishing. Collation of angling statistics.	Fast response to environmental change. High mobility, physiological tolerances and osmoregulatory mechanisms provide insight into connectivity and ecological conditions.	Angling statistics, Ecology & Fish Data Explorer	North Norfolk Anglers, Environment Agency NBN Atlas	Annually	Mar - Oct
Species Composition	Coastal Pollinators	Diversity, population abundance and distribution	Transect surveys, netting and pan trapping	Mobile but fragmented habitat reduces mobility, reflect coastal habitat interconnectivity, indicator of plant-pollinator network recovery	UK Pollinator Monitoring Scheme	Butterfly Conservation, NBIS Records, UKCEH	Annually	Jun - Oct
Habitat Condition	Water Quality	Water Quality Status, levels of nitrogen, phytoplankton, dissolved oxygen, salinity	Water sampling (WFD)	Restoration of coastal habitats can lead to increased water quality	Water Quality Data Archive, Catchment Data Explorer	Environment Agency	Monthly/ Annually	Throughout the year

Ecosystem Attribute	Indicator	Metric(s)	Measuring methods	Rationale	Data sources	Data Custodians	Data collection frequency	Recommended monitoring period
Ecosystem Function: Food Web Complexity	Higher Trophic Species (e.g., otter)	Diversity, population abundance and distribution	Observational surveys, acoustic monitoring (marine mammals). Spraint survey, camera trapping (otters).	Species at higher trophic levels indicate food web complexity and abundance of lower trophic levels.	SCANS ship & aerial survey. National Otter Survey.	Sea Mammal Research Unit. Mammal Society. Norfolk County Council	Sea mammals: every 10 years Otters: 2-5 years	Throughout the year
Ecosystem function: nutrient & carbon cycling	Soil nutrients	SOM, soil nitrogen and soil organic carbon	Soil sampling	Carbon & nitrogen levels indicate carbon storage and nutrient availability for plant and microbial communities	NATMAP Carbon	UKCEH, Natural England, LandIS	N/A	Throughout the year
Structural Diversity: vegetation	Saltmarsh zonation	Sward height, extent/area cover, distribution	Structured walk survey and transect surveys with GPS to assess zonation and vegetation structure	A varied vegetation structure is important for invertebrate diversity. Sward height is an indicator of overgrazing. Changes in extent and/or loss of different communities is an indicator of an external force (e.g.,sea level rise).	Saltmarsh Extent & Zonation	Environment Agency	Annually	May to October
Social	Socio-economic value	Community attitudes and wellbeing, new jobs created, nature tourism	Community & visitor surveys	Community support, social and economic benefits are key to restoration success.	Stakeholder focus groups, surveys, questionnaires, Local Nature Recovery Strategy	Norfolk County Council	Annually	Throughout the year

4. Indicator Species Overview

Table 2. This table provides further detail on the species-specific ecosystem restoration indicators; the key species groups and key species within those groups. We have provided data collection frequency and survey time periods based on existing surveys and the speed at which the species may respond to environmental change (lead or lag indicators).

	Indicator species	Key habitats	Restoration indicator	Exisiting monitoring data	Data collection frequency	Survey time period
Diadromous fish	Sea bass	Estuaries, lagoons, coastal waters, and rivers	Interconnectedness	NBN Atlas (National Trust Species Records, Seasearch Marine Surveys)	Annually	Mar-Jun (in shoals to spawn)
	European eel	Estuaries, freshwater, reedbeds, coastal marshes	Interconnectedness	Environment Agency Ecology and Fish Data (NFPD and Biosys)	Biennially	Jun-Oct
	Smelt	Saltmarsh, estuaries, rivers	Interconnectedness & habitat condition	Environment Agency fishery catch statistics	Annually	May to Oct
Wading & coastal birds	Curlew	Wet grassland/ farmland, heathland, and moorland	Interconnectedness & habitat condition	WeBS and Breeding Wader survey (BTO, JNCC, RSPB) for long term monitoring eBird (for distribution modelling)	Annually	Nov-Feb (wintering bird season)
	Oystercatcher	Estuarine mudflats, saltmarshes, sandy and rocky shores, oyster beds	Interconnectedness & habitat condition	Breeding Wader survey (BTO, JNCC, RSPB), and NBN Atlas	Annually	Throughout the year
	Little tern	Sand and shingle beaches	Habitat condition	Natural England, JNCC, RSPB and NBN Atlas	Annually	March-July (breeding bird season)
	Lapwing	Mudflats, marshes, wet meadows	Interconnectedness & habitat condition	WeBS survey (BTO, JNCC, RSPB)	Annually	Nov-Feb (wintering bird season)
	Bar-tailed godwit	Estuaries, wetlands, sandy & muddy shores	Interconnectedness & habitat condition	WeBS survey (BTO, JNCC, RSPB)	Annually	Nov-Feb (wintering bird season)
	Avocet	Coastal wetlands, brackish marshes	Interconnectedness & habitat condition	WeBS and Breeding Wader survey (BTO, JNCC, RSPB)	Annually	March-July (breeding bird season)
	Redshank	Open marshes, mires, saltmarshes, mudflats	Interconnectedness & habitat condition	WeBS and Breeding Wader survey (BTO, JNCC, RSPB) for long term monitoring eBird (for distribution modelling)	Annually	Nov-Feb (wintering) & March-July (breeding bird season)
Bird of prey	Marsh harrier	Reedbeds, coastal marshes, wetlands	Habitat condition	BTO (Northwest Norfolk Ringing Group)	Biennially	Throughout the year, best time in spring and summer
Saltmarsh angiosperms	Common glasswort	Saltmarshes and beaches	Interconnectedness	NBN Atlas (National Trust Species Records,	Biennially	May-Oct
	Sea purslane	Sandy coastline, saltmarshes	Interconnectedness	BSBI database, Norfolk Biodiversity Information Service	Biennially	July-Sept

	Indicator species	Key habitats	Restoration indicator	Exisiting monitoring data	Data collection frequency	Survey time period
	Common saltmarsh-grass	Saltmarshes, mudflats & other coastal saline habitats	Interconnectedness	Environment Agency & Defra (BIOSYS)	Biennially	May-Oct
	Eel grass	Seabed of coastal waters both intertidal and subtidal	Interconnectedness & habitat condition	NBN Atlas, and Marine Monitoring surveys	Annually	May-Oct
	Tasselweeds	Shallow coastal waters	Interconnectedness & habitat condition	NBN Atlas and Botanical Society of Britain & Ireland	Annually	May-Oct
Coastal fish	Flounder	Seabed of coastal waters, estuaries and sometimes freshwater	Interconnectedness & habitat condition	NBN Atlas, National Fish Populations database (NFPD) and BIOSYS (Biological survey) database	Annually, more intensive assessments every 2-3 years	May-Oct
	Sole	Sandy/ muddy seabed's, estuarine	Habitat condition	NBN Atlas and Marine Biological Association	Annually	Jun-Sep (move inshore)
	Plaice	Sandy seabed, estuaries	Habitat condition	NBN Atlas and Marine Biological Association	Annually	N/A
	Mullet	Brackish lagoons, sandy/muddy seabed	Interconnectedness & habitat condition	NBN Atlas and Marine Biological Association	Annually	N/A
Amphibians	Natterjack toad	Sand dunes, coastal grazing marshes, ephemeral pools	Habitat condition	JNCC monitoring framework.	Annually	Night surveys Apr-May (peak breeding season)
Coastal pollinators	Sea aster bee	Saltmarsh, estuaries, mudflats, sand dunes	Interconnectedness	Norfolk Biodiversity Information Service, National Trust Species Records	Biennially	mid-Aug to mid-Oct
	Scarce pug	Sea wormwood in saltwater and freshwater habitats	Habitat condition	NBN Atlas, Butterfly Conservation, NBIS Records and 'iRecord Surveys	Annually	Aug-Oct
	Pantaloon bee	Sandy coastal habitats, dunes, heathland, saltmarsh	Interconnectedness	Norfolk Biodiversity Information Service	Biennially	Jun - Aug
Aquatic mammals	Eurasian otter	Estuaries, freshwater, saltmarshes, mudflats	Habitat condition	NBN Atlas, Mammal Society and JNCC	Annually	Throughout the year
	Harbour porpoise	Along coasts, bays, harbours, estuaries, large rivers	Habitat condition	NBN Atlas, SCANS surveys coordinated by the Sea Mammal Research Unit at University of St Andrews	Biennially	Jan-Apr

	Indicator species	Key habitats	Restoration indicator	Exisiting monitoring data	Data collection frequency	Survey time period
Crustaceans	Shore crab	Seagrass, intertidal habitats such as oyster beds, rockpools	Interconnectedness	Seasearch Marine Surveys, Natural England	Annually	Summer
Molluscs	Cockles (Cerastoderma spp.)	Saltmarshes, mudflats, estuaries, sandy beaches, coastal lagoons	Habitat condition	NBN Atlas (Conchological Society of Great Britain & Ireland and Seasearch Marine Surveys in England)	Biennially	Spring tide periods (>6.5m)
	Dog whelk	Wave exposed to sheltered rocky shores from the mid shore downwards	Habitat condition	Seasearch Marine Surveys, Marine Biological Association	Biennially	Spring - Summer
	European flat oyster	Shallow coastal water with mud, rocks, muddy sand, muddy gravel seabed	Habitat condition	NBN Atlas and the Marine Biological Association	Biennially	Spring - Summer
	Razor clams (Ensis spp.)	Saltmarshes, mudflats, estuaries, sandy beaches, coastal lagoons	Habitat condition	Conchological Society of Great Britain and Ireland	Biennially	Spring – Summer

5. Selected indicators to assess connectivity and restoration success

Table 1 provides a top-level summary, outlining the proposed indicator system for assessing multi-habitat coastal ecosystem restoration, based on three key ecosystem attributes: biodiversity/species composition, structural diversity and ecological processes (Ruiz-Jaen and Aide, 2005).

This section delves into the rationale for each selected ecosystem indicator. By assessing these indicators, or a selection of these indicators, we aim to quantify the nuances of coastal ecosystems and gauge the success of multi-habitat restoration initiatives.

5.1. Landscape Connectivity

Habitat connectivity is a measure of the accessibility and flow between habitats needed to maintain key ecological processes such as succession, migration and the ability of a species to meet its habitat requirements over its entire life history. Understanding the degree to which coastal habitats are connected and functional is a key element of understanding wholescape processes and restoration success. A well-connected network of coastal habitats provides a variety of benefits, facilitating nutrient and seed dispersal, and linking 'core' areas and important sites with others by nature corridors. This connectivity relieves pressure on vulnerable species and habitats by improving opportunities for foraging, nesting, and seeding refuge which may also improve species abundance and diversity. Animal movements are essential for ecosystem functioning because they act as mobile links and mediate key processes such food web, metapopulation and disease dynamics, which have been shown to provide sources for reorganisation after major disturbance events (Torres et al., 2018).

Connectivity can be assessed by mapping coastal habitats and indicators derived from this could measure the fragmentation of the mapped habitat networks or degree of fragmentation by barriers in the landscape (e.g., barriers to flow and fish passage). For example, by measuring effective mesh size (Moser et al., 2007) of mapped habitat networks to indicate the degree to which networks comprise of a connected-whole or a series of more fragmented habitat networks. Effective mesh size – and other measures of fragmentation – can be calculated using the *'landscapemetrics'* R package.

Habitat connectivity acts as a lead indicator and successful multi-habitat restoration might be characterised by and increase in landscape scale habitat connectivity through improved linkages, corridors and functional pathways, and connecting isolated habitat.

5.2. Coastal and Wetland Birds

Birds have evolved morphological and behaviour traits to utilise a diversity of habitats and resources over space and time. They are responsive to environmental changes, have important ecological functions (such as seed dispersal), they're relatively easy to survey and have great resonance with the public. As such they are excellent indicators of i) the health and connectivity of habitats, and ii) the state of recovery of the biodiversity-ecosystem functioning relationship (He et al., 2023).

In the context of North Norfolk's coastal habitats, and a wholescape approach to coastal restoration, coastal/wading birds and birds of prey as a suite of species serve as excellent indicators of multihabitat restorations and interconnectivity between different coastal habitats. Wading and coastal birds often rely on a network of coastal habitats for breeding, feeding and roosting (Beerens et al., 2015). Monitoring their population distributions and abundances helps assess the effectiveness of restoration efforts in creating and maintaining contiguous and functional coastal habitats.

The redshank, lapwing, curlew, bar-tailed godwit, oyster catcher and little tern are all key coastal/wading birds of North Norfolk and benefit from a variety of coastal habitats. The redshank for example undergoes am essential lifecycle transition within coastal ecosystems. They nest and raise their young on coastal wetland and salt marshes and often move to mudflats and estuaries to forage for invertebrates as they grow (Sharps et al., 2016). This makes their presence and distribution an excellent indicator for the interconnectivity of North Norfolk's coastal habitats (see Annex 1 for more information).

Coastal birds of prey, particularly marsh-breeding predators such as the marsh harrier, are also good indicators of restoration success. Their prominent position in the food web and adaptability make them responsive to shifts in prey availability and habitat quality. Predatory birds are often limited by the ability to exploit food resources, as such can be good indicators of lower trophic levels and related ecosystem functions.

The impacts of changing land use, intensification of agriculture, land drainage, habitat fragmentation and forest expansion have all been implicated in long-term declines in BTO monitoring data for species such as curlew, redshank, lapwing and oystercatcher. The BTO and partners facilitate a large-scale survey to monitor long-term population changes of breeding waders in England, as well as the WeBS Wetland Bird survey.

Restoration success for birds would be evidenced by notable increase in populations of key species, expanding habitat range and distribution, as well as increased reproductive success. As well as monitoring the individual species populations within this suite of species, bird community indices such as the Wetland Bird Index can be used to gauge the overall status of the wetland bird community, as well as measures of diversity (bird species diversity and functional diversity). However, the climate-related challenges including shifting temperatures and sea levels, impact nesting and feeding habitats. Resident species may experience range shifts, while migratory birds must adapt to altered conditions across regions. Monitoring global populations of these indicator species is essential, providing context when compared to local North Norfolk monitoring efforts.

5.3. Benthic Macroinvertebrates

Benthic macroinvertebrates such as molluscs and crustaceans, emerge as good indicators of the biological health of aquatic environments as they spend most of their lives in water, are easy to monitor and differ in their tolerance to pollution. Unlike fish, macrobenthos have more limited mobility, and therefore cannot escape pollution. Evaluating the abundance, distribution and variety of macrobenthos in a waterbody gives an indication of the condition of that aquatic ecosystem.

Molluscs, including razor clams, European flat oyster, dog whelks and cockles are key macrobenthos group assessed as a good bioindicator. Due to their sedentary nature, molluscs show community level changes in response to habitat disturbances and reflect the degree of environmental contamination by heavy metals and pollution. Crustaceans, such as the shore crab, are also useful as early indicators of restoration success and can be quick to occupy newly available habitat, providing indication of positive changes in the ecosystem. Evaluating the presence/absence and abundance of these indicator species gives an indication of the biological condition of an aquatic ecosystem. Aquatic habitats in healthy biological condition can support a wide variety and high number of benthic macroinvertebrates, including many that are intolerant of pollution.

5.4. Diadromous and Coastal Fish

Fluctuations in coastal fish assemblages are indicative of the overall health and connectivity within coastal ecosystems. Fish can be quick to inhabit newly inundated estuarine and coastal habitats, serving as a potential indicators of early restoration success. This is particularly relevant when their habitat utilisation, diversification and abundance exceeds the development of focal vegetation communities (Rummell et al., 2023). Their fast response can be attributed to their high mobility, adaptive habitat requirements and physiological tolerances, enabling them to utilise a diverse range of foraging and sheltering opportunities in restored coastal habitats. Some key North Norfolk coastal fish species including plaice, flounder, sole and mullet. These species commonly use marshes, estuaries and lagoons as juvenile habitats. In the event of successful coastal restoration, positive impacts on nursery habitats are anticipated, evident through observable increases in the populations of juvenile individuals of these species.

Diadromous fish are a suite of fish species which exhibit intricate migratory behaviours between freshwater and saltwater ecosystems to complete essential life stages (Jones, 2006). As such, they make robust indicators of aquatic habitat interconnectedness. Notable diadromous fish species in north Norfolk include sea bass, smelt and European eel. By monitoring these species, we gain specific information pertaining to the restoration of migratory pathways, the connectivity of diverse aquatic habitats, and the recovery of fish populations. The restoration of migratory pathways, increased food availability for juveniles, and improved spawning and nursery habitat in connected and restored habitats in North Norfolk are expected to lead to an increase in juvenile bass upriver.

Given the reliance of diadromous fish on habitats extending beyond North Norfolk, understanding their complex lifecycles and considering external climatic changes is crucial. Climate change poses challenges for diadromous fish; changing ocean conditions may impact spawning and migration and shifts in ocean currents and temperature may alter their range. Monitoring global data trends and collaborating with international conservation initiatives is essential to discern whether population changes result from local management practices or broader influences.

5.5. Coastal Pollinators

Using coastal pollinators as indicators of restoration success is grounded in their ecological significance and responsiveness to habitat changes. Many pollinators, such as bees and butterflies rely on a variety of plants and nesting sites throughout their life cycles and coastal ecosystems offer a range of flowering plants. These pollinators exhibit high mobility and dependence on floral resources, and so their presence and activity can indicate the ease with which the species move between coastal ecosystems, reflecting habitat interconnectivity.

Assessing the recovery of pollinators and their associated plants can be a useful first proxy for determining the effects of restoration on pollination. For example, pollinator abundance is likely positively associated with floral visitation rate which is an important predictor of pollination (Scott-Brown & Koch, 2020). Restoration activities may help to remediate the impacts of agricultural land use on pollinators and pollination. In many cases, pollinators recover quickly after restoration of degraded ecosystems (Breland et al., 2018). However, plant–pollinator networks in restored ecosystems are sometimes less complex than in natural communities suggesting that pollination function may not recover completely.

5.6. Water Quality

Water quality is one of the most important factors in aquatic ecosystems and functioning coastal ecosystems can improve water quality through nitrogen storage and denitrification Restoration often aims to remove or mitigate environmental stressors such removing polluting agents and increase water quality. Therefore, an improvement in water quality would be an early indicator or restoration success. However, it is essential to prioritize the restoration of water quality itself before implementing any further restoration actions.

Estuarine, coastal and river water body status provides a high-level overview of water quality across North Norfolk. Monitoring water quality status at a catchment is pertinent to the wholescape approach. The overall status used to classify water bodies in this data considers biological quality alongside physico-chemical and hydro morphological quality. Dissolved oxygen, phytoplankton and nitrogen are all key indicators of water quality, encompassed by the water body status, because they are essential for survival of aquatic life Dissolved oxygen levels in water indicate the amount of oxygen available for fish other organisms. Phytoplankton are at the base of the aquatic food chain and changes in abundance can indicate shifts in nutrient levels and overall ecosystem dynamics.

Nitrogen is an essential nutrient for plant growth, but elevated nitrogen concentrations can contribute to algal blooms and hypoxia. Monitoring nitrogen levels helps assess the impact of nutrient loading on coastal ecosystems. The Water Quality Archive also provides data on water quality measurements across coastal and estuarine waters and rivers carried out by the Environment Agency

5.7. Higher Trophic Species

Species at higher trophic levels are often highly connected and functionally important to ecosystems. Higher trophic level species such as aquatic mammals exert strong influences on the diversity and abundance of other taxa within the ecosystem. These effects occur through direct pathways, including predation and the redistribution of nutrients, as well as indirect pathways, such as the modification of physical environments through foraging activities (Perino et al., 2019). Recovering diverse species communities requires maintaining viable populations and enabling the recovery of declining and depleted populations, which are typically at higher trophic levels (Torres et al., 2018).

Monitoring species of higher trophic levels is a good indicator of ecosystem function and food web complexity. In the case of aquatic mammals such as otter and harbour porpoise, their presence and dynamics reflect top-down control, influencing lower trophic levels and cascading effects throughout the food web. Higher trophic level species are often linked to prey availability and therefore typically inhabit ecosystems where prey items are abundant. The presence of otters is a sign of restored fish abundance and good water quality. Harbour porpoises are included as indicator species for several national and international agreements (Ijsseldiik et al., 2018). They are sensitive to pollution and over-fishing and environmental disturbances.

5.8. Soil Nutrients

The mixing of freshwater and saltwater is a fundamental driving force that determines the structure and function of tidal coastal habitats. Soils are an important component of tidal and coastal habitats and carbon, nutrient and sediment dynamics are good indicators of ecosystem function. They sequester organic matter, nitrogen, carbon and phosphorus, support complex biochemical reactions and contribute to long-term coastal habitat stability through deposition of mineral sediment and accumulation of organic matter (Zhao et al., 2016). Coastal ecosystems are known to be carbon sinks and play a crucial role in mitigating climate change. Monitoring carbon levels in coastal soils can help us understand the carbon sequestration potential of these ecosystems and their contribution to mitigating climate change. Soil organic matter (SOM) content provides insight into overall soil health and its ability to support vegetation. Monitoring SOM levels in coastal soils can give insight into the health of the soil and the potential for carbon sequestration. And nitrogen is an essential nutrient for plant growth and is often a limiting factor in coastal ecosystems. Monitoring nitrogen levels in coastal soils can help us understand the nutrient status of the soil and the potential for plant growth. Nitrogen levels in coastal soils can also be used as an indicator of nutrient pollution from human activities such as agriculture and wastewater treatment (Yu et al., 2016).

5.9. Saltmarsh Zonation and Structure

Saltmarshes act as crucial transitional zones between terrestrial and aquatic environment and have dynamic responses to environmental change exhibiting sensitivity to variations in water levels, salinity, and substrate conditions. Monitoring changes in zonation, extent and sward height within salt marsh communities provides a representative ecological indicator and alterations in zonation and shifts in sward height can mirror changes in water levels, salinity, and substrate conditions, serving as indicators of the effectiveness of management interventions in restoring natural dynamics. Changes in extent and loss of different communities become indicative of broader ecosystem shifts, suggesting potential external forces like sea-level rise-induced drowning. Sward height changes, on the other hand, offer valuable indications of overgrazing.

5.10. Socio-wellness

Integrating social indicators into the indicator assessment framework is crucial for capturing the multifaceted relationship between coastal ecosystems and the communities they sustain. Social indicators play a pivotal role in understanding the human dimension of restoration success. Measures such as community engagement levels, attitudes towards restoration, local economic impacts, and the well-being of residents provide insights into the reciprocal influences between ecological restoration and human societies.

Nature-based tourism and green job creation are key economic elements of restoration success. Economic benefits of tourism to enterprises and businesses, for example, are likely be produced by an increase in nature-based tourism. Successful nature-based tourism can also act to further incentivise sustainable land-use practices to protect and restore natural assets across North Norfolk's coast. The number of nature-based tourism visits as a proportion of the total visits, measured by applying visitor survey data, would be a suitable indicator to reflect the social element of restoration success. The number of new green jobs created would indicate the relative size of the green economy. An increased demand for green jobs indicates a demand for workers in roles which enable them to contribute actively to nature restoration across North Norfolk's coast.

Assessing community engagement levels, positive attitudes and wellbeing signify local support and indicates positive influences of restored coastal ecosystems on community life, offering a holistic view of restoration success. Structured questionnaires and focus groups can be deisgned to capture perceptions, opinions and overall satisfaction regarding the coastal restoration initiatives.

6. Multi-habitat species

Table 3: List of species that are known to utilise more than one coastal habitat throughout their life stages in North Norfolk and species that utilise both saltwater and freshwater environments.

	Coastal habitats used	Life stage details	Both saltwater & freshwater?
European eel	Rivers, coastal waters	Undergo an ontogenetic habitat shift. Spawn in the Sargasso Sea, migrate to rivers and grow in estuaries.	✓
Sea bass	Coastal waters, kelp forests, sandy beaches, estuaries, rivers, lagoons	Spawn on inshore waters, inhabit coastal waters.	✗
Smelt	Saltmarsh, estuaries, rivers	Spawn in shallow, fast flowing rivers, juvenile nurseries in saltmarsh habitats, adults inhabit estuaries.	✓
Flounder	Seafloor, seagrass beds, sand flats, estuaries.	Juveniles live in estuaries until they morph into flat fish and migrate to deeper waters.	✓
Sole	Sandy and muddy seabed's and in estuarine habitats	Juveniles live in estuaries and subtidal sandbanks until they morph into flat fish and migrate to deeper waters.	✓
Plaice	Sandy, gravely and muddy seabed, tidal pools, subtidal sandbanks	Juveniles live in tidal pools and subtidal sandbanks until they morph into flat fish and migrate to deeper waters.	✓
Brown/Sea Trout	Streams, rivers, lakes and saltwater habitats.	Migrating from the sea into freshwaters to spawn.	✓
Natterjack toad	Coastal sand dune systems, coastal marshes, sandy heaths, temporary pools.	Toads will spawn in the temporary pools, which will emerge as small toads after metamorphosis.	✓
Common frog	Coastal sand dune systems, coastal marshes, sandy heaths, temporary pools.	Frogs will spawn in the temporary pools, which will emerge as small frogs after metamorphosis.	✗
Curlew	Mudflats, coastal and floodplain grazing	Feed on mudflats, nest and breed in coastal and flood plain grazing	✗
Oystercatcher	Mudflats, coastal waters	Forage on mudflats, build nests near coastal waters such as saltmarsh, sand and shingle	✗
Redshank	Mudflats, saltmarsh, estuaries	Forage on mudflats and estuaries, but nest on coastal marshes, lowland wet grasslands, and rough pasture.	✗
Little tern	Beaches, coastal waters	Sandy or shingle beaches for nesting coastal waters for feeding.	✗
Reed bunting	Reed beds, coastal grasslands, saltmarsh, coastal scrub	Reed bunting utilise reed beds for nesting and the surrounding coastal habitats for food sources.	✗
Harbour seal	Sandy, gravely and muddy beaches, tidal flats, kelp forests, estuaries, saltmarsh	Seals use beaches for resting, birthing and nursing, and the surrounding coastal habitats for foraging and hunting opportunities.	✗
Shore crab	Shallow intertidal zones, rocky/sandy habitats, tidal pools	Shore crabs alternate between benthic (bottom dwelling) adult and planktonic (living in the water column) larval stages	✗

7. Key species conservation status

We accessed essential data on the conservation status of key species in North Norfolk by utilising two primary data sources. The Integrated Biodiversity Assessment Tool (IBAT) provided access to the global IUCN Red List database, enabling us to retrieve data on the international conservation statuses of species in the region. Additionally, we consulted the Joint Nature Conservation Committee (JNCC) Red Lists for Great Britain to gather specific information on the conservation statuses and trends of species within the UK, including North Norfolk.

Table 4 : Relevant species across the North Norfolk area and their current conservation status (JNCC, 2023, IUCN 2023). This list includes key indicator species as well as other relevant species utilising multiple coastal habitats (marine, freshwater and terrestrial). The full list of species within the study area, obtained from IBAT is available as supplementary information.

	Common name	**Latin name**	**IUCN red list category (global)**	**IUCN Population trend (global)**	**GB Red list category**
Birds	Redshank	*Tringa totanus*	Least concern	Unknown	Vulnerable (non-breeding)
	Curlew	*Numenius arquata*	Near Threatened	Decreasing	Endangered (breeding)
	Oystercatcher	*Haematopus ostralegus*	Near Threatened	Decreasing	Least Concern (breeding)
	Bar-tailed godwit	*Limosa limosa*	Near Threatened	Decreasing	Endangered (breeding), Least Concern (non-breeding)
	Marsh harrier	*Circus aeruginosus*	Least Concern	Stable	Near Threatened (breeding)
	Hen harrier	*Circus cyaneus*	Least Concern	Decreasing	Vulnerable (breeding)
	Red Kite	*Milvus milvus*	Least Concern	Increasing	Least Concern (breeding)
	Common Sandpiper	*Actitis hypoleucos*	Not assessed	Unknown	Vulnerable (breeding)
	Purple Sandpiper	*Calidris maritima*	Least Concern	Decreasing	Critically Endangered (breeding), Endangered (non-breeding)
	Turnstone	*Arenaria interpres*	Least Concern	Decreasing	Vulnerable (non-breeding)
	Black Redstart	*Phoenicurus ochruros*	Least Concern	Increasing	Endangered (breeding), Near Threatened (non-breeding)
	Common Eider	*Somateria mollissima*	Near Threatened	Unknown	Vulnerable (non-breeding)
	Great Crested Grebe	*Podiceps cristatus*	Least Concern	Unknown	Vulnerable (breeding), Least Concern (non-breeding)
	Little Grebe	*Tachybaptus ruficollis*	Least Concern	Decreasing	Least Concern (breeding), Least Concern (non-breeding)
	Fulmar	*Fulmarus glacialis*	Least Concern	Increasing	Least Concern (breeding)
	Redshank	*Tringa totanus*	Least Concern	Unknown	Near Threatened (breeding), Vulnerable (non-breeding)

Common name	Latin name	IUCN red list category (global)	IUCN Population trend (global)	GB Red list category
Ringed Plover	*Charadrius hiaticula*	Least Concern	Decreasing	Vulnerable (breeding), Near Threatened (non-breeding)
Great Bittern	*Botaurus stellaris*	Least Concern	Decreasing	Near Threatened (breeding), Vulnerable (non-breeding)
Little tern	*Sterna albifrons*	Least Concern	Decreasing	Vulnerable (breeding)
Snipe	*Gallinago gallinago*	Least Concern	Decreasing	Least Concern (breeding), Near Threatened (non-breeding)
Lapwing	*Vanellus vanellus*	Near Threatened	Decreasing	Endangered (breeding), Vulnerable (non-breeding)
Dark-bellied Brent goose	*Branta bernicla bernicla*	Least Concern	Unknown	Least Concern (non-breeding)
Knot	*Calidris canutus*	Near Threatened	Decreasing	Least Concern (non-breeding)
Bewick's swan	*Cygnus columbianus*	Least Concern	Unknown	Critically Endangered (non-breeding)
Black-headed gull	*Chroicocephalus ridibundus*	Least Concern	Unknown	Least Concern (breeding)
Common tern	*Sterna hirundo*	Least Concern	Unknown	Near Threatened (breeding)
Sandwich Tern	*Thalasseus sandvicensis*	Least Concern	Stable	Least Concern (breeding)
Grey heron	*Ardea cinerea*	Least Concern	Unknown	Near Threatened (breeding), Least Concern (non-breeding)
Kingfisher	*Alcedo atthis*	Least Concern	Unknown	Least Concern (breeding)
Little Egret	*Egretta garzetta*	Least Concern	Increasing	Least Concern (breeding), Least Concern (non-breeding)
Swallow	*Hirundo rustica*	Least Concern	Decreasing	Least Concern (breeding)
Swift	*Apus apus*	Least Concern	Stable	Endangered (breeding)
Snow Bunting	*Plectrophenax nivalis*	Least Concern	Decreasing	Endangered (breeding), Least Concern (non-breeding)
Shore Lark	*Eremophila alpestris*	Least Concern	Decreasing	Endangered (non-breeding)
Teal	*Anas crecca*	Least Concern	Unknown	Least Concern (breeding), Least Concern (non-breeding)
Sanderling	*Calidris alba*	Least Concern	Unknown	Least Concern (non-breeding)
Mallard	*Anas platyrhynchos*	Least Concern	Increasing	Least Concern (breeding), Near Threatened (non-breeding)
Shelduck	*Tadorna tadorna*	Least Concern	Increasing	Endangered (breeding), Endangered (non-breeding)
Pink-footed goose	*Anser brachyrhynchus*	Least Concern	Increasing	Least Concern (non-breeding)

	Common name	Latin name	IUCN red list category (global)	IUCN Population trend (global)	GB Red list category
	Greylag Goose	*Anser anser*	Least Concern	Increasing	Least Concern (breeding), Least Concern (non-breeding)
	Shoveler	*Anas clypeata*	Least Concern	Decreasing	Least Concern (breeding), Least Concern (non-breeding)
	Spoonbill	*Platalea leucorodia*	Least Concern	Unknown	Endangered (non-breeding)
	Avocet	*Recurvirostra avosetta*	Least Concern	Unknown	Least Concern (breeding), Least Concern (non-breeding)
	Guillemot	*Uria aalge*	Least Concern	Increasing	Least Concern (breeding), Least Concern (non-breeding)
	Razorbill	*Alca torda Linnaeus*	Least Concern	Increasing	Least Concern (breeding)
	Dunlin	*Calidris alpina*	Least Concern	Decreasing	Endangered (breeding), Vulnerable (non-breeding)
Fish	Sea bass	*Dicentrarchus labrax*	Least Concern	Unknown	Not assessed
	Flounder	*Platichthys flesus*	Least Concern	Decreasing	Not assessed
	Smelt	*Osmerus eperlanus*	Least Concern	Unknown	Not assessed
	European eel	*Anguilla anguilla*	Critically Endangered	Decreasing	Not assessed
	European sturgeon	*Acipenser sturio*	Critically Endangered	Decreasing	Not assessed
	Brown Sea Trout	*Salmo trutta*	Least Concern	Unknown	Not assessed
	Three-spined Stickleback	*Gasterosteus aculeatus*	Least Concern	Unknown	Not assessed
	Common goby	*Pomatoschistus microps*	Least Concern	Unknown	Not assessed
	Plaice	*Pleuronectes platessa*	Least Concern	Increasing	Not assessed
	Sand Goby	*Pomatoschistus minutus*	Least Concern	Stable	Not assessed
	Golden Grey Mullet	*Chelon auratus*	Least Concern	Unknown	Not assessed
	Thicklip Grey Mullet	*Chelon labrosus*	Least Concern	Unknown	Not assessed
Mammals	Otter	*Lutra lutra*	Near Threatened	Decreasing	Least Concern
	Harbour porpoise	*Phocoena phocoena*	Least Concern	Unknown	Not assessed
	Grey seal	*Halichoerus grypus*	Least Concern	Increasing	Not assessed
	Harbour seal	*Phoca vitulina*	Least Concern	Unknown	Not assessed
	Minke whale	*Balaenoptera acutorostrata*	Least Concern	Unknown	Not assessed
Plants	Common glasswort	*Salicornia europaea*	Not assessed	Unknown	Least Concern
	Dwarf eelgrass	*Zostera noltei*	Least Concern	Decreasing	Vulnerable
	Common eelgrass	*Zostera marina*	Least Concern	Decreasing	Near Threatened
	Common saltmarsh grass	*Puccinellia maritima*	Not assessed	Unknown	Least concern
	Sea Purslane	*Atriplex portulacoides*	Not assessed	Unknown	Least concern

	Common name	Latin name	IUCN red list category (global)	IUCN Population trend (global)	GB Red list category
	Rock sea lavender	*Limonium binervosum*	Not assessed	Unknown	Least Concern
	Jersey cudweed	*Helichrysum luteoalbum*	Not assessed	Unknown	Not assessed
	Sea heath	*Frankenia laevis*	Not assessed	Unknown	Near Threatened
	Perennial glasswort	*Sarcocornia perennis*	Not assessed	Unknown	Least Concern
Fungi & Lichen	Spiny Iceland Lichen	*Cetraria aculeata*	Not assessed	Unknown	Not assessed
Invertebrates	Sea aster mining bee	*Colletes halophilus*	Not assessed	Unknown	Not assessed
	Scarce Pug	*Eupithecia extensaria*	Not assessed	Unknown	Endangered
	Banded Demoiselle	*Calopteryx splendens*	Least Concern	Stable	Least Concern
	Black Tailed Skimmer	*Orthetrum cancellatum*	Least Concern	Stable	Least Concern
	Broad-bodied chaser	*Libellula depressa*	Least Concern	Stable	Least Concern
	Brown Hawker	*Aeshna grandis*	Least Concern	Unknown	Least Concern
	Common Blue Damselfly	*Enallagma cyathigerium*	Not assessed	Unknown	Not assessed
	Four-Spotted Chaser	*Libellula quadrimaculata*	Least Concern	Stable	Least Concern
	Common Darter	*Sympetrum striolatum*	Least Concern	Unknown	Least Concern
	Emperor dragonfly	*Anax imperator*	Least Concern	Stable	Least Concern
	Hairy dragonfly	*Brachytron pratense*	Least Concern	Stable	Least Concern
	Migrant Hawker	*Aeshna mixta*	Least Concern	Increasing	Least Concern
	Large Red Damselfly	*Pyrrhosoma nymphula*	Least Concern	Stable	Least Concern
	Red-eyed damselfly	*Erythromma najas*	Least Concern	Stable	Least Concern
	Scarce Emerald Damselfly	*Lestes dryas*	Not assessed	Unknown	Near Threatened
	Willow emerald damselfly	*Chalcolestes viridis*	Not assessed	Unknown	Not assessed
	Norfolk Hawker	*Aeshna isosceles*	Least Concern	Unknown	Not assessed
Reptiles & Amphibians	Natterjack toad	*Epidalea calamita*	Least Concern	Decreasing	Endangered
	Common frog	*Rana temporaria*	Least Concern	Stable	Least Concern
	Common toad	*Bufo bufo*	Least Concern	Stable	Near Threatened
	Grass snake	*Natrix helvetica*	Not assessed	Unknown	Least Concern
	Great crested newt	*Triturus cristatus*	Least Concern	Decreasing	Least Concern
	Smooth newt	*Lissotriton vulgaris*	Least Concern	Stable	Least Concern
	Common lizard	*Zootoca vivipara*	Least Concern	Unknown	Least Concern
Molluscs	Common cockle	*Cerastoderma edule*	Not assessed	Unknown	Not assessed
	Dog whelk	*Nucella lapillus*	Not assessed	Unknown	Not assessed
	Common razor shell	*Ensis magnus*	Not assessed	Unknown	Not assessed
	Common Mussel	*Mytilus edulis*	Not assessed	Unknown	Not assessed
	Edible Crab	*Cancer Pagurus*	Not assessed	Unknown	Not assessed
	European green crab	*Carcinus maenas*	Not assessed	Unknown	Not assessed

	Common name	Latin name	IUCN red list category (global)	IUCN Population trend (global)	GB Red list category
	Common Limpet	*Patella vulgata*	Not assessed	Unknown	Not assessed
	European flat oyster	*Ostrea edulis*	Not assessed	Unknown	Not assessed

8. Annex 1. Literature review of potential indicator species

This annex presents a literature review focusing on potential indicator species across North Norfolk. The review follows the structure outlined in table 2, providing further information into species selected as indicators and those deemed unsuitable after research.

8.1. Diadromous Fish

Diadromous Fish exhibit complex migratory behaviours between freshwater and saltwater ecosystems, and as such, make robust indicators of coastal habitat interconnectedness. These fish include the anadromous species that spawn in freshwater but most of their lives are spent at sea, and the catadromous species that spawn at sea and spend most of their lives in freshwater. The species that live in estuarine habitats may spawn in either the sea or estuaries but are dependent on estuaries for key life stages (Jones, 2006). The need for different coastal habitats for the key life stages of these fish demonstrates their importance as an indicator species for coastal habitat connectedness.

The transition from seawater to freshwater is integral to the life stages of many species of fish. Diadromous fish develop osmoregulatory mechanisms for different levels of salinities in different environments. Freshwater to seawater transition involves hormonally mediated changes in gill ionocytes and the proteins associated with hypo-osmoregulation, increased seawater ingestion and water absorption in the intestine. Species of fish attain salinity tolerance through early development, gradual acclimation or environmentally or developmentally cued adaptations (Zydlewski, & Wilkie, 2012). By monitoring these species, we gain specific information pertaining to the restoration of migratory pathways, the connectivity of diverse aquatic habitats, and the recovery of fish populations.

8.1.1. European seabass (Dicentrarchus labrax)

The European seabass is a predatory fish found around most of the UK. According to NBN Atlas there are 167 records of sightings in Norfolk's multi-coastal habitats, these sightings are from 2015 up to 2021. They are highly mobile, migrating inshore for the summer months where they are mainly found in estuaries and can be found surprisingly far upstream in rivers. In the winter months, they migrate to the sea and will gather in large shoals in the spring to spawn. They mainly feed on crustaceans and smaller fish such as sand eels. Estuaries provide an important habitat for juvenile seabass, the sheltered conditions here along with a plentiful food supply making it an extremely suitable place to grow (wildlifetrusts.org). Young bass tend to form schools and the adults are more likely to be found in smaller numbers (Reeve, 2007).

They are considered of Least Concern globally on the IUCN Red List of Species, but ICES list the regional stock as over-exploited and rapidly declining (IUCN).

Most of the data is collated on the NBN atlas.

European Seabass records from NBN Atlas between 2003-2023

European seabass is a demersal fish, living and feeding near the bottom of the sea in the littoral zone between 10 m and 70 m in depth over most substrata. European sea bass is primarily a marine fish but are found in brackish water and in summer months enter estuaries and rivers. Records on NBN

Atlas show that there have been many sightings at Cley Beach, near the River Glaven, as well as many sightings near 'Rosalie Wreck, Weybourne, Norfolk'.

European seabass undergo ontogenetic habitat shift. Seabass utilise inshore habitats including rivers in the summer months, but in winter they migrate to the sea and will spawn in large shoals in spring.

Seabass are slow-growing, long-lived generalist predators with a complex lifecycle utilising both freshwater, marine and estuarine environments, making them an extremely suitable indicator of coastal habitat connectivity. The European seabass has a spawning and feeding migration as well as a complex recruitment process which is precarious and influenced by many drivers. Prey availability and temperature are two key environmental drivers that affect rates of growth and reproduction. Juvenile presence and abundance also provides an indicator of habitat connectivity as they rely on specific nursery habitats like shallow coastal waters.

Quantification of growth variability in juvenile fishes has been used as a measure of habitat quality, with higher growth being achieved in habitats of higher "quality" (Ciotti et al., 2013). Therefore, as a result of their tendency to maintain residency to specific nursery sites for their first four years, measurements of growth variability in European bass captured from a variety of estuarine nursery habitats may provide an important assessment of the nursery habitat "quality".

Current data is currently made up of human observation and is recorded on NBN Atlas, with there being 167 recorded sightings of European seabass in the North Norfolk area, this data beingaccessible via the NBN Atlas website. Seasearch also provides data for North Norfolk, and this information is collated on NBN Atlas. Seasearch surveys 1km squares, they collect the data, revisit the squares and record how many years the square has been surveyed.

To determine future restoration success, European seabass are best surveyed through Seine netting, and electrofishing, both methods being standard government procedure. Underwater counts should be taken during the spring when European seabass gather in shoals to spawn and this should be repeated every year, the latter already occurring in North Norfolk (seascape) but this can be extended to more sites along the coast.

8.1.2. European eel (Anguilla anguilla)

The European eel starts its life as a larva or Leptocephalus hatching in the Sargasso Sea. From there, they migrate across the Atlantic and arrive in the river estuaries of North Norfolk, notably the River Glaven. This is also where adult eels, up to 30 years old, leave the freshwater river Glaven each autumn to head back to the North Atlantic to breed. The glass eels feed on worms and shrimps in the estuary and river as they mature to become elvers, followed by yellow and then silver eels and they undergo an ontogenetic diet shift from invertebrates to fish. Eels are critically endangered globally, and populations are in decline across Europe, and East Anglia is no exception. However, increasing numbers of eels have been observed.

Eels undergo ontogenetic habitat shift. As glass eels, they prefer brackish water, but as they mature, they move up the river into freshwater habitats and find refuge in reedbeds, shallow marshes and creeks. Once they have matured into silver eels, they shift towards saltier waters to prepare for their journey back to the Sargasso Sea to breed. European eels serve as robust indicators of coastal habitat connectivity due to their extensive migrations through freshwater, estuarine, coastal and marine environments, and habitat versatility. Major factors impacting eels are habitat alteration such as wetland reclamation and conversion, as well as river barriers and river channelisation, all of which reduce the habitat connectivity needed for the eels to move up and downstream. Formerly common throughout all Norfolk River systems, and once an important part of the local economy; it is now a UK Biodiversity Action Plan species.

Conservation management for eels is best focussed on improving connectivity by removing barriers to upstream migration and assisting migration across 'problem' barriers that cannot be removed or modified (Harwood et al., 2021).

The Environment Agency conducts fisheries monitoring in various aquatic environments, including rivers, lakes, transitional zones, and coastal waters. Fish data, including site information, species, catch numbers, and fish measurements, is accessible via the 'Ecology & Fish Data Explorer.' This dataset is made available under the Open Government License and is sourced from the National Fish Populations Database (NFPD) and the Biological Survey Database (Biosys). Eels are best surveyed through electric fishing surveys or trapping between June and October, annually.

8.2. Wading and coastal birds

Wading birds as a suite of species are excellent indicators of multihabitat restorations and the interconnectivity between different coastal habitats. Their dynamic habitat selection, seasonal movements and quick response to changes in habitat quality make them invaluable indicators of coastal and wetland systems (Beerens et al., 2015)

The impacts of changing land use, intensification of agriculture, land drainage, habitat fragmentation and forest expansion have all been implicated in long-term declines in BTO monitoring data for species such as curlew, redshank, lapwing and oystercatcher. The BTO and partners facilitate a large-scale survey to monitor long-term population changes of breeding waders in England, as well as the WeBS Wetland Bird survey.

8.2.1. Redshank (Tringa totanus)

The redshank is a resident in Norfolk and so can be seen throughout the year with numbers increasing along the coast in the wintering bird season. The Norfolk redshanks have been surveyed at NWT Cley Marshes, the estuary at Wells Harbour, the saltmarshes of Blakeney and NWT Holme Dunes. The species is of Least Concern globally, however it is listed as Vulnerable in the Great Britain red list.

The species undergoes essential life cycle transitions within coastal ecosystems. They nest and raise their young on coastal wetland and salt marshes (around half of British redshank breed on saltmarsh), benefiting from the protection and abundant food sources offered by these habitats. As they grow, they exhibit an ontogenetic habitat shift, often moving from salt marshes to mudflats and estuaries to forage for invertebrates. This makes their presence and distribution an excellent indicator for the interconnectivity of North Norfolk's coastal habitats. A field study in Norfolk showed that the density of breeding redshank within coastal and inland grazing marshes was positively associated with the presence of wet features within each field. On coastal grassland, shallow wet features and vegetation structure have been shown to be important to several species of breeding waders (Eglington et al. 2008) and soil invertebrates are more accessible when water levels are just below the soil surface (Ausden et al. 2001). Although redshank breed in various habitats, saltmarshes are internationally important for the species (Sharps et al., 2016).

Redshank records from NBN Atlas between 2003-2023

8.2.2. Curlew (Numenius arquata)

The curlew is a large wader, it's haunting call can be heard from February to July on its breeding grounds – wet grassland, farmland, heathland, and moorlands. From July onwards, coastal numbers start to build up, peaking in July. The UK's breeding population of Eurasian curlews is of national importance, being estimated to represent more than 30 percent of the west European population.

Curlew are red listed in the UK under the BTO's Birds of Conservation Concern (BTO, 2021). They are also a Priority Species under the UK-Post 2010 Biodiversity Framework. Curlew are listed as Near Threatened on the global IUCN Red List of Threatened Species.

Curlew records from NBN Atlas between 2003-2023

Curlews breed in wet grasslands and moorlands and are common on migration at wetlands throughout the country. From July they head towards the coast and large estuaries, where they spend the winter. They survive on a diet of worms, shellfish and shrimps which they find in the ground. In Norfolk, resident populations of curlew can be found in the Brecks of East Anglia, while overwintering populations are found all along the North Norfolk coast, specifically 'NWT Cley Marshes' and 'NWT Holme Dunes'

Curlews are an excellent indicator of coastal habitat connectedness due to their national importance, their abundance throughout North Norfolk and their reliance on different habitats for different parts of their lifecycle such as relying on estuaries and marine habitats for overwintering.

8.2.3. Lapwing (Vanellus vanellus)

The lapwing used to breed commonly over much of lowland Britain, but surveys have shown a substantial reduction in the number of breeding locations, resulting from changes in land management and increased predation pressure. In winter, the lapwing is widely distributed in lowland Britain, but BTO Surveys have shown that numbers have shifted eastward (perhaps a response to milder winters) and increased in coastal wetlands as birds appear to feed more on mudflats at low tide (BTO).

The lapwing is listed as Near Threatened by the IUCN and is red listed as a UK bird of conservation concern by the British Trust of Ornithology (BTO, 2021). According to the UK breeding bird survey, lapwing numbers fell by 17% between 2011 and 2021, and by 62% between 1995 and 2021 (BTO). In Norfolk, lapwings are primarily restricted to managed nature reserves, where they experience notable success in terms of breeding and overall survival in most cases. The decline in nesting on farmland is attributed to the shift towards autumn sowing of crops, causing the crops to grow too tall for lapwings to nest in during the spring. Additionally, the drainage of wetlands and the reduction of uncultivated grassland, largely due to more intensive hill farming practices, have further contributed to the overall decline of lapwing populations (Norfolk Wildlife Trust).

The NBN Atlas has recorded Lapwings all along the NNC, however datasets looking purely at Norfolk are difficult to find (NBN). The UK breeding bird survey is likely the most comprehensive record of the lapwing population. The lapwing is an appropriate indicator of habitat connectedness due to its utilisation of both farmland and wetland habitats. There is also evidence of agri-environment schemes providing clear benefits to farmland lapwing populations highlighting their sensitivity to farming practices and the potential to reverse population declines (Sheldon et al., 2004).

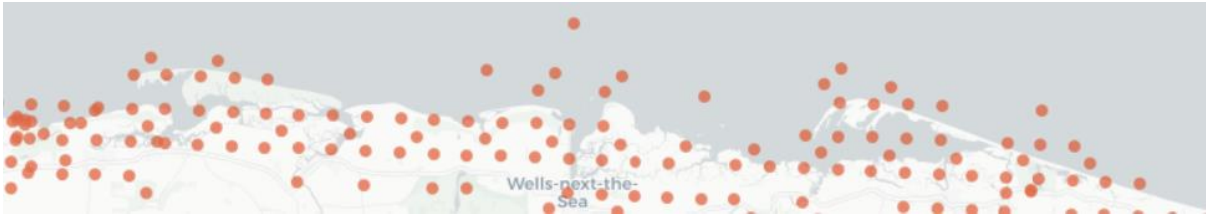
8.2.4. Bar-tailed godwit (*Limosa lapponica*)

The bar-tailed godwit is a large, tall wader that breeds in Arctic Scandinavia and Siberia, and migrates here in the thousands, either for the whole winter or en route to wintering grounds further south. Large numbers can be spotted in estuaries such as the Thames, Dee, Humber and Wash (Wildlife Trusts). Bar-tailed godwits feed on the muddy shores all around the coast. They are best seen in the two hours either side of high tide; at low tide they may feed many miles into estuaries. Bar-tailed godwits probe the mud (even if it is covered in 10-15 cm of water) for molluscs, crustaceans and worms (Wash Wader Research Group).

The bar-tailed godwit is listed as Near Threatened by the IUCN, and is amber listed by the BTO as a UK bird of conservation concern (BTO). The NNC is a particularly important site for the bar-tailed godwit since roughly 5% of the national wintering population reside here (Natural England, 2018). According to the BTO's 2021/22 wetland bird survey, Bar-tailed godwits have shown a 29% decline in England over the past ten years (Austin et al. 2023).

The Wetland bird survey provides a comprehensive record of bar-tailed godwit numbers and their population trends across the UK. The NBN atlas shows this species' presence has been recorded many times across the NNC (NBN).

Due to their feeding habits which cover a range of tidal zones, the bar-tailed godwit is a useful indicator for habitat connectedness as it highlights the health of the coastline at different distances from the shoreline.



Bar-tailed godwit records from NBN Atlas between 2003-2023

8.2.5. Oystercatcher (*Haematopus ostralegus*)

The oystercatcher is very noisy wading bird with a loud 'peep-ing' call. On the coast, it specialises in eating shellfish, particularly cockles and mussels in estuarine mudflats, saltmarshes, sandy and rocky shores which it either prises or hammers open with its strong, flattened bill (Durell et al., 2004). Originally a coastal species, the oystercatcher has moved further inland over the last 50 years to breed on waterways and lakes. Most UK birds still spend their winters by the sea, however, and are joined by birds from Norway and Iceland. Widespread around the coast, with large wintering numbers at major estuaries. Also nests inland on flooded gravel pits and large rivers (RSPB). Oystercatchers do not start breeding until they are at least three years old. There is strong mate and site fidelity, with one record of a pair defending the same site for twenty years. A single nesting attempt is made per breeding season, which is timed over the summer months. The nests of oystercatchers are simple affairs, scrapes in the ground which may be lined, and placed in a spot with good visibility (RSPB).

Classified in the UK as Amber under the Birds of Conservation Concern 5: the Red List for Birds (2021). Listed as Near Threatened on the global IUCN Red List of Threatened Species (BTO). The species breeds widely, both around the coast and inland, particularly in northern Britain, whilst during winter large flocks congregate on our estuaries. In Ireland the breeding population remains predominantly coastal. Britain & Ireland support a significant proportion of the global population of this species (Wildlife Trust).

Ringing studies highlight that there is little interchange between the Atlantic subpopulation which includes those breeding in Iceland, the Faeroes, Britain and Ireland and the continental subpopulation, which is made up of birds from Scandinavia and the Low Countries (BTO).

Oystercatcher records from NBN Atlas between 2003-2023

The main threat to the species is the over-fishing of benthic shellfish and the resulting disappearance of intertidal mussel and cockle beds (Atkinson et al. 2003). Bait digging has also been identified as a threat through loss of prey species and disturbance to the benthic fauna (van de Pol et al. 2014). The species is also threatened by habitat degradation on its wintering grounds due to land reclamation, pollution, human disturbance. A decrease in the Oystercatchers population could indicate one or more of these threats are taking place, which will also affect other species.

The BTO/JNCC/RSPB Breeding Bird Survey is a partnership jointly funded by the British Trust for Ornithology (BTO), Royal Society for Protection of Birds (RSPB) and JNCC and is carried out by volunteer birdwatchers throughout the UK. There have been 27 of these Breeding Bird Survey's, the last of which was published in 2021. Oystercatchers are recorded throughout the year but nest between is during the summer months.

8.2.6. Little tern (*Sterna albifrons*)

Little terns are small migratory seabirds which winter in Western Africa returning to the UK in April where they remain to breed until late summer, nesting exclusively on the coast in well-camouflaged shallow scrapes on beaches, spits or inshore islets. They do not forage far from their breeding site, which dictates a necessity for breeding close to shallow, sheltered feeding areas where they can easily locate the variety of small fish and invertebrates that make up their diet (JNCC, 2018).

Little terns are listed as least concern by the JNCC (globally), but in the UK they are amber listed as a bird of conservation concern due to the declines in their breeding populations (JNCC, 2018). At the time of the North Norfolk Coast (NNC) SPA designation it supported up to 400 pairs of little terns representing 20% of the British breeding population. Since designation little tern numbers on the coast have declined 17%. The NNC little terns are fledging on average 0.3 chicks per pair, below the number required to maintain their current population (Natural England, 2018 & JNCC, 2021).

Little tern records from NBN Atlas between 2003-2023

Research on breeding little terns in Portugal found human disturbance to be a significant factor in little tern breeding success. Little terns were up to 34 times more likely to succeed when measures were in place to reduce human disturbance (Medeirosa, et al., 2007). On the North Norfolk Coast as part of the national EU LIFE Little Tern Recovery Project, nesting sites are fenced and warrened (Natural England, 2018). Funding for these protective measures under this project ended in 2018, but the RSPB works with volunteers who fence some of the nests now. Any impacts on the fish population that the terns eat will also affect their population. This could be due to overfishing, pollution and other factors.

There are a number of organisations that hold data on the little tern, these include: Natural England, JNCC, RSPB and NBN Atlas. If more surveys are to be undertaken, they should be conducted between April and May when the little terns arrive back on UK shores.

8.2.7. Great bittern (*Botaurus stellaris*)

Previously widespread, bitterns became extinct in the UK in the late nineteenth century before returning and increasing to around 80 booming males in the 1950s. The number of Bitterns in the UK then declined to a low of 11 booming males in 1997 but has subsequently increased and has been rising consistently over the last ten years, with a new record total of 227 pairs counted in 2019 (BTO).

The extensive wet reedbeds that Bitterns require for breeding are provided at clusters of sites in Kent, East Anglia, Somerset and Yorkshire. In winter, bitterns are much more widespread and can be found at many smaller sites with a mix of reedbeds, pools and riverbanks.

This species can be found on the following statutory and conservation listings and schedules: UK Birds of Conservation Concern as Amber listed, the Species of European Conservation Concern as Least Concern and the IUCN Red List of Threatened Species (global) as least Concern (BTO and IUCN).

Bittern can be found all year round in the reedbeds of the Norfolk Broads, their characteristic booming calls can be heard from March until June (Norfolk Wildlife Trust).

Great bittern records from NBN Atlas between 2003-2023

As the bittern is a top predator in the wetland habitats it will be affected by any changes in the number of fish and amphibians it predates. Both prey groups are susceptible to pollution and other harmful practices, which will have a detrimental effect on the bittern due to the build-up of chemicals in its system or a diminished food source. Breeding bitterns are also a good indicator of a large healthy and undisturbed reedbed (BTO).

There are a number of different organisations that hold data on bitterns, with surveys being carried out on an annual basis, particularly for breeding birds. These include: NBN Atlas, BTO and Bird life international. Surveys for breeding birds are undertaken from March to June whilst listening for the males' booming call. Winter surveys are also undertaken to determine the number that have come to overwinter in the UK.

8.2.8. Ringed plover (*Charadrius hiaticula*)

The ringed plover is a small, dumpy, short-legged wading bird. They mostly breed on beaches around the coast, although they have also now begun breeding inland in sand and gravel pits and former industrial sites. Many UK birds live here all year round (including in Norfolk), but birds from Europe winter in Britain, and birds from Greenland and Canada pass through on migration (RSPB). The Ringed Plover nests on bare gravel, shingle and sand on the coast and around flooded gravel pits and reservoirs. In summer, invertebrates are their main diet and, in the winter, primarily marine worms, crustaceans and molluscs (RSPB, 2013).

The ringed plover is listed as Least Concern by the IUCN, however the BTO has red listed them as a UK bird of conservation concern (BTO). The North Norfolk Coast is an important site for ringed plovers with the SPA supporting approximately 2.6% of the British breeding population. However, the breeding population of ringed plovers has shown a steady and consistent decline on the North Norfolk Coast. The last full count of the NNC in 2007 recorded 202 pairs between Old Hunstanton and Weybourne. In 2016 a near complete count on the North Norfolk Coast SSSI recorded a population of 143 pairs at 12 sites. These populations show a serious long-term decline from c.435 pairs in 1984 and 283 pairs in 1993. Current visitor levels on the North Norfolk Coast are likely to be significantly reducing available habitat suitable for breeding ringed plover. The population has declined on all the main breeding sites except Scolt Head, a remote and less accessible site, where the breeding population has actually increased. Liley and Sutherland researched ringed plover breeding on a 9km stretch of the Norfolk coast from Wolferton Creek to South of Hunstanton (just outside the NNC NCA). They predicted that if nest loss from human activity was prevented the ringed plover population would rise by as much as 8%. A complete absence of human disturbance would lead to an 85% increase in the population. However, if visitor numbers doubled, then the population would decrease by 23% (Natural England, 2018). This clear link between the pressure exerted on the population by human activity and the resulting population change makes this species a useful indicator of restoration success.

There are a number of datasets available monitoring Ringed Plover populations over the years, but the largest ongoing project is likely the Breeding Bird Survey run by the BTO, JNCC and RSPB. This survey is carried out every year between April and June leading to an annual report, the most recent available one is from 2022 (BTO).

Ringed Plover records from NBN Atlas between 2003-2023

8.3. Birds of prey

Marsh breeding predatory birds are valuable components of healthy ecosystems and are useful indicators of successful wetland and coastal restorations. Their prominent position in the food web and adaptability make them responsive to shifts in prey availability and habitat quality.

8.3.1. Marsh harrier (*Circus aeruginosus*)

The marsh harrier nests in large reedbeds, feeding on frogs, small mammals and birds, such as moorhen and coot. Once very rare, it has spread from its stronghold in East Anglia to other parts of the country where reedbed habitat is found.

The marsh harrier has become increasingly common in Eastern England, where they were originally reported to be a summer visitor but are now recorded consistently all year round. The marsh harrier is one of the great conservation success stories in recent times in Norfolk and lowland England. In the 19th Century they were abundant in Norfolk and throughout East Anglia, but during the latter part of the century they had become extinct in the UK through habitat loss and persecution. In 1982 the first UK nest of marsh harriers in an arable field was recorded in Norfolk and this habitat has been used regularly by the species ever since.

Classified in the UK as Amber under the Birds of Conservation Concern and protected under the Wildlife and Countryside Act 1981 (BTO). Marsh harrier are listed as Least Concern under the Species of European Conservation Concern, and they are listed as Least Concern on the global IUCN Red List

(BTO). The most recent report of the UK Breeding Bird survey shows marsh harrier numbers to be fairly stable over the previous ten years (BTO, 2022).

Marsh harrier records from NBN Atlas between 2003-2023

8.4. Saltmarsh angiosperms

Salt marsh areas are crucial transitional zones between terrestrial and aquatic environments and are characterised by specific plant species that are adapted to brackish or saline conditions. These areas are hugely important for the interconnectivity of coastal ecosystems and the presence of key salt marsh species suggests the availability and connectivity of these critical zones. Salt marsh species are often sensitive to variations in water levels, salinity and substrate conditions and changes in these factors can indicate altered hydrology and shifts in habitat connectivity.

Monitoring the zonation and changes in sward height within salt marsh communities emerges as a representative ecological indicator offering insights into the dynamic interplay of plant species with their environment. Zonation alterations and shifts in sward height can be reflective of changes in water levels, salinity, and substrate conditions as a result of management interventions. Changes in extent and loss of different communities become indicative of broader ecosystem shifts, suggesting potential external forces like sea-level rise-induced drowning. Sward height changes, on the other hand, offer valuable indications of overgrazing.

8.4.1. Common glasswort (*Salicornia europea*)

Common glasswort, also called 'marsh samphire', is found growing on saltmarshes and beaches. It has adapted to thrive in high salt concentrations, showcasing its halophytic characteristics. It is often one of the pioneering saltmarsh species that colonise and transform the saltmarsh to make the habitat more suitable for other successional species.

According to the JNCC Vascular Plant Red List for GB, common glasswort is Least Concern.

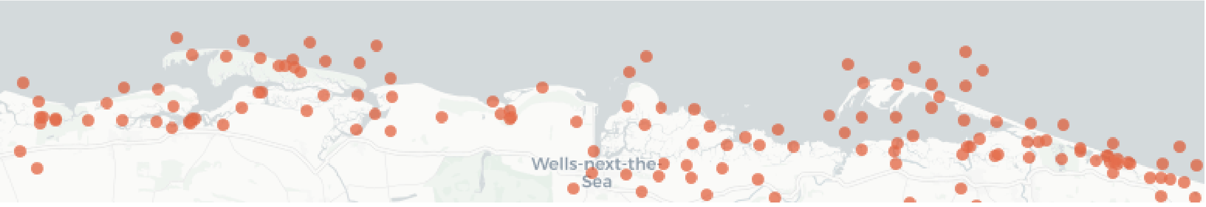
Common glasswort records from NBN Atlas between 2003-2023

Common glasswort utilises many of North Norfolk's coastal habitats, predominantly mudflats and saltmarshes. In North Norfolk there are records on the NBN Atlas at 'Holkham Beach', 'Scolt Head Island NNR' as well as sightings on 'Titchwell Marsh' and 'The Marrams'.

Common glasswort grows on saltmarshes and beaches and whilst it does not utilise freshwater, twice a day (depending on its location), it is submerged in seawater with the shifting of the tides. It is an annual plant so can be found all year round, so surveys can be done at any time.

8.4.2. Sea purslane (*Atriplex portulacoides*)

Sea purslane is found mostly round the coasts of England, Wales, and eastern Ireland where it is common but there is little to be found in Scotland or western Ireland.



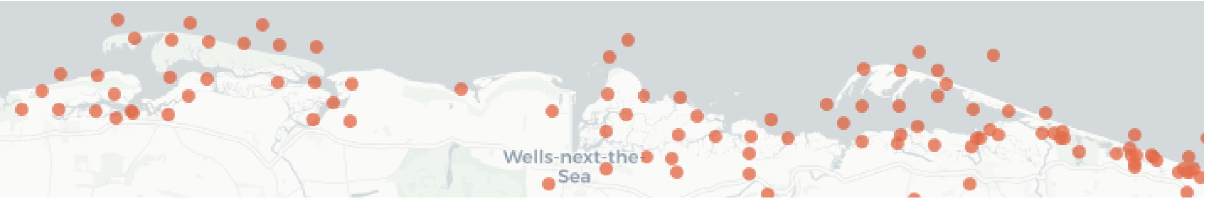
Sea purslane records from NBN Atlas between 2003-2023

Sea purslane is also an important ecological species, as it plays a vital role in the ecosystem of coastal regions. It helps to stabilise sand dunes and prevent erosion, and it provides a habitat for a range of marine and bird species. In addition, sea purslane can also help to improve soil quality by increasing organic matter and nutrient levels. The plant has a high salt tolerance, which means that it can grow in soils that are too saline for other plant species, making it an important pioneer and successional species in coastal ecosystems. This makes it an important tool for restoring degraded soils in coastal areas. Sea purslane is also a valuable plant for phytoremediation, which is the use of plants to remove pollutants from soil and water. The plant has been shown to be effective at removing heavy metals and other pollutants from contaminated soils, making it a potential tool for cleaning up polluted coastal areas.

One of the biggest threats to sea purslane is habitat loss and degradation. Coastal development, pollution, and climate change are all factors that can impact the health and vitality of coastal ecosystems, including those that support sea purslane populations. Efforts to protect and conserve these habitats are therefore critical to the long-term survival of this important plant species. Most of the data on Sea Purslane can be found on NBN Atlas, which has correlated data from the Vascular plant records verified via iRecord and National Plant Monitoring Scheme. This plant can also be surveyed throughout the year as it is an evergreen but may be easier to spot when it flowers between July and September.

8.4.3. Common saltmarsh grass (*Puccinellia maritima)*

Common saltmarsh grass is commonly found in salt marshes and other coastal saline habitats, such as salt meadows and tidal mudflats. It is highly salt-tolerant and can also grow on nutrient-poor soils. The plant can survive in submergence for short period of time and can grow in waterlogged soils. Because of its high salt tolerance, it is considered a valuable plant for revegetation of salt-impacted soils and also, it is an important species in coastal ecosystem as it can provide habitats for various species. The deep root system of common saltmarsh grass also helps to stabilise the soil and prevent erosion. In addition, this grass plays a key role in nutrient cycling, as it takes up nutrients from the soil and releases them back into the ecosystem when it decomposes. Salt marshes are known to be effective carbon sinks, and common saltmarsh grass is a major contributor to this process. As the grass takes up carbon dioxide from the atmosphere during photosynthesis, it stores this carbon in its roots and the surrounding soil.



Common saltmarsh grass records from NBN Atlas between 2003-2023

Despite its importance, common saltmarsh grass is facing a number of threats. One of the main threats is habitat loss, as coastal development and sea level rise continue to encroach on salt marshes. In addition, pollution from agricultural runoff and other sources can harm common saltmarsh grass and the organisms that depend on it.

Most of the data on common saltmarsh grass can be found on NBN Atlas, which has correlated data from the Vascular Plant Records verified via iRecord and National Plant Monitoring Scheme. This plant can be found throughout the year so can be surveyed any time.

8.4.4. Rock sea lavender *(Limonium binervosum*)

The species of Sea lavenders which are endemic to Britain all belong to the *Limonium binervosum* aggregate (rock sea-lavenders). The taxonomy of this group was revised in 1986 and nine species and numerous infra-specific taxa are now recognised. Of the nine species, eight are believed to be endemic to Britain, these are *Limonium britannicum*, *L. dodartiforme*, *L. loganicum*, *L. paradoxum*, *L. parvum*, *L. procerum*, *L. recurvum* and *L. transwallianum*. These species grow almost exclusively on rocks and sea-cliffs of a wide range of geological types although a few have also been recorded from other habitats.

This species has not been assessed for the IUCN Red List. The native range of this species is West Europe to Morocco. It is a perennial and grows primarily in the temperate biome. They occur in a wide range of coastal habitats including on sea-cliffs, dock walls, shingle banks and saltmarshes. The species is not found in the water, but it comes into contact (wave splash & rain) with both saltwater and freshwater, with neither having a detrimental effect. Rock sea lavender is a useful indicator species due to its sensitivity to trampling, erosion of soil on sea cliffs and sea level rise. The BSBI holds the majority of available data and can be accessed via the NBN Atlas (NBN Atlas).

Rock Sea Lavender records from NBN Atlas between 2003-2023.

8.4.5. Perennial glasswort *(Sarcocornia perennis*)

Perennial glasswort is a unique plant species that is well adapted to thrive in harsh, salty environments. Perennial glasswort is a succulent plant that grows to a height of around 30cm, with fleshy, cylindrical stems and small, scale-like leaves that are often reduced to a vestigial point. This plant is classified as a halophyte, which means it is adapted to grow in soils with high salt concentrations. Perennial glasswort achieves this by using specialised cells in its stems to store salt, which helps it to maintain an osmotic balance with its environment (Wild Flower Web). It is often one of the pioneering saltmarsh species that colonise and transform the saltmarsh to make the habitat more suitable for other successional species.

It is widespread in saltmarsh habitats and generally found where firmer sands or gravels underlie the mud and allow this perennial species to get established. As a perennial, this species forms solid mats of green stems, arising from creeping, woody bases. As well as the fertile stems that carry florets clustered in threes, plants have thinner, sterile stems that do not bear florets and often have arching tips (Flora of East Anglia).

According to Davy et al., (2006) and the NBN Atlas, perennial glasswort is found at a number of locations along the North Norfolk Coast (NBN Atlas). Perennial glasswort is listed as Least Concern on the Great Britain and England red lists, and not scarce in Norfolk (Norfolk Flora Group, 2017).

Perennial Glasswort records from NBN Atlas between 2003-2023.

8.4.6. Eelgrass (*Zostera marina & Zostera noltei*)

Seagrass conservation benefits from a wide recognition of the importance of seagrasses to populations of "charismatic megafauna" (Lee Long. & Thom, 2001). Seagrass meadows often occur in heterogenous environments where the varied environment is arranged clearly along perceived gradients such as salinity, turbidity in estuaries, depth along slopes, or gradients of exposure (Duarte, C.M. & Kirkman, H., 2001). The presence of seagrass beds stabilises the sediment and helps protect coastlines from erosion.

Seagrass is one of the few true plants that live in the sea, being a flowering plant that produces flowers and seeds. They also have a significant rhizome which allows the plant to grow vegetatively, storing carbon and providing stability. Protecting fragile seagrass beds from damaging activities is needed to ensure the habitat itself and the species that rely on seagrass and interconnected coastal habitats are safeguarded.

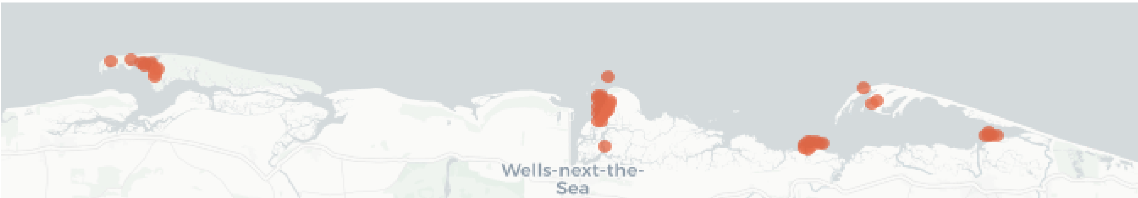
Eelgrass is listed as Least Concern on the IUCN Red List. Seagrass beds are a Priority Habitat under the UK-Post 2010 Biodiversity Framework and a Feature of Conservation Importance for which Marine Conservation Zones can be designated. They are on the OSPAR List of Threatened and/or Declining Species and Habitats (declining in Region II – North Sea and Region III – Celtic Sea and threatened in Region V – Wider Atlantic).

Eelgrass are grass-like flowering plants with dark green, long, narrow, ribbon shaped leaves with rounded tips. Eelgrass forms dense swards which supports a diverse fauna and flora and may act as a nursery for fish and shellfish. Eelgrass are found primarily on sand to fine gravel in the subtidal zone, typically down to a depth of 4 m, in sheltered waters such as shallow inlets, bays, estuaries and saline lagoons (Marine Life Information Network).

Three species of eelgrass occur in the UK. These are the dwarf eelgrass (*Zostera notlii*) which is found highest on the shore: the narrow leaved eelgrass (*Zostera angustifolia)*, which is found on the mid to lower shore and common eelgrass (*Zostera marina)*, which is predominantly sub littoral. Preferred habitats are intertidal or shallow subtidal sands/muds which are sheltered from significant wave action. Eelgrass beds are an important food source for several bird species including brent goose (*Branta bernicla*) and wigeon (*Mareca penelope*). Plants can also be colonised by a range of micro and macroalgal species. In certain areas the habitat is an important nursery area for flatfish (Environment Agency, 1998).

Seagrasses are widely recognised as indicators of a healthy coastal marine environment, thriving in various habitats such as estuarine environments, sub-tidal fine gravel, and sheltered bays. While seagrasses are highly susceptible to pollution and nutrient enrichment, it is worth noting that in some cases they can tolerate or even benefit from a certain level of anthropogenic nutrient input (Vieira *et al*, 2022). Dwarf eelgrass (*Zostera noltei*) is more of an estuarine species, found higher up on the shore than common eelgrass, and is also more tolerant of desiccation so can be entirely exposed at low tide. This trait makes it an interesting species from a habitat interconnectivity angle.

Off the coast of Norfolk, seagrass beds are believed to only be found off Blakeney Point, Brancaster and Breydon Water. While they are listed as Least Concern internationally, all three species of eelgrass are considered to be scarce in the UK (Environment Agency, 1998). *Zostera* beds can be used as a bioindicator due to their sensitivity to habitat changes, particularly from contaminants polluting the coast (Marine Life Information Network, 2022). Seagrass beds are also vulnerable to the effects of many of the major human activities in the coastal zone, including coastal development and physical habitat disturbance. Large scale land reclamation can completely destroy eelgrass beds over wide areas. Other forms of coastal development (e.g., construction of harbours or marinas, pipeline laying, channel dredging) can also adversely affect eelgrass beds by altering the local hydrographic regime and sediment balance (Davison & Hughes, 1998).



Eelgrass records from NBN Atlas between 2003-2023.

The data on NBN Atlas is collated from Natural England's Marine Monitoring surveys, and Seagrass Spotter run by Project Seagrass also holds citizen science data which is verified. Whilst there is currently no data on Seagrass Spotter for North Norfolk, NBN Atlas shows that there have been recent records of seagrass in this area. It is very easy to monitor seagrass due to its accessibility at low depths (around 4m) (Tyler-Walters, H., 2008). OSPAR has comprehensive survey information for seagrass dating back over 20 years. Natural England and the Environment Agency also have some survey records but again little has been surveyed in recent years. Following in-situ restoration work, significant population shifts can be seen as soon as 3 months, however monitoring strategies need to be longer than five years in order to determine whether a restoration project has been successful (Hendy & Ragazzola, 2021).

Seagrasses (WFD-UKTAG, 2014) are assessed as one of the Biological Quality Elements for Classification under Article V of the Water Framework Directive (WFD) in order to define the ecological status of a transitional coastal water body and develop methods to assess the impact of human-induced pressures.

The WFD seagrass assessment tool is an approved UKTAG method. The tool is composed of three individual parameters, each of which is compared to baseline data or data from the previous assessment. The parameters are:

- Taxonomic composition – number of observed species compared to number of previously recorded species.
- Shoot density / % cover loss – estimated percentage cover expressed as percentage cover loss/gain.
- Spatial bed extent –percentage loss or gain of the total area of seagrass beds.

Data should be collected annually. As more data are collected a 5-year rolling mean should be used to reduce potential 'noise' caused by a high degree of natural inter-annual variability (Marine Scotland, 2023).

8.4.7. Tasselweeds (*Ruppia maritima & Ruppia cirrhosa*)

Tasselweeds are native to coastal saltwater and brackish water habitats in North America, Europe, and Asia. They are submerged aquatic perennial plants, the leaves are green, long, thin, and thread-like. They produce small, inconspicuous flowers that are pollinated by wind, and they are important species for the coastal environment, as they provide habitats for fish and invertebrates, and help to stabilise shorelines by reducing wave energy. Tasselweeds are also considered as a valuable food source for aquatic animals and some species of waterfowl. Due to its salt tolerance, it can be used as a tool for the phytoremediation of salt-polluted soils and water. More specifically, beaked tasselweed occurs in soft sediments in sheltered shallow coastal waters, from full salinity to nearly freshwater but mainly in brackish waters of lagoonal habitats, lochs, estuaries, creeks and pools in salt marshes, wetlands, ditches and lakes. (Marine Life Information Network).

Ruppia maritima records from NBN Atlas between 2003-2023.

Ruppia cirrhosa records from NBN Atlas between 2003-2023.

Tasselweeds tolerate a wider range of ionic strengths and salinities than any other aquatic angiosperm, occurring between 0.6 -390g/l (Kantrup, 1991). However, the reported salinity tolerances vary with region and with species. Their exclusion from very low saline to freshwater, or nearly full seawater is probably due to competitive exclusion by other aquatic plants or seagrasses. (Marine Life Information Network).

Internationally, beaked tasselweed is listed as Least Concern, but the species is considered Near Threatened in England (Stroh et al., 2014). Tasselweeds beds are sensitive to a variety of environmental changes such as phytoplankton blooms and smothering by algae and epiphytes triggered by nutrient enrichment. Other references to the sensitivity of tasselweed to changes in water quality are contained within Davison and Hughes (1998) who report that tasselweed species appear to be less sensitive to metabolic imbalance caused by internal high nitrate concentrations than eelgrass (*Zostera*) species. This sensitivity to nutrient enrichment makes tasselweed a potential indicator of chemical leaching from human activity either onshore or offshore, and therefore a potential indicator of mitigation success as well.

Both beaked tasselweed and spiral tasselweed have been recorded at various locations on the Norfolk coast, however there is currently little data available outlining overall population health, but due to the speed with which tasselweed beds can recover, restoration success could be measured over relatively shorter time frames compared to other species (NBN Atlas).

8.4.8. Sea sandwort / sea chickweed (*Honckenya peploides*)

Sea sandwort, is a species of flowering plant in the family Caryophyllaceae. It is native to Europe, Asia and North America. It is a small herbaceous perennial plant with a prostrate habit, forming mats on the ground. It has small, delicate leaves and produces small, white or pink flowers. This species is adapted to grow in coastal habitats, such as sandy beaches and dunes, saltmarsh and rocky shores, and is considered to be a salt-tolerant and drought-resistant species (Wild Flower Web).

Sea sandwort also plays an important ecological role in the intertidal zone. It helps to stabilize the sandy substrate, preventing erosion and providing a habitat for a variety of other species, including insects, birds, and small mammals. The plant's small, white flowers also provide a source of nectar for bees and other pollinators (Wild Flower Web).

The NBN Atlas shows sea sandwort has been recorded at many sites along the North Norfolk Coast (NBN Atlas). The majority of data held by the NBN Atlas for this species comes from the Botanical Society of Britain and Ireland. The JNCC has listed sea sandwort as Least Concern on its vascular plant red list (Stroh et al., 2014).

Sea sandwort records from NBN Atlas between 2003-2023

8.5. Coastal fish

Fish assemblages are considered valuable monitoring targets for coastal and marine ecosystems because their populations can reflect ecosystem condition and connectivity and support key ecosystem services and ecological functions. Coastal fish assemblages have been shown to respond quickly to coastal and wetland restoration initiatives (Rummell et al., 2023). Their fast response is likely due to their high mobility, broad habitat needs and physiological tolerances which allows them to exploit the diveristy of foraging and sheltering opportunities available within coastal habitat restoration.

8.5.1. Smelt (*Osmerus eperlanus*)

European smelt is a sea fish that runs up the rivers for freshwater spawning and they are a UK Biodiversity Action Plan priority species. Smelt are sensitive to water quality and make a good indicator species given its life history, sensitivity to polluted waters and need for river connectivity. Pressures to populations include pollution, barriers to migration, river channel alteration and habitat loss, which can prevent smelt from spawning successfully. NBIS and NBN records show a presence on either side of the North Norfolk coast area; in the River Great Ouse and the Middle-Level Main Drain, as well as some of the Broadland rivers. Surveys have revealed evidence of two populations in the River Burn and the River Glaven (Colclough, 2013). They congregate near river mouths in winter and usually ascend rivers between February and April, returning to the sea soon after spawning occurs.

Smelt records from NBN Atlas between 2003-2023

The IUCN Red List has listed smelt as Least Concern with the population trend currently unknown. It lives in coastal waters and estuaries and migrates into large, clean rivers to spawn in the spring (Maitland & Lyle, 1997). Whilst their numbers are not abundant in North Norfolk, they have been selected as a suitable indicator for coastal habitat connectedness due to their sensitivity to water quality. Conservation measures should include habitat restoration and management of spawning grounds, making sure that spawning smelt have access to these grounds, and ensuring that future commercial fishing is sustainable. Other proposed measures relate to the recovery of stocks in rivers where smelt previously occurred through a suitable translocation programme, with research indicating that large numbers of smelt eggs can be obtained readily during the spawning run and these can be transferred and hatched elsewhere (Maitland& Lyle, 1997)

NBN Atlas currently collates the data of records for smelt. Electrofishing is the most accepted sampling method, this should be done annually, May to October.

8.5.2. Brown sea trout (*Salmo trutta)*

Brown sea trout spend their adult life at sea in coastal areas and return to freshwater to spawn in autumn. The freshwater juveniles then undergo physiological changes as they migrate to salt water (smoltification) (Marine Life Information Network). Due to their migration patterns, brown trout are a highly useful indicator of habitat connectivity since they rely on a variety of habitats to be in good condition and for there to be smooth transitions between them.

Brown trout is not listed on the IUCN red list, however it is a UK BAP priority fish species (JNCC, 2007). The NBN Atlas shows the Brown trout to be found throughout North Norfolk with the rivers Stiffkey and Glaven having an abundant population, though patchy distribution. (NBN Atlas, Atlantic Salmon Trust). The majority of data comes from the Database for the Atlas of Freshwater Fishes at the Biological Records Centre (NBN Atlas).

Brown sea trout records from NBN Atlas between 2003-2023

The Environment Agency's fish and ecology open data also has records of Brown sea Trout throughout North Norfolk. This database extracts data from the National Fish Populations database (NFPD) and Biosys (Biological survey). The dataset contains site survey information, the numbers and species of fish caught, fish lengths, weights and ages (where available), for all the freshwater fish surveys carried out across England from 1975 onwards.

Electrofishing is the accepted and most commonly used method to sample Brown trout and this can be conducted as juveniles when they spend 1-3 years in freshwater before migrating to the sea as adults. Many head back to the sea after spawning, and some return to spawn again and again, usually to their natal river.

8.5.3. Flounder (*Platichthys flesus*)

Often found in coastal waters, including estuaries and sometimes freshwater the European flounder is one Britain's native flatfish. Flounder can grow up to 50cm long, and it has a flattened body allowing it to lie on the ocean floor. They are listed as Least Concern on the IUCN Red List of Endangered species, and it is common around all British and Irish coasts.

Typically, Flounders feed by entering the intertidal zone with the incoming tide and feeding heavily at high tide. Fully developed Flounder feed upon a variety of infaunal groups including bivalves, polychaetes, crustaceans, and small fish.

Flounder records from NBN Atlas between 2003-2023

The ontogenetic shift that occurs during a flounder's lifecycle divides the population into ecologically distinct stages, including a noticeable shift to predominantly macrofauna (Aarnio et al., 1996). They are most commonly found within 50m of the shore, but the distribution may be local within specific areas. They predominantly reside in estuaries and other low-salinity waters; this species lives and thrives when resident in either the sea, or brackish water, and is the only European flatfish to penetrate further into estuaries and able to live in freshwater for long periods (Summers, 1979; Hemmer-Hanson et al., 2007).

The Flounder utilises different coastal habitats throughout North Norfolk. Notably, Scolt Head National Nature Reserve and off Cley Beach, Salthouse Beach, and Weybourne Beach and further down the coast at Sheringham Beach. There are also records of Flounder upriver, notably at Burham Overy Watermill on the River Burn. Flounder undergoes ontogenetic habitat shifts, during the early life stages they are dependent on estuarine environments. Flounder is regarded as a semi-catadromous species, known to enter the estuaries at their larval stage, and prefers low-salinity upstream habitats to settle (Amorim, et al., 2018).

Flounders are a good indicator of coastal habitat interconnectivity due to their reliance on different coastal habitats for key parts of their lifecycle. While being important nursery areas, estuaries are also among the most threatened coastal ecosystems, the high level of anthropogenic pressures to which they are subjected cause degradation, even at fine temporal and spatial scales, it is likely that responses from species that utilise these habitats, in this case the Flounder, will also reflect this, especially in different life stages.

The current data for the Flounder throughout North Norfolk is primarily on NBN Atlas which collates many data sources. Freshwater and marine survey data are extracted from the National Fish Populations database (NFPD) and Bioysys (Biological survey) database. Flounder are best surveyed through electric fishing or trapping surveys and this is to be done between May and October.

8.5.4. Sole (*Solea solea*)

Sole is usually found on sandy and muddy seabed's and also in estuarine habitats, from depths of one to around 70m, except in winter when it moves offshore and can be found down to depths of around 120m (Marine Biological Association). The biogeographical range of sole extends from the northwest African coast and the Mediterranean Sea in the south, reaching as far north as the Irish Sea, southern North Sea, Skagerrak, and Kattegat (ICES).

At spawning time, some migrate to the same grounds in the southern North Sea every year. This includes the subtidal sandbanks in North Norfolk that provide an important nursery ground for young commercial fish species, including sole (JNCC).

Sole are currently listed as a species of Least Concern within the European IUCN Red List. Despite this status, like many other benthic species, sole face a number of threats across their range. Loss of or disturbance to their spawning grounds, caused by factors such as pollution and storms, can significantly reduce larval survival rates. Overfishing exacerbates the problem by disrupting the population structure, leading to an abundance of smaller-sized fish due to the targeted removal of older and larger individuals. These changes in sole population dynamics have far-reaching consequences for the local food web, as sole serves both as prey and predator.

Sole records from NBN Atlas between 2003-2023.

Most of the population data on the sole can be found in NBN Atlas or the Marine Biological Association, but there does not seem to be any active monitoring of the sole in Norfolk. As soles move inshore in the summer months, it is best to undertake surveys then (IFCA).

8.5.5. Plaice (*Pleuronectes platessa*)

Plaice is an important species in European waters that has been exploited for centuries. It is a diamond-shaped flatfish that lives on sandy seabed's all around the UK, feeding on molluscs and worms (IUCN, 2013). Plaice may be found from the western Mediterranean Sea, along the coast of Europe as far north as the White Sea and Iceland. They are classified as a Priority Species under the UK Post-2010 Biodiversity Framework and are listed as of Least Concern on the IUCN Red List (Wildlife Trust).

As Plaice larvae grow, they move to the seabed and migrate to their nursery grounds in estuaries and along sandy coasts, but rarely enter freshwaters. These nurseries include the subtidal sandbanks in North Norfolk that provide an important nursery ground for young commercial fish species, including plaice (JNCC).

Plaice records from NBN Atlas between 2003-2023.

Due to the specific habitat requirements of the early life stages of plaice in combination with the relatively small size of these habitats, nursery habitat may limit the population size that can occur in a specific sea area (IUCN, 2013). Loss of, or disturbance to the nursery will negatively affect the juvenile's survival, this could include pollution, storms and other factors. Overfishing is also a potential problem, as the removal of the older/larger stock will result in a bottom-heavy age population structure, or smaller sized fish. A drop in plaice numbers can also indicate a decline in its food source which could be caused by a number of factors.

Most of the population data on the plaice can be found in NBN Atlas or the Marine Biological Association, but there does not seem to be any active monitoring of the plaice in Norfolk. There is no specific time to survey for plaice, as it is more important to take into account the depth of the water because it will impact the age group surveyed.

8.6. Reptiles & Amphibians

8.6.1. Natterjack toad (*Epidalea calamita*)

The natterjack toad has a localised distribution in the UK and has undergone substantial historical declines due to habitat loss and fragmentation. The remaining strongholds are dune systems and upper saltmarshes along the coasts of Merseyside, Cumbria and Dumfriesshire; with smaller and more isolated coastal populations in Lincolnshire, Norfolk, Suffolk, Kent, Dorset, Denbighshire, Flintshire, Cheshire and Lancashire. In coastal areas, their range has shrunk due to urbanisation and loss of habitat due to other land-use changes.

The natterjack toad is a 'pioneer-opportunist' which relies upon sparsely-vegetated habitats with shallow, ephemeral ponds. In Britain, the natterjack toad is confined to coastal sand dune systems, coastal grazing marshes and sandy heaths; they are often associated with shallow, warm ponds in sand dune slacks as they require warmer water in which to breed successfully. Breeding ponds in certain areas can easily become saline, and as a result populations can adapt to living in salt water at low concentrations. There are around sixty populations in the UK, with only about 3,000 breeding females in total. The natterjack toad is a UK BAP Priority Species, with a long-standing reintroduction programme, and intensive conservation efforts. Inbreeding depression has contributed to the decline of some isolated populations, and chytrid fungus has been cited as another possible cause of declines. Although declining in the north of its European range, the natterjack toad is listed as a species of least concern on the IUCN Red List because it is locally abundant across much of its range (CIEEM, 2013).

The Norfolk coast supports up to an estimated 400 breeding females, which represents over 15% of the UK population. Their abundance has declined across the UK with current populations only a quarter of what it should be (Natural England, 2018). Due to the importance of North Norfolk for the UK's natterjack toad population, they would be a highly appropriate species to monitor considering the importance of boosting their numbers but also ensuring any restoration practices do not inadvertently harm their habitat.

The JNCC has a comprehensive monitoring framework for the natterjack toad, since their distribution is relatively well understood, all sites are monitored annually, or at least every three years (JNCC, 2018b).

Natterjack Toad records from NBN Atlas between 2003-2023.

8.7. Coastal pollinators

Many pollinators, such as bees and butterflies rely on a variety of plants and nesting sites throughout their life cycles and coastal ecosystems offer a range of flowering plants (Angiosperms). Pollinators tend to be highly mobile and sensitive to floral resources, and so their presence and activity can indicate the ease with which the species move between coastal ecosystems, reflecting habitat interconnectivity. Below are some key pollinator species that rely on the connectivity between multiple coastal habitats across North Norfolk.

8.7.1. Sea aster bee (*Colletes halophilus*)

The sea aster mining bee is a rare bee restricted to the margins of salt marshes in East Anglia and the Thames estuary, with occasional populations along the south and east coasts. The UK supports internationally important populations, with the bee being globally restricted to the North Sea coastline. The species is a good indicator of coastal habitat interconnectivity as it requires a mosaic of habitats, foraging on sea aster in salt marshes and mudflats, but also requiring areas for nesting in the form of bare, sandy, south-facing banks.

The sea aster mining bee's relatively limited distribution may be due to the combined effects of its oligolectic nature and its preferences for salt marsh habitats, both limited resources which can increase its vulnerability (Harris and Johnson, 2004). The warmer climate of the south-east may also prove particularly important for this late emerging bee and may restrict its migration further north-west.

Sea aster mining bee records from NBN Atlas between 2003 and 2023

The IUCN Red List states that the sea aster mining bee is decreasing, they are a rare and endangered bee and are a UKBAP priority species.

Their typical nesting habitat is located in the transitional zone between intertidal salt marsh and dry land which has been largely lost through the large-scale provisioning of sea walls along our coastlines, thereby reducing opportunities for this species. Brownfield habitats in coastal areas with disturbed and bare ground can provide both foraging and nesting opportunities for this species (Robins et al., 2013). In North Norfolk specifically, there are records of sightings along the road to Brancaster Beach, as well as records on RSPB Titchwell Marsh, the sand dunes and marshes of Holme Dunes National Nature Reserve and there are many records for this species on Blakeney National Nature Reserve. This demonstrates their suitability as an indicator of coastal habitat interconnectivity due to their reliance on many different coastal habitats throughout North Norfolk and their sensitivity to climatic changes and oligolectic nature.

The sea aster bee is typically active during the flowering period of sea aster, usually from late summer to early autumn (mid-August to mid-October). A study conducted by Buglife (Hardy, 2013), visited sites in order to identify additional nesting aggregations, sites were visited between 10 am and 5pm when the bees are more active, and on days with low windspeed and warm temperatures. This sampling method could be easily applied to North Norfolk and repeated annually to continue to monitor numbers.

Currently there is recorded data on NBN Atlas with up-to-date sightings up to 2022, these records being a combination of National Trust Species Records and records verified by iRecord.

8.7.2. Scarce pug (*Eupithecia extensaria*)

The scarce pug is a moth with a very small range, being nearly endemic to North Norfolk. Work on a European macro-moths red list has revealed only one area outside England where it is found. In England, the Lincolnshire population is rapidly declining and appears close to extinction (Norfolk Moths). The scarce pug is Endangered and is a rare, restricted species with ongoing distribution decline. It is a Biodiversity Action Plan Priority Species and the IUCN Red List states that the Scarce pug is endangered.

UK records for this species from 2000 onwards were sourced records from just two 10km squares, with a record of a singleton from one additional 10km square in the whole of Norfolk.

Scarce pug records from NBN Atlas between 2003-2023

The scarce pug larvae can be found from mid-August to the start of September feeding on sea wormwood, a distinctive aromatic silver/blue plant, found along the edges of saltmarsh along the North Norfolk coast.

Scarce pug utilises a myriad of North Norfolk habitats including saltwater and freshwater habitats. NBIS data shows this species on the marshes of the 'River Burn', as well as 'Stiffkey Meals Dunes' and records throughout 'Scolt Head Island National Nature Reserve.'

The scarce pug is a suitable indicator species for coastal habitat connectedness due to its limited range and near localisation to North Norfolk. It utilises different coastal habitats such as saltmarsh and sand dunes and its larvae depend on sea wormwood, which is abundant throughout North Norfolk across multi-coastal habitats.

Sea Wormwood records from NBN Atlas between 2003 and 2023

Most data for the scarce pug is found on NBN with data collated from 'Macro-moth distribution records for the UK from Butterfly Conservation, up to 2019', 'NBIS Records to December 2016' and 'iRecord Surveys'. Moths are easy to sample and this is to be done over multiple nights throughout August, September and October which is to be carried out annually.

8.7.3. Pantaloon bee (*Dasypoda hirtipes*)

The pantaloon bee or hairy-legged mining bee is a species of solitary mining bee. It gets the name pantaloon bee, from the hirsute hind legs of the females which apparently swell up with pollen, deposited in the golden hairs of the hind tibiae as the bee forages making them look as if they are wearing pantaloons.

The pantaloon bee occurs across Eurasia from southern Britain to China. It occurs as far north as southern Finland and southern Scandinavia and south to North Africa and the Canary Islands. Within Britain it is found in southern England as far north as Norfolk and western Wales, it is also found on Jersey and Guernsey in the Channel Island.

The IUCN Red List currently lists the pantaloon bee as data deficient, which means that there is insufficient data to determine its conservation status at a global level. However, the pantaloon bee is listed as Near Threatened in Germany and Sweden, Vulnerable in Switzerland, and Endangered in Norway and Slovenia. Population data on the pantaloon bee is limited, and the available information varies depending on the region and the population. In some areas, the species is still relatively abundant and widespread, while in other regions populations have declined significantly.

Pantaloon bee records from NBN Atlas between 2003-2023

These bees are commonly associated with coastal and heathland habitats, where the females will excavate nesting cavities in sandy soils. They often nest in large groups, although each female tends to their own individual nest. They tend to forage only on flowers from the aster family, particularly ones with yellow composite flowers like Hawk's beards, Ragworts, Common fleabane, Hawkbits, Cat's ear and Oxtongues.

The pantaloon bee faces several threats that have contributed to its decline in some regions. One of the main threats is habitat loss and fragmentation due to increases in agriculture and urbanisation. As a ground-nesting species, pantaloon bees require suitable soil conditions and vegetation for foraging. The loss of these habitats can limit their distribution and abundance. Another major threat is the use of pesticides, which are toxic to pantaloon bees and other pollinators. Exposure to pesticides weakens their immune system, impairs their navigation and foraging abilities, and reduces their reproductive success. Parasites and diseases such as Varroa mites weaken the bees' health and make them more susceptible to other stressors. Climate change is another force that plays on pantaloon bee populations by altering the timing of flowering of their food plants or altering the microclimate conditions that affect their nesting and foraging behaviours.

Most of the data on the pantaloon bee can be found on NBN Atlas or Biological Records Centre. The best time to survey for them is June to August as that is when they can be seen flying around foraging.

8.8. Aquatic mammal species

Aquatic mammals offer key indicators of coastal restoration quality. Monitoring changes in distribution and abundance of key marine mammals can give insights into the status of prey availability and trophic complexity of the ecosystem.

8.8.1. Eurasian Otter (*Lutra lutra*)

In the mid-20th century, the UK's otter population underwent a significant decline, mainly due to habitat loss and water pollution. However, conservation efforts led to improvements in water quality have resulted in a population recovery.

Currently, otters are strictly protected by the Wildlife and Countryside Act (1981). Otters rely on a range of aquatic and riparian habitats, in both freshwater and coastal environments, including coastal wetlands, estuaries, saltmarshes, and mudflats. They are apex predators, playing a crucial role in the ecosystem. For otters to thrive, it is essential that their habitats and associated species are in fairly good condition. They primarily feed on fish, as well as amphibians, crustaceans, and occasionally birds and small mammals.

The otter is listed as Near Threatened globally, but of Least concern in England. However, in Scotland and Wales, they are listed as Vulnerable. The population has continually increased over the last 25 years and their range is expanding in England with numbers of otters also increasing in Norfolk.

The resurgence of otter populations in England serves as a tangible indicator of improved coastal conditions. Otters are good bioindicator species due to their sensitivity to environmental changes, diverse habitat range, and dependence on healthy aquatic ecosystems. The presence and health of otter populations can reflect good water quality, prey availability and overall ecological health.

Mammal populations naturally fluctuate year to year, so monitoring otters annually or biannually will provide sufficient data at the required resolution to distinguish between short-term variations and long-term trends. Surveys can be undertaken at any time of year, but ideally when water levels and vegetation are low and otter signs are therefore more visible.

Data on otter populations in North Norfolk is collected and managed by various organisations. The Mammal Society collect data through the National Otter survey in 1-year periods, the sixth survey being carried out in 2022/2023. JNCC monitor otters and publish data in the England Otter Survey Database. The Norfolk Wildlife Trust monitor the presence of otters on the river Glaven.

Eurasian otter records from NBN Atlas between 2003-2023

8.8.2. Harbour porpoise (*Phocoena phocoena*)

The harbour porpoise is often found in both freshwater and saltwater habitats, along coasts, bays, harbours, estuaries, and large rivers in waters generally less than 650 feet deep (Marine Biological Association).

The harbour porpoise is commonly seen in coastal areas, although it ranges over much of the European continental shelf, feeding on schooling fish such as herring (*Clupea harengus*) and mackerel (*Scomber scombrus*). It is the most common and widely distributed of all cetacean species in northern Europe, favouring comparatively shallow, cold waters. There are seasonal concentrations of harbour porpoises off south-west and western Ireland, west Wales, the west coast of Scotland, Northern Isles, and eastern Scotland - porpoises may be permanent residents in these areas, with the greatest numbers usually present between July and October (JNCC, 2015)

The harbour porpoise is listed as Least Concern both internationally and in the North Sea (IUCN Red List). Their local status in Norfolk is poorly known, but anecdotal sighting records and stranding data indicates that harbour porpoises were previously more common in Norfolk coastal waters and that the population declined during the middle part of the twentieth century. However, in the last decade, there has been an increase in sightings and strandings along the entire Norfolk coast, with a peak in records during the winter and early spring (Jan-April) (Norfolk County Council, 2007).

Harbour porpoises are susceptible to several threats such as being caught as bycatch, environmental contaminants from onshore and offshore activities (e.g., PCBs), boat collisions and depleted herring stock (JNCC, 2015). This susceptibility makes them an appropriate indicator of restoration success as addressing any of these issues should result in boosted population numbers.

Surveying for cetaceans generally requires longer time periods to notice significant population changes (JNCC, 2015). The most comprehensive survey data for Harbour Porpoises in the North Sea comes from the SCANS surveys coordinated by the Sea Mammal Research Unit at University of St Andrews, which takes places roughly every ten years. The most recent results come from the SCAN III survey in 2016 (Hammond et al., 2016).

Harbour porpoise records from NBN Atlas between 2003-2023

8.8.3. Minke whale (*Balaenoptera acutorostrata*)

The minke whale is the smallest and most abundant of the baleen whales. The minke whale has a worldwide distribution in tropical, temperate and polar seas of both hemispheres. The species seasonally migrates from polar feeding grounds to warm temperate to tropical breeding grounds although animals in temperate regions may remain there throughout the year. Minke whales are widely distributed in relatively small numbers along the Atlantic seaboard of Europe, mainly from Norway south to France, and in the northern North Sea (Marine Life Information Network).

Around the UK, minke whale occur mainly in shelf waters in water depths of 200m or less. While they can be found in the southern North Sea and English Channel, they are less common in these areas. The species is found in offshore waters, but due to low survey effort and lower density, their presence in these areas is underrepresented on the distribution map which more closely resembles the species distribution in coastal and shelf waters. (JNCC, 2018a).

Minke whales are listed as Least Concern by the IUCN, and recent surveys such as the SCANS surveys have not found any strong trend in population growth or decline (JNCC et al., 2016). Their status off East Anglia and the NNC, is relatively unknown with occurrences not being particularly common. Cetaceans such as minke whales are susceptible to several threats such as entanglement, boat collisions, changes in prey dynamics due to climate change, shipping noise, water pollution (e.g., persistent organic pollutants which they are particularly sensitive to due to bioaccumulation and biomagnification) and prey depletion due to fishing activity (JNCC, 2016). These threats can highlight the pressure being put on the habitat and population changes can indicate success in restoration/conservation measures.

The majority of available data comes from the SCANS surveys, with the JNCC having a few of their own assessments which take this data into account (Hammond et al., 2016; JNCC, 2022).

Minke whale records from NBN Atlas between 2003-2023

8.9. Crustaceans

Similar to fish, crustaceans are potentially valuable indicators of coastal and wetland restoration success as they have high mobility, generalist diets, broad habitat needs and physiological tolerances allowing them to exploit the diversity of foraging and sheltering opportunities available within the restoring coastal habitats, and responded quickly to environmental changes.

8.9.1. Shore crab (*Carcinus maenas*)

Shore crab is an easily identifiable crab of estuaries, sheltered rocky shores and offshore waters. Shore crabs are omnivorous; animal matter makes up the majority of the diet but some plant matter including algae and cord grass (*Spartina spp.)* is consumed. The diet of large shore crabs mainly consists of molluscs and the common mussel (*Mytilus edulis)* is the most important of these (Marine Life Information Network).

Shore crab is found on all types of shore, from high water to depths of 60 m in the sublittoral zone, but it is predominantly a shore and shallow water dwelling species. It tolerates a wide range of salinities and is especially abundant in estuaries and saltmarshes (Marine Life Information Network). Juvenile crabs prefer gravel or cobble areas or mussel beds where they can shelter under rocks and seaweed to avoid predation and cannibalism. Juvenile crabs frequently display striking colours and mottling patterns that may help to camouflage them in geometrically complex habitats with variable substrates. As crabs age they move into lower intertidal and subtidal zones, where they are able to shelter under rocks, boulders and macroalgae in rocky areas and amidst eelgrass and fouling communities or in burrows along cord grass banks in estuaries. Both juveniles and adults prefer areas with high structural complexity and avoid open sandy areas that do not offer any refuge, although adults are common in muddy sands where they can burrow for concealment (Young & Elliot, 2020). The shift in habitat preference makes the Shore crab an excellent indicator of habitat connectivity due to their need for transitional habitats and ecotones.

The shore crab is a very common species and is highly invasive outside of its native range, and as such, is not listed under the IUCN red list (Marine Life Information Network). The NBN Atlas holds the majority of available data, with the best records coming from the JNCC's Marine Nature Conservation Review (NBN Atlas). This NBN Atlas data highlights the array of sites along the NNC where shore crabs can be found. Due to the high fecundity of shore crab, significant population changes can be seen in a relatively short timeframe allowing for a comprehensive monitoring programme to be carried out in only a few years (Young & Elliot, 2020).

Shore crab records from NBN Atlas between 2003-2023

8.10. Molluscs

8.10.1. European flat oyster (*Ostrea edulis*)

The flat oyster is included in the UK Biodiversity Action Plan Priority, as a species of principal importance, it is also on the Scottish Biodiversity List and the OSPAR List of Threatened and/or Declining Species and Habitats.

Flat oysters are associated with highly productive estuarine and shallow coastal water habitats on firm bottoms of mud, rocks, muddy sand, muddy gravel with shells and hard silt. In exploited areas, suitable habitat is/has been created in the form of 'cultch' - broken shells and other hard substrata, at a depth range 0-80 m.

The species are widely distributed around the British Isles but less so on the east and north-east coasts of Britain and Ireland. The main stocks are now in the west coast of Scotland, the south-east and Thames estuary, the Solent, the River Fal, and Lough Foyle. Internationally they can be found from the Norwegian Sea south through the North Sea down to the Iberian Peninsula and the Atlantic coast of Morocco, the Mediterranean Sea, and extending into the Black Sea (Marine Biological Association, 2023).

In Norfolk the data on flat oyster presence varies depending on the source, for example NBN Atlas have records of flat oysters off the Norfolk coast but the Marine Biological Association does not.

Flat oyster records from NBN Atlas between 2003-2023

Flat oysters can be used as an indicator of restoration success/habitat condition, as there is some evidence that reduced growth, weight and poor conditions are a consequence of high population densities (300 per square yard) (Marine Biological Association, 2023). The pollutants that oysters have been found to be most susceptible to are tributyltin, some heavy metals (especially silver, mercury, and copper), chlorine and organochloride pesticides which have the biggest impact on the larvae form (Tyler-Walters and Williams, 2023). A quick drop in numbers can also indicate overexploitation of natural beds (Marine Biological Association, 2023).

Most of the population data on the flat oyster can be found in NBN Atlas or the Marine Biological Association and there does not seem to be any active monitoring of the flat oyster in Norfolk. If surveys are to be undertaken to get a more accurate understanding of the flat oyster presence in Norfolk there is no specific time this should be undertaken (but breeding occurs between June – September).

8.10.2. Cockles *(Cerastoderma edule* and *Cerastoderma glaucum)*

The common cockle (*Cerastoderma edule*) and the lagoon cockle (*Cerastoderma glaucum*) are both found at various points along the Norfolk coast. The common cockle has a thick, oval shell with concentric ridges which are off-white, yellowish or brownish in colour. The lagoon cockle has a thinner shell which is larger and predominantly off-white with grey edges. The common cockle inhabits the surface of sediments, burrowing to a depth of no more than 5 cm. Found on clean sand, muddy sand, mud or muddy gravel from the middle to lower intertidal, sometimes sub-tidally. Common cockles usually live at salinities between 15 and 35 PSU but can tolerate salinities as low as 10 PSU. The Lagoon Cockle is found submerged in saline lagoons or more rarely on the low shore of estuaries. Adults usually burrow shallowly in soft sediments. The failure of the species to colonise the higher shore is believed to be due to an inability to tolerate aerial exposure and its consequent conditions. (Marine Life Information Network).

Neither species has been assessed by the IUCN, and the best data comes from the NBN Atlas. A 2006 survey did however find the lagoon cockle at Broadwater, Holkham Salt Holes and Abraham's Bosom in Norfolk (Norfolk Wildlife Trust, 2006). There is very little data looking at abundance of cockles with the primary focus being presence data. The presence of the species is considered a good indicator of habitat condition due to its sensitivity to a variety of pressures including substratum loss, increased turbidity, physical disturbance, synthetic chemicals, heavy metals, hydrocarbons, and increased temperature (Hiscock et al., 2005). Several studies have highlighted the low level of resistance that both cockle species have to inorganic chemicals, such as tributyl tin compounds (Williams & Tyler-Walters, 2023). The intertidal cockle surveys are preferably conducted during spring tide periods

(>6.5m). These allow best access to the beds either using a boat at high water or walking to the beds at low water.

Common cockle records from NBN Atlas between 2003-2023

Lagoon cockle records from NBN Atlas between 2003-2023.

8.10.3. Razor clams (Ensis spp.)

Razor shells or razor clams are a burrowing species and live buried in the sand around the low tide mark and on the seabed out to around 60m deep. Razor clams filter feed on plankton and detritus and quite often, the two small siphons are all that is visible. After storms, huge numbers of razor clam shells often wash up on beaches. There are three very similar species of razor shell found in UK seas, although as a group they are unmistakeable. They have two long, thin shells, brownish in colour, with pale worn patches near the hinge (Wildlife Trusts).

Razor clams occur virtually everywhere in sublittoral and muddy sands but favourable conditions, such as the lee of reefs, rocks and islands make for high densities known as 'beds' which interchange individuals with the surrounding areas where they occur in a more dispersed pattern. Razor clam beds do occur at the extreme low water of spring tides but the species is much more common in depths of about 10 m (Marine Life Information Network).

Razor clams are not listed by IUCN, and like other molluscs, most of the available data looks at presence rather than abundance and is held by the Conchological Society of Great Britain and Ireland. Razor clams are a suitable indicator species for the coastal environment due to their intolerance of a variety of pressures. Razor clams. are intolerant of substratum loss and physical disturbance and are highly intolerant of synthetic chemicals and hydrocarbons (Hiscock et al., 2005). These traits make them useful for assessing both chemical and physical pressures on the coastal environment.

Razor clam records from NBN Atlas between 2003-2023

8.10.4. Dog whelk (*Nucella lapillus*)

Dog whelks are found on wave-exposed or sheltered rocky shores from the mid shore downwards and in estuarine conditions along the Norfolk coast. They are rarely present in the sublittoral zone but may be abundant in areas exposed to extremely strong tidal stress. They are gregarious and common amongst barnacles and mussels on which they feed (Marine Life Information Network).

The National Biodiversityty Network has the most comprehensive record of dog whelk records, however the data is primarily looking at presence rather than abundance (NBN Atlas).

Similar to other molluscs, dog whelks are susceptible to a number of human-induced pressures. These pressures include substratum loss, synthetic chemicals, hydrocarbons, increased salinity and industrial effluents (Hiscock et al., 2005).

8.11. Poaceae

8.11.1. Marram grass (*Ammophila arenaria*)

Marram grass is a a perennial grass tolerant of salt, wind and sand and is commonly found in sandy coastal habitats such as dunes. It is also a pioneer species and can be found in the early stages of dune formation where it plays an important role in stabilizing and building dunes. It is a valuable plant for coastal stabilization and erosion control, and is also used to protect coastal habitats and communities against storm surges, waves, and flooding. It is also a valuable wildlife habitat, and it is known to be a good nesting spot for birds (Wild Flower Web).

The majority of available data comes from the Botanical Society of Britain & Ireland and can be accessed via the NBN Atlas (NBN Atlas). Marram grass is a highly abundant plant, being found all along UK coasts, including Norfolk, and as such its conservation status has not been assessed.

Marram grass records from NBN Atlas between 2003-2023.

8.11.2. Common reed (*Phragmites australis*)

Reedbeds are wetlands dominated by stands of the common reed *Phragmites australis*, wherein the water table is at or above ground level for most of the year. They tend to dominate areas of open water and ditches, and small areas of wet grassland and carr woodland may be associated with them. There are about 5,000ha of reedbeds in the UK, but of the 900 or so sites contributing to this total, only about 50 are greater than 20ha, and these make a large contribution to the total area. Reedbeds are amongst the most important habitats for birds in the UK (JNCC, 2016). Common reed has the important function of stabilising and protecting wetland habitats, although in some contexts its domineering nature can result in it becoming invasive through outcompeting native plant species, leading to changes in ecosystem structure and function.

Similar to Marram grass, the majority of available data for Common reed comes from the BSBI, but due to its extensive range, the species' conservation status has not been assessed (NBN Atlas).

Common Reed records from NBN Atlas between 2003-2023.

8.12. Annelids

8.12.1. Ragworm (*Hediste diversicolor*)

Ragworm is one of the most common intertidal polychaetes in estuaries. Adults inhabit muddy substrata in a more-or-less permanent U or J-shaped burrow that may be up to 20 cm in depth. The species also occurs under stones on mud where the burrow is adjacent to the stone. Ragworm is widespread in brackish water environments throughout north-west Europe (Marine Life Information Network).

Ragworm is an euryhaline species and can withstand great variances in salinity. In marine dominated habitats, ragworm behaves as a brackish water animal and is found in the least saline portion of the available ground (Marine Life Information Network). This species is ecologically very significant because it has a key role in the functioning of estuaries, a major link in benthic food webs and through sediment reworking by bioturbation activity (Gillet et al., 2018).

The JNCC classifies ragworm as Super abundant (SAFCOR scale) on UK shorelines, and as a result there are few datasets predicting overall abundance (JNCC).

Ragworm records from NBN Atlas between 2003-2023

8.13. Lichen & liverwort

8.13.1. Spiny Iceland lichen *(Cetraria aculeata)*

Spiny Iceland lichen is a dark brown to black fruticose, soil lichen from the family Parmeliaceae. The thalli of Spiny Iceland lichen form shrubby tufts of up to 1–5 cm height, main branches are from 1 to 4 mm wide, terminal branches up to 1 mm wide. The species is found fertile and seems to propagate mainly by thallus fragmentation. Despite the apparent lack of ascospores, which can be dispersed across long distances, the species has a very wide distribution. At intermediate latitudes it is mostly found in high mountain ecosystems, but its distributional range also extends into forest gaps, woodland and steppe ecosystems, or coastal and riparian sand deposits of the Mediterranean and temperate zones (Karnefelt, Mattsson & Thell, 1992).

In Norfolk, spiny Iceland lichen is associated with bare sand within dune ecosystems, where soils are more acidic creating dune heaths. A peculiarity of this habitat is that the lichen has no attachment to the substratum other than slight embedding in the surface of the bare sand. They occur as growth forms scattered all over the area in a very open association, and most probably do not originate in this bare area, but are blown on to it by wind and retained by entanglement in loose sand (Brown & Brown, 1968).

Spiny Iceland lichen, like many other bryophytes, is highly sensitive to nitrogen deposition, meaning they can be used as an indicator for varying levels of environmental contaminants (Stevens et al., 2011).

According to the British Lichen Society, Spiny Iceland lichen's conservation status is Least Concern, with a fairly widespread distribution across the UK, however there is currently little data monitoring population changes for this species in Norfolk and the rest of the UK.

Spiny Iceland lichen records from NBN Atlas between 2003-2023

8.13.2. Liverwort petalwort (*Petalophyllum ralfsii*)

Liverwort petalwort is a small, green, thallose liverwort. Its tiny size makes finding and identifying it particularly difficult but fortunately, it cannot be confused with many other species and is quite distinctive in appearance. Individuals are no more than 15x10mm in size and typically much smaller than that. Liverwort petalwort consists of a midrib flanked by two flat leaf like wings, on which near-parallel ridges of lamellae radiate from the midrib to the margin. It is these features that liken it to a miniature lettuce due to its rosette like appearance. It grows in open, damp, calcareous dune slacks, often on low hummocks rather than on the very wet ground, on compacted sandy/muddy bryophyte-rich turf. It has occasionally been recorded in other coastal grasslands where conditions are similar. Despite this, stabilisation of dune systems around the British and Irish coasts has been a significant driver of a steady decline in populations over the past few decades (British Bryological Society). It has always been widely but sparsely distributed in the UK. A high proportion of the known localities are in south-west England and Wales, and in Europe it has a predominantly Mediterranean distribution (JNCC).

Liverwort petalwort is not just a nationally rare species; it is one of only a few British/Irish liverworts that enjoy full legal protection through listing on Schedule 8 of the Wildlife & Countryside Act (1981, as amended). It is also red-listed as Vulnerable in Europe and is included on Annex II of the Habitats Directive (British Bryological Society). The UK and Ireland may now be its stronghold (JNCC).

According to NBN Atlas there have been seven recordings of liverwort petalwort in Norfolk as seen in the NBN Atlas. According to the JNCC, the area in Norfolk is Grade C this means for this species it is least national importance.

Liverwort petalwort records from NBN Atlas between 2003-2023.

As the liverwort petalwort is found in freshwater habitats, saltwater is detrimental to the plant's health, so will be affected by habitat erosion, saline incursion, and trampling. This is why managed retreat projects that have increased in recent years, pose a direct threat to petalwort by allowing salt water to enter dune slacks (Natural England, 2020).

The JNCC holds the majority of the distribution data, but Natural England and British Bryological Society also have some, but if more surveys were undertaken, they should be carried out between September and April. Several visits should be made through each season and the highest count taken as the peak count. It is advised to survey earlier in the season as Winter and Spring rainfall may result in a rapid raising of the water table causing some populations to be flooded and therefore difficult, if not impossible, to survey. Between April and June, female plants may start to produce sporophytes if sexual reproduction has taken place, with this being more likely to take place after a wet autumn and winter. Sporophytes may begin to develop early in spring before maturing in June. Plants favour firm, compacted sand, avoiding loose or mobile sand although plants can withstand being buried beneath several millimetres of sand. It is mainly found in areas with persistently low vegetation that includes many small perennials caused by a lack of nutrients, intense grazing or slight disturbance on lightly trampled footpaths. It will often colonise small areas of bare ground caused by disturbance and may sometimes grow beneath longer grasses.

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