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World Class Science for the Marine and Freshwater Environment

Water quality in the Stiffkey and Glaven catchments and Blakeney Harbour

Estuaries and Coasts Investigations Fund

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Cover. Photograph of Blakeney Harbour, Norfolk, looking east toward Morston and Blakeney. The harbour includes salt marshes, tidal mudflats and reclaimed farmland. It lies within the North Norfolk Coast Site of Special Scientific Interest and is protected through Natura 2000, Special Protection Area (SPA), International Union for Conservation of Nature (IUCN) and Ramsar listings. The reserve is an Area of Outstanding Natural Beauty (AONB) and a World Biosphere Reserve. Photo courtesy of The National Trust.

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Significant findings

- In the Stiffkey catchment, the estimated average faecal coliform loadings (cfu/day) from Great Walsingham STW and Stiffkey STW were 2.1 x 10^{12} and 7 x 10^{10}, respectively. In the Glaven catchment, coliform loadings from Holt STW and from Cley next the Sea STW were 5.5 x 10^{12} and 7.8 x 10^{9}, respectively.
- Mean loadings of *E. coli* (cfu/day) were, on average, 1 $\log_{10}$ higher in the River Stiffkey than in the River Glaven.
- At Blakeney Point, the average daily loadings of *E. coli* from birds were 3.5 x 10^{11} cfu/day while the loadings from grey seals were 1.2 x 10^{14} cfu/day.
- Concentrations of *E. coli* in shellfish indicated that mussels and oysters are more likely to align with B than with A classification under Regulation (EC) No 854/2004. Class B shellfish require a post-harvest purification treatment before marketing for human consumption.
- Concentrations of ammonia found in the Stiffkey and Glaven rivers (0.03–0.15 mg/l; as 90^{th} percentile) indicated “high” status under Water Framework Directive (WFD) and are consistent with the results found at a larger number of sites in this catchment by the Environment Agency. The ammonia standard for “high” status that applies to this catchment (2=Lowland high alkalinity) under WFD is 0.3 mg/l.
- The variation of salinity in the harbour explained 81% of the variation of dissolved inorganic Nitrogen (DIN). The WFD transitional water for DIN (normalised to a standard salinity of 25 psu for transitional waters) indicated that the waters of Blakeney Harbour are characteristic of “good” status.
- The highest concentrations of orthophosphate were found in the River Stiffkey at Binham Tributary (0.052–0.514 µM), Stiffkey Bridge (0.031–0.393 µM) and Wighton Bridge (0.063–0.270 µM); and in the River Glaven at Wiveton Bridge (0.119–0.420 µM). A seasonal pattern emerged from the monitoring data with elevated orthophosphate concentrations in the summer-autumn period.
- The ratio of nitrate:orthophosphate was more associated with flows in the River Stiffkey during the period April–September than during the period October–March. This indicates greater mobilisation of nutrients in the growing season.
- Of the 20 most common species of phytoplankton found in the harbour, 13 are common in UK coastal waters.
- Species of *Alexandrium* and *Dinophysis* were not recorded in any of the samples.
- No association was found between the abundance of *Pseudo-nitzschia* spp. and ratios of total inorganic nitrogen:phosphate and total inorganic nitrogen:silicate.

- The phytoplankton monitoring results obtained indicate that the plankton communities were functioning well during the study period and did not support the overall "Bad" classification status of Blakeney Harbour currently given under the WFD monitoring. However, it should be noted that the data collected in this investigation are limited (11 months).

Non-technical summary

This report presents the results of water quality investigations undertaken in the Stiffkey & Glaven catchments and in Blakeney Harbour to better understand the sources and quantities of faecal indicator bacteria (FIB), nutrients and phytoplankton and to identify measures to ensure good status under the Water Framework Directive (WFD). The suspected causes of water quality deterioration in surface waters included runoff from agricultural land; discharges of treated effluents from sewage treatment works (STW), non-water company package treatment plants and septic tanks; discharges from boats; and wildlife.

Water samples were collected at 4 freshwater sites and at 7 marine sites during the period November 2016–September 2017 and tested for water quality parameters. The sampling sites were selected to represent the spatial and temporal variability of contamination in the rivers upstream and downstream of the main STW and in the harbour. The investigation also included a re-analysis of historical WFD compliance monitoring data. The water quality parameters considered in the investigations were *Escherichia coli*, total oxidised nitrogen, nitrite, phosphate, silicate, ammonium, suspended particulate matter, chlorophyll, phaeopigments, phytoplankton, fluorescence, turbidity, oxygen, photosyntetically active radiation, salinity and temperature.

In general, water management issues associated with FIB were found to be of higher significance than those associated with nutrients. Average FIB loadings from sewage effluent discharges in the upper catchment were, on average, 100 times higher than the loadings from STW in the lower catchment. However, significant differences were found in bacterial loadings at the mouths of the rivers. The bacterial loadings from the River Stiffkey were, on average, 10 times higher than the loadings from the River Glaven. Local inputs of FIB from birds were similar to the loadings from the River Stiffkey while loadings from grey seals were 1,000 times higher than the loadings from this river. In the harbour, mean levels of FIB in seawater were highest at sites on the shoreline and lowest in the mouth of the harbour. Mean concentrations in shellfish flesh were within the range for class B under Regulation (EC) No 854/2004. Shellfish from class B areas would require a post-harvest purification treatment (usually depuration) before marketing for human consumption.

The concentrations of nutrients in the rivers and in the harbour were low. In the Stiffkey and Glaven rivers, concentrations of ammonia were indicative of “high” status and were consistent with the results found at other sites in the catchment as part of WFD monitoring. The historical monitoring data indicated sites with elevated levels of orthophosphate in the River Stiffkey (Binham Tributary, Stiffkey Bridge, Wighton Bridge) and in the River Glaven (Wiveton Bridge). Concentrations of orthophosphate in the River Stiffkey decreased as flows in the river increased indicating dilution of phosphate in this part of the catchment. In contrast, concentrations of nitrogen increased as river flows also increased. This is likely to be associated with inputs of contamination in the lower reaches of the catchment (for example, sewage discharges) and/or mobilisation and entrainment of sediments in the rivers during high-flow conditions. The ratio of nitrate:orthophosphate was significantly associated with river flows in April–September which suggests greater mobilisation of nutrients in the growing season. At marine sites, the levels of dissolved inorganic nitrogen normalised to a standard salinity of 25 psu for transitional waters were characteristic of “good” status.

The diversity of phytoplankton species found in Blakeney Harbour was relatively small. The most abundant groups were *Phaeocystis* spp., microflagellates, *Chaetoceros* spp., cyanobacteria and *Pseudo-nitzschia* spp. Of the group of phytoplankton species that are capable of producing toxins, *Alexandrium* spp. and *Dinophysis* spp. were not observed in any of the samples, *Pseudo-nitzschia* spp. was recorded but below the trigger level of 150,000 cells/l and *Karenia* spp. was observed at low concentrations. The phytoplankton data collected at four sites in Blakeney Harbour were assessed against single cell count and total taxa count thresholds used in WFD assessments and indicated compliance with “high” classification status. Chlorophyll measurements taken in the harbour did not exceed the median thresholds considered in the multimetric assessment of the directive. Taken together, these results indicate that the plankton communities were functioning well during the study period and that the data do not support the “Bad” classification status given under the WFD monitoring. However, it should be noted that the data collected in the field studies are limited and that WFD assessments are based on much larger datasets.

The results of this study provide insight into the variability of water quality in the rivers, identify areas of the catchments that may be of particular water quality concern, and add information concerning contributions from point and non-point sources of contamination to the total loadings impacting the waters in Blakeney Harbour. It is recommended that interventions at sub-catchment level to reduce diffuse pollution from agricultural land are more likely to result in further reductions in the levels of FIB in surface waters and better WFD compliance than measures targeting point sources.

Abbreviations

ASP – amnesic shellfish poisoning

cfu – colony forming units

DIN – dissolved inorganic nitrogen

d/s – downstream

FIB – faecal indicator bacteria

GES – good environmental status

GF/F – glass fibre filter

Mg – milligram

MPN – most probable number

NH_4 – ammonium

NO_2 – nitrite

NRT – Norfolk Rivers Trust

PAR – photosynthetically active radiation

PO_4 – phosphate

RBMP – River basin management plan

SiO_4 – silicate

SPM – suspended particulate matter

STW – sewage treatment works

SWPA – shellfish water protected area

TOxN – total oxidised Nitrogen

u/s – upstream

µmol – micromole

WFD – Water Framework Directive

Glossary

Catchment - The area from which precipitation contributes to the flow from a borehole spring, river or lake. For rivers and lakes this includes tributaries and the areas they drain.

Chlorophyll - a group of green pigments in photosynthetic organisms involved in harvesting light by absorption, excitation and transfer of energy.

Confidence interval - Statistic used to estimate how far away the population mean is likely to be from the sample mean with a given degree of certainty (usually 95% although other values can be used depending on the level of confidence required).

Deterioration (water quality) - It is a requirement of the WFD that none of the quality elements used in the classification of water body status deteriorates from one status class to a lower one.

Diffuse pollution - Pollution from widespread activities with no one discrete source, e.g. pesticides, urban run-off, etc. Pollution resulting from scattering or dispersed sources that are collectively significant but to which effects are difficult to attribute individually.

Dissolved inorganic nitrogen - term generally used in the assessment of saline waters where nitrogen is the more limiting nutrient. It is a measure of the sum of Ammonia and Total Oxidised Nitrogen.

Estuarine waters - Waters that are intermediate between fresh and marine water.

Nitrite - An intermediate in the oxidation of ammonia to nitrate. Many effluents, including sewage, are rich in ammonia, which in turn can lead to increased nitrite concentrations in receiving waters. Therefore, high levels of nitrite in river waters may indicate pollution.

Phaeopigments - degradation products of chlorophyll.

Phosphorus - the limiting nutrient for plant growth in freshwater with small quantities occurring naturally mainly from geological sources. Phosphorus in natural waters and wastewaters is usually found in the form of phosphates. One of its inorganic forms is orthophosphate, which is the most readily available form for uptake during photosynthesis. High concentrations of orthophosphate generally occur in conjunction with algal blooms.

Phytoplankton - Unicellular algae and cyanobacteria, both solitary and colonial that live, at least for part of their lifecycle, in the water column.

Ramsar site - A wetland area designated for its conservation value under the 1971 Convention on Wetlands of International Importance, especially as Waterfowl Habitat. The Ramsar Convention seeks to promote the conservation of listed wetlands and their wise use.

Site of Special Scientific Interest - An area of land notified under the Wildlife and Countryside Act 1981 by the appropriate nature conservation body as being of special interest by virtue of its flora and fauna, geological or physiogeographical features.

Special Area of Conservation - A category of Natura 2000 site that is designated under the Habitats Directive.

Special Protection Area - A category of Natura 2000 site that is designated under the Birds Directive.

Total oxidized nitrogen - the sum of nitrate and nitrite. It is commonly determined using colorimetric means and because nitrite is generally a very small fraction of the TOxN concentration in rivers, TOxN is taken to be equivalent to the nitrate concentration.

Transitional water - A Water Framework Directive term for bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters but are substantially influenced by freshwater flows. Transitional waters include estuaries and saline lagoons.

Urban Wastewater Treatment Directive - European Directive 91/271/EEC. A basic measure under the Water Framework Directive which lays down minimum standards for the provision of sewerage systems and sewage treatment.

Water Framework Directive - Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy.

1. Introduction

1.1 Purpose and scope of the investigation

The Water Framework Directive (WFD) requires that environmental objectives are set for all surface waters in the UK to enable these waters to achieve either "good environmental status" (GES) (for natural water bodies) or "good ecological potential" for heavily modified water bodies[1]. In summary, the environmental objectives of the WFD are to promote sustainable use of water as a natural resource; to achieve at least GES by 2015 (or, where this is not possible, by 2027); to prevent deterioration and enhance status of aquatic ecosystems and associated wetlands; and to conserve habitats and species that depend directly on water. The ecological status of a waterbody is determined by assessments of biological, physico-chemical and hydromorphological "quality elements" and, based on the assessment of the quality elements, waterbodies are categorised as one of five status classes (high, good, moderate, poor, bad) (European Communities, 2000).

Blakeney Harbour is a coastal lagoon on the coast of Norfolk which functions as a nursery ground and feeding ground for a number of important species of birds, finfish and shellfish. The harbour supports many water-based recreational activities (boating, swimming, fishing) and once supported an important commercial fishery for mussels and oysters. While the harbour continues to serve all these functions, it has experienced episodic deteriorations in water quality. In 2015, the ecological status of the Stiffkey & Glaven transitional waters was given an overall "bad" classification on the basis of biological criteria (phytoplankton) under the WFD (Table 1). The River Glaven was given "moderate" classification under the WFD river classification criteria.

Table 1 Classification status of surface waters in the Stiffkey and Glaven catchments under Water Framework Directive, 2015[a].

Water Body Name	Waterbody category	Overall waterbody class[b]	Phytoplankton blooms class	Ammonia (physical-chemical)[c] class	Phosphate class
Stiffkey & Glaven	Transitional	Bad	Bad	-	-
Blakeney Spit Lagoon	Coastal	Good	-	-	-
Glaven	River	Moderate	-	High	High
Stiffkey	River	Good	-	High	Good

Data source: Environment Agency Catchment Planning System. [a] There are different classification systems for these four waterbodies, i.e. Stiffkey and Glaven are assessed under the WFD river classification tools, Stiffkey and Glaven as a transitional water and Blakeney as a coastal water body. Further information on classification criteria: http://www.wfduk.org/. [b] Ecological Status is classified in all waterbodies, expressed in terms of five classes (high, good, moderate, poor or bad). These classes are established on the basis of specific criteria and boundaries defined against biological, physico-chemical and hydromorphological elements. Biological assessment uses numeric measures of communities of plants and animals (for example, fish and rooted plants). Physico-chemical

[1] Bodies of water that have undergone significant changes in their natural character due to human intervention.

assessment looks at elements such as temperature and the level of nutrients, which support the biology. Hydromorphological quality looks at water flow, sediment composition and movement, continuity (in rivers) and the structure of physical habitat. The overall ecological status of a waterbody is determined by whichever of these assessments is the poorer. [c] Physico-chemical comprise elements that support biology (pH, dissolved oxygen, nutrient levels).

The Blakeney Harbour Shellfishery has failed to meet the Guideline standard under the Shellfish Water Protected Areas (England and Wales) Directions since 2011 (Environment Agency, 2015). In addition, in 2014 the microbiological classification of Simpool Head bivalve mollusc production area (BMPA) under Regulation (EC) No 854/2004[2] was downgraded from B to C (Food Standards Agency, 2017).

Previous studies conducted in the Stiffkey and Glaven catchments found elevated concentrations of faecal indicator bacteria (FIB) in parts of the river catchments (The Norfolk Rivers Trust, 2014). Excessive nutrient loadings from sewage discharges and surface water runoff have been considered to be potential causes of episodic water quality deterioration in Blakeney Harbour. Blooms of toxin-producing phytoplankton, possibly associated with the high nutrient loadings, have also occurred in Blakeney Harbour. There has been concern that the future of shellfish farming in Blakeney Harbour may be compromised because of siltation in the harbour channel associated with natural causes or dredging activities causing mussel seed to be washed away or die (Wild Trout Trust, 2010; Eastern Daily Press, 2014) and levels of FIB in the shellfish to elevate causing classification downgrades(Blakeney Parish Council, 2015).

A better understanding of the sources and quantities of FIB, nutrients and phytoplankton entering Blakeney Harbour from the catchments of the rivers Stiffkey and Glaven is necessary for identifying measures to ensure that the classifications of the rivers and transitional waters achieve “good” status under the WFD requirements. Cefas conducted studies in collaboration with the Norfolk Rivers Trust (NRT) and Environment Agency through funding provided by the “Estuaries and Coasts Investigations Fund”. The specific objectives of the studies were to:

1. Quantify levels of FIB and nutrients in the Stiffkey and Glaven catchments and Blakeney Harbour;
2. Ascertain if the failure of the phytoplankton metrics (as moderate in Glaven and bad in Stiffkey) are valid given additional data collection;
3. Make recommendations on actions to help achieve “good” status; and
4. Engage with key local water users and partner organisations and share key findings and identify ways to improve water quality.

In addition to the WFD assessment processes, this work will provide additional mechanisms for improved understanding of the water quality issues in this area and stimulate the development of local partnerships and projects to deal with these issues.

[2] Regulation (EC) No 854/2004 laying down specific rules for official controls on products of animal origin intended for human consumption (European Communities, 2004).

1.2 Description of the study area

The surface water catchment relevant to this study covers the Rivers Stiffkey and Glaven which drain to Blakeney Harbour (Figure 1). The River Stiffkey (mean flow=0.55 $m^3 s^{-1}$) flows North from Swanton Novers towards the tidal limit at Freshes Creek. The River Glaven also flows North from Holt towards the tidal limit at Cley next the Sea. The rivers drain to Blakeney Harbour, a percolating coastal lagoon on the North Norfolk coast. The lagoon comprises six small pools of shingle overlaid by soft mud between areas of saltmarsh and a protective barrier of sand and shingle. Blakeney Harbour is a Site of Special Scientific Interest, a Special Area of Conservation, a Special Protection Area, and a Ramsar site.

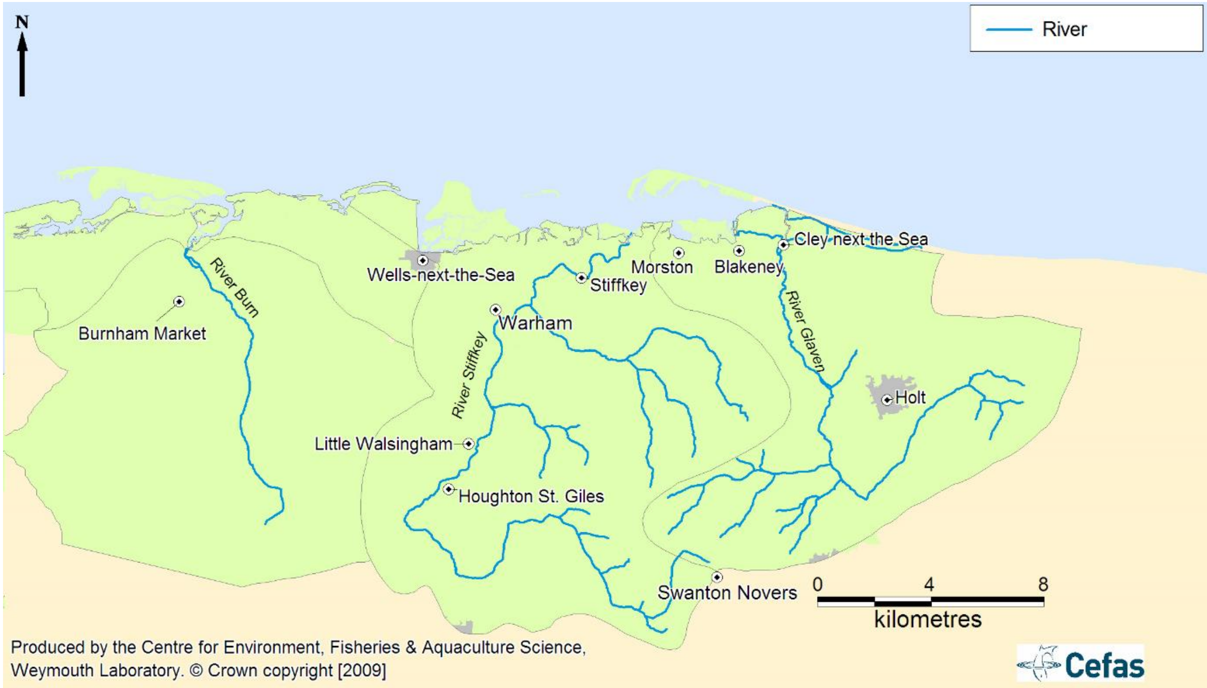


Figure 1 Catchments of the rivers Stiffkey and Glaven.

Both catchments have a relatively flat topography. Land cover is predominantly rural and includes arable fields and grassland used for pasture. There are also areas of urbanised land close to the coast, including the towns of Stiffkey, Blakeney and Cley next the Sea. A more detailed description of this catchment is given in the sanitary survey report (Cefas, 2010). Different land cover types generate different levels of contamination in surface waters. The highest loadings of FIB and phosphorous arise from urbanised areas with intermediate contributions from pastures and sparsely populated areas (Kay et al. 2008; White and Hammond, 2006).

2. Potential causes of water quality deterioration

The Environment Agency's River Basin Management Plan (RBMP) for the Anglian region identifies four types of pressures on surface water quality in the Stiffkey and Galven catchments which are relevant to this study (Defra and Environment Agency, 2016):

- Total oxidised nitrogen (TOxN) in rivers (at risk).
- Phosphorous (rivers) (at risk).
- Nutrient nitrogen (estuaries and coastal waters) (probably not at risk).
- Phosphorous from agriculture (rivers) (Stiffkey catchment at risk; Glaven catchment not at risk)

Table 2 lists additional information collected during the course of the project on the likely causes of water quality deterioration.

Figure 2 shows a conceptual diagram that illustrates the potential pathways that link the sources, pressures and effects on water quality. For example, on the right hand side of the diagram, it is illustrated how increased nutrients can lead to algal growth, increased biological oxygen demand and reduced dissolved oxygen concentrations. In the Stiffkey and Glaven catchments, livestock excreta and application of animal manures to farmland and fertilisers to arable crops were anticipated to significantly contribute to total loadings from agricultural land. Septic tank discharges and misconnections were expected to contribute higher concentrations of contaminants than combined sewer overflows. Given the rural character of the catchment, contributions from sewage discharges were expected to be localised and lower than those from livestock production areas. The risk of surface water pollution from landfill leachate would be associated with a site at Edgefield in the upper Glaven catchment which covers an area of approximately 9.5 hectares near the village of Holt and is located approximately 400 m from the river Glaven (Norfolk Environmental Waste Services Ltd, 2012).

Table 2 List of suspected causes of water quality deterioration in Blakeney Harbour identified in the literature.

Type of pollution	
Agricultural runoff Runoff of nutrients and faecal indicator bacteria from agricultural land, including livestock production areas, slurry management, leachate from silage clamps, application of fertilisers and farmyard manure	
Sewage discharges Discharges of treated effluents from water company wastewater treatment works, non-water company package treatment plants and septic tanks, and untreated sewage from sewer overflows during high rainfall.	
Discharges from boats The discharge of sewage from boats is a potential source of microbiological contamination within the harbour. The highest risk of contamination is likely to be associated with boats in overnight occupation on moorings or at anchor.	
Wildlife Large populations of birds and seals contributing faecal indicator bacteria to the harbour.	

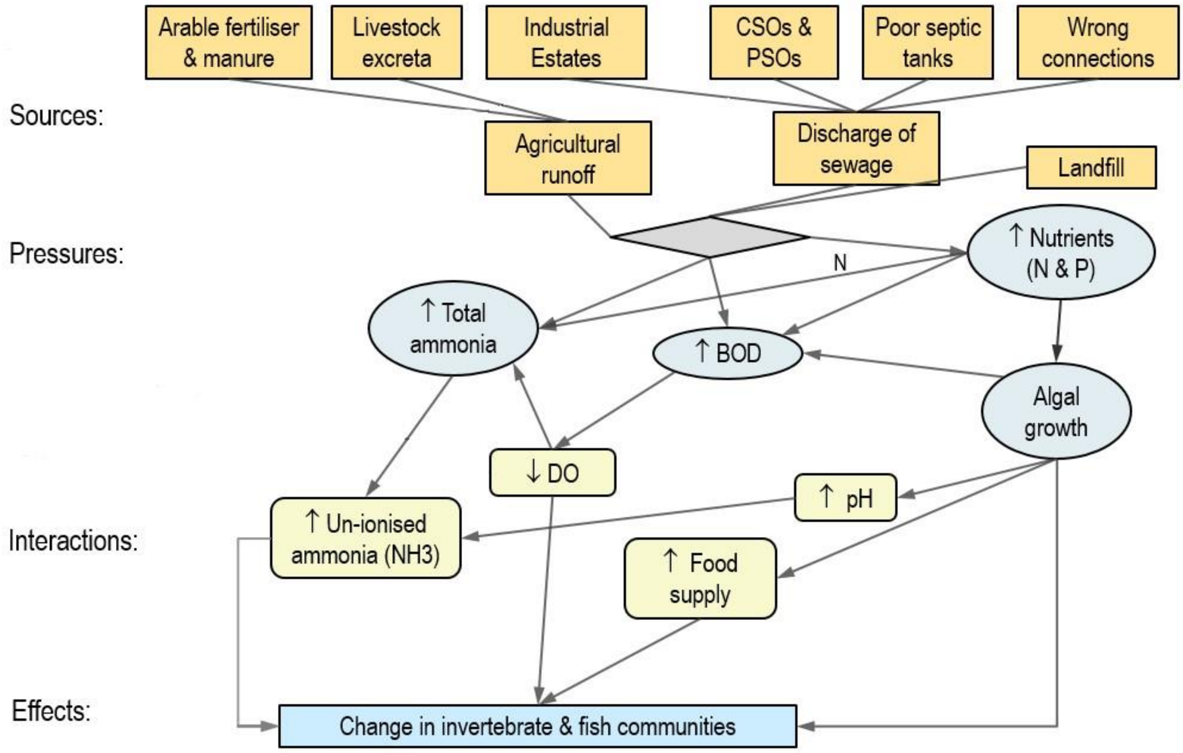


Figure 2 Simplified conceptual diagram of sources, pressures and effects on water quality in Blakeney Harbour. Modified from Hulme and Rukin (2015).

3. Methods of data collection

The investigation comprised a desk review of historical monitoring data together with a programme of field studies in the catchments of the Rivers Stiffkey and Glaven and Blakeney Harbour during the period November 2016–September 2017. The field sampling was conducted during dry- and wet-weather periods. Water samples were collected in the rivers, sewage discharges and in the harbour and tested for *E. coli* bacteria, nutrients, phytoplankton, suspended particulate matter (SPM), chlorophyll and phaeopigments.

3.1 Sampling programme

Water samples were collected at representative sites in the rivers Stiffkey and Glaven and in Blakeney Harbour (Figures 3–4). The sampling locations were selected to represent river water quality upstream and downstream of Stiffkey sewage treatment works (STW) and Cley next the Sea STW. These discharges contribute a significant proportion of the faecal contamination loading from treated effluent in the catchment. Additional sampling sites were identified on the shoreline because evidence from previous water quality investigations undertaken by Cefas (2010) suggested higher concentrations of FIB in inshore areas of the harbour. Additional sites were identified for seawater sampling to represent a gradient of nutrient and FIB contamination in the main channels of the harbour and to inform recommendations on the most representative sites for WFD compliance monitoring.

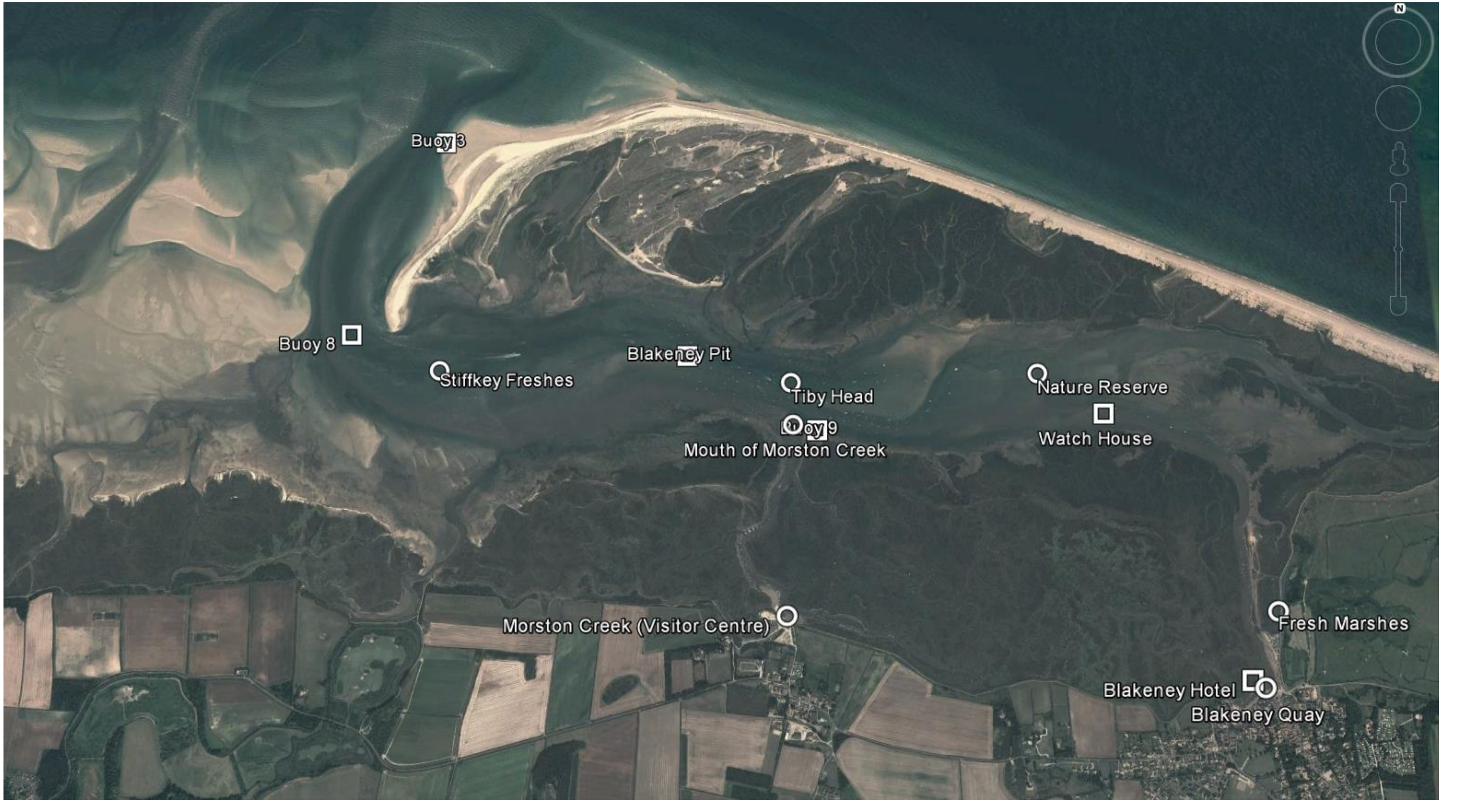


Figure 3 Location of sampling sites in Blakeney Harbour. Circles - Cefas monitoring sites (present study); squares - EA monitoring sites.

Figure 4 Location of sampling sites in the Stiffkey and Glaven catchment. Circles - Cefas monitoring sites (present study); squares - EA monitoring sites.

3.2 Sample collection and preparation

Nine field surveys were carried out during the period November 2016–September 2017. The field staff deployed to the study site were subdivided into two teams. Simultaneously, one team collected samples in the rivers while the other team collected samples in the harbour. At sampling sites in the rivers, samples were collected in the morning to represent periods of peak flows through the STW discharges. In the harbour, most samples were collected at or around high water taking into account the time required to submit the samples to the testing laboratories.

Water samples for microbiological testing were collected manually directly into 250 ml sterile disposable plastic containers (Sterilin) using a sampling pole. These samples were stored in the dark inside cool boxes with freezer packs during transport to Cefas Weymouth Laboratory. Occasionally, it was necessary to use a sample courier service to transport samples to Weymouth Laboratory. All samples were analysed within 48 h of collection.

Additional water samples were collected at the same sites for quantification of concentrations of nutrients, chlorophyll, phaeopigments and SPM. Each sample (250 ml) was filtered on site through Whatman™ glass fibre filter (GF/F) papers. Sixty ml of the filtrate were transferred to polycarbonate containers and preserved with 0.1 ml of 16 g/l mercuric chloride solution. The samples were then stored in cool boxes which were transferred to a fridge at approximately 4°C during transport and until testing at Cefas Lowestoft Laboratory. For quantification of chlorophyll and phaeopigments, the GF/F paper containing the chlorophyll sample was carefully folded and placed in a 5 ml cryovial. The cryovial was then stored in a dry shipper in the field and transferred to a -80°C freezer. All of these samples were analysed within 4 weeks of collection.

For quantification of SPM, known volumes of water (100–500 ml/sample; depending on particle load) were filtered through pre-weighed Whatman™ cyclopore track etched membrane filters. The filters were placed within a plastic lidded petri dish and stored in a desiccator. These samples were analysed within 5 weeks of collection.

Water quality parameters (turbidity, fluorescence, temperature, salinity, photosynthetically active radiation) were measured in the water column at the time of sampling using the Cefas built Ecosystem Monitor 2. This instrument comprises a FSI CT sensor for conductivity and temperature, a Seapoint Fluorometer and an Optical Backscatter Sensor for fluorescence and turbidity respectively, a Licor photosynthetically active radiation (PAR) sensor and a Druck pressure sensor. A single profile was taken at depth at each sampling station.

3.3 Laboratory analyses

3.3.1 Escherichia coli

Concentrations of *E. coli* were quantified in water samples following standard EA methods based on membrane filtration (Standing Committee of Analysts, 2009). *E. coli* were isolated by sub-culture of up to 10 colonies from each membrane on nutrient agar at 37°C for 24 h. The pure cultures were tested for oxidase then inoculated onto MacConkey agar and incubated at 44°C for 24 h to confirm lactose fermentation. Cultures were also inoculated onto tryptone nutrient agar and incubated at 44°C for 24 h. Indole formation was demonstrated by adding two or three drops of Kovacs' reagent to each plate and the development of a pink-red colour in the agar. Colonies that were oxidase negative and positive for lactose and indole were recorded as confirmed *E. coli*. The proportion of *E. coli* from each membrane was then used to calculate the *E. coli* count on the corresponding coliform plate. The results were expressed as colony forming units (cfu)/100 ml.

3.3.2 Nutrients

Nutrient analyses were performed using a SEAL Analytical AA3 continuous flow analyser via colorimetric methods for TOxN (total oxidised nitrogen=nitrate+nitrite), nitrite (NO_2), phosphate (PO_4) and silicate (SiO_4) and a fluorometric method for ammonium (NH_4) according to Seal Analytical protocols (1996a-d).

3.3.3 Chlorophyll and phaeopigments

Chlorophyll was extracted into 8 ml of 90% acetone and the analyses were performed using a Turner 10AU-005-CE fluorimeter according to procedures described by Tett (1987). Each sample was then analysed for phaeopigments by adding two drops of 1.2 M hydrochloric acid to the acetone extract and the measurement was repeated using the Turner 10AU-005-CE fluorimeter.

3.3.4 Suspended particulate matter

Samples for quantification of suspended particulate matter were collected by filtration on pre-cleaned and pre-weighted filters, washed free of salts, dried and re-weighted once a week until three consistent values were achieved following the procedures described by Yeats and Brugmann (1990).

3.3.5 Salinity

Sub-samples of water were collected in 200 ml glass bottles for salinity testing. A plastic neck insert was applied to each bottle to prevent evaporation. Salinity concentrations were quantified using a Guildline Portasal 8410a salinometer as described by Wilson (1981). These samples were analysed within 5 weeks of collection.

3.3.6 Phytoplankton

Surface water samples were collected, mixed and sub samples processed by *in situ* filtration and freezing and preserved with Lugol's Iodine for phytoplankton identification and counting. The samples were identified to the lowest practical taxonomic level possible and counted using the Utermöhl method.

3.4 Additional data

The results of WFD monitoring carried out in the Stiffkey and Glaven catchments during the period 2005–2017, UV efficacy monitoring carried out at Wells-next-the-Sea STW and Cley next the Sea STW during the period 2012–2016, information on WFD classification of sites for ammonia and phosphate for 2016, and current water quality standards for rivers (WFD for ammonia and phosphate and Nitrates Directive for nitrate) were provided to Cefas by the Environment Agency. Information on the frequency of sewage overflows in the study area was provided by Anglian Water. Average river flow data for the River Stiffkey at Warham were downloaded from the National River Flow Archive (http://nrfa.ceh.ac.uk/data/station/meanflow/34018).

3.5 Statistical analyses

Exploratory analysis of the water quality data was undertaken and summary statistics produced. These included minimum, maximum, 95% confidence intervals, geometric mean and arithmetic mean. These statistics were used to assess the distribution, ranges and central location of the data. The distributions of the water quality data showed a much closer approximation to normality when $\log_{10}$ transformed as is commonly the case for this sort of environmental data. All data were therefore transformed prior to correlation analyses. Monitoring results below the limit of detection of the testing methods were reduced by one significant figure (X-1). Side-by-side boxplots were used to illustrate important characteristics of the water quality data (for example, data distributions per sampling site and per season), to describe the results of hypothesis tests and visually assess whether the data fit the assumptions of the tests employed. Linear regression was used to model the relationships between the water quality parameters (e.g. the variation of *E. coli* concentrations in seawater and distance between the shoreline and the monitoring points). The strength of relationships was assessed using the coefficient of determination (R^2), adjusted for degrees of freedom, and expressed as a percentage. The relationships between the water quality parameters was also assessed using the Pearson's correlation coefficient (r) on $\log_{10}$ transformed data. The statistical significance was assessed at 95% and 99% confidence levels.

4. Results

4.1 Faecal indicator bacteria

4.1.1 Faecal bacteria in sewage discharges

Sewage effluents in the Stiffkey and Glaven catchments are treated at several sewage treatment works (STW), the largest of which are associated with urban settlements at Wells-next-the-Sea, Great Walsingham, Holt and Cley next the Sea (Figure 5; Table 3). Details of all consented sewage discharges are given in the sanitary survey report (Cefas, 2010). None of these discharge directly to the tidal waters. Wells-next-the-Sea STW and Cley next the Sea provide UV disinfection. This method of wastewater treatment is very effective in inactivating microorganisms that have the potential to cause infection in humans.

The sewerage infrastructure is also served by five sewer overflows which discharge either directly to the harbour or to rivers and are likely to contribute to bacteriological loadings to the harbour. The loadings of faecal coliforms[3] from these sewage-related sources were estimated using reference concentrations published by Cefas (2010) and Kay et al. (2008) and consented dry weather flows for these STW.

The results indicate that, in the Stiffkey catchment, the average coliform loadings from Great Walsingham STW are 2 $\log_{10}$ higher than loadings from Stiffkey STW. In the Glaven catchment, coliform loadings from Holt STW are 3 $\log_{10}$ higher than loadings from Cley next the Sea STW. This indicates that, on average, the upper reaches of the rivers just downstream of the STW that discharge secondary-treated sewage are likely to contain higher levels of microbiological contamination than the lower reaches just downstream of the STW that operate UV disinfection.

Table 4 summarises the results of UV disinfection efficacy carried out at Wells-next-the-Sea STW and Cley next the Sea STW. This testing is carried out by the water company to demonstrate that the disinfection plant is performing to the required standard and to contribute to achieving the microbiological objectives of the Bathing Waters Directive and Shellfish Water Protected Areas (England and Wales) Directions. The results indicate that UV disinfection has been consistently effective at both plants. The geometric mean concentrations of *E. coli* are similar to mean concentrations reported for a large number of UV-treated effluents in other parts of the UK (Kay et al. 2008). It should be noted that UV disinfection is less effective in removing pathogenic viruses than FIB (Campos et al. 2013).

[3] Faecal coliforms are a subset of total coliform bacteria and are therefore more associated with contamination of faecal origin. However, this group contains species of *Klebsiella*, which are not necessarily faecal in origin. For bathing and shellfish waters, faecal coliforms were used as the primary faecal indicator organism until relatively recently, when regulators began recommending *E. coli* as better indicators of health risk.

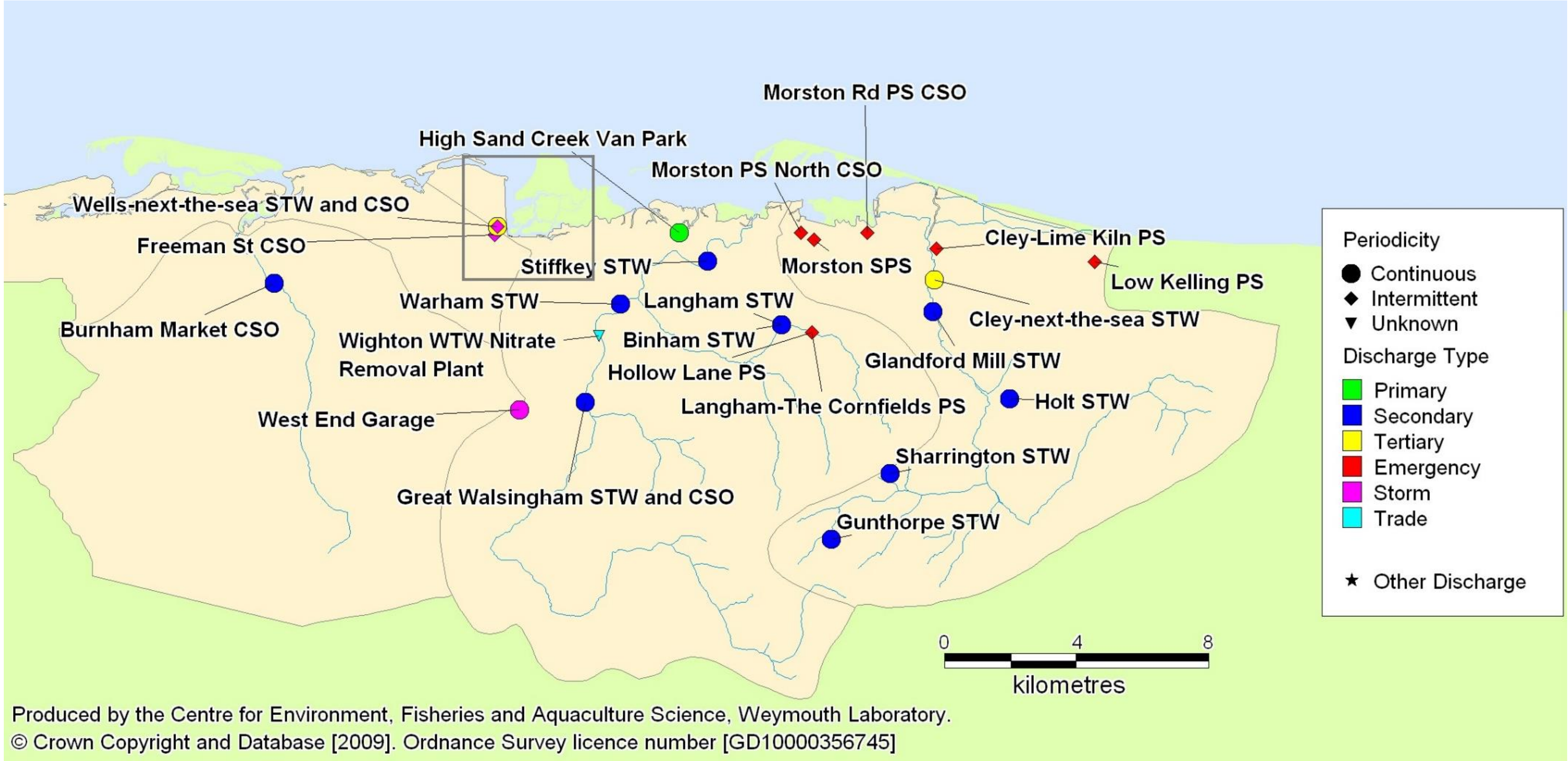


Figure 5 Sewage discharges in the Stiffkey and Glaven catchments.

Table 3 Estimated faecal coliform loadings from the main continuous and intermittent discharges in the Stiffkey and Glaven catchments.

Name	Treatment/Type	Dry weather flow (m^3/day)	Estimated bacterial loading (cfu/day)	Receiving water
Continuous				
Wells-next-the-Sea STW	UV disinfection	1,125	2.9×10^9 (a)	Tributary of Wells Creek
Holt STW	Secondary (biological filtration)	1,090	5.5×10^{12}	Tributary of River Glaven
Cley next the Sea STW	UV disinfection	650	7.8×10^9 (a)	River Glaven
Great Walsingham STW	Secondary	419	2.1×10^{12}	River Stiffkey
Warham STW	Secondary	17	8.5×10^{10}	River Stiffkey
Wighton WTW Nitrate Removal Plant	Trade effluent	10	-	River Stiffkey
Stiffkey STW	Secondary	14	7.0×10^{10}	River Stiffkey
Intermittent				
Wells-next-the-Sea STW SO	Storm overflow	-	8.0×10^5 (b)	Tributary of Wells Creek
Freeman Street CSO	Combined sewer overflow	-	2.5×10^6 (b)	Tributary of Wells Creek
Cley SPS	Pumping station overflow	-	2.5×10^6 (b)	Tributary of River Glaven
Morston SPS	Pumping station overflow	-	2.5×10^6 (b)	Stream to Blakeney Harbour
Morston Road PS	Pumping station overflow	-	2.5×10^6 (b)	Stream to Blakeney Harbour

(a) Estimated based on concentrations of faecal coliforms measured in the final effluent (Cefas, 2010). (b) Estimated based on effluent concentrations typical of storm overflow discharges (Kay et al. 2008). STW-sewage treatment works; WTW-water treatment works; SO-storm overflow; CSO-combined sewer overflow; SPS-sewage pumping station; PS-pumping station.

Table 4 Summary statistics of levels of *E. coli* in final effluent from Wells-next-the-Sea STW and Cley next the Sea STW, January 2012–November 2016.

	Sewage treatment works	
	Wells-next-the-Sea	Cley next the Sea
Upper 95% confidence interval (cfu/100 ml)	40	342
Lower 95% confidence interval (cfu/100 ml)	18	131
Maximum (cfu/100 ml)	1,999	36,000
Minimum (cfu/100 ml)	1	8
Geometric mean (cfu/100 ml)	27	212
Number of samples	60	59

The supply of coliform bacteria in rivers is also influenced by the operation of storm sewage overflows, particularly following rainfall events. According to information provided by Anglian Water, there were 6 spills from Wells-next-the-Sea STW SO and 7 spills from Freeman Street CSO during the period 1 January 2013–18 October 2017 (time of writing). Both discharge to a tributary ditch system of Wells Harbour. The Freeman Street CSO is located further upstream in the ditch system where a significant amount of retention time is provided by both the ditch system and a new lagoon/sustainable urban drainage system which would promote bacterial die-off before the effluent reaches Wells Harbour (Anglian Water, pers. comm.). Therefore, it is considered that sewer overflows are unlikely to significantly impact water quality in Blakeney Harbour.

4.1.2 Faecal bacteria in freshwater

Loadings of *E. coli* in the rivers Stiffkey and Glaven were estimated using the *E. coli* concentrations detected in freshwater samples collected during the period November 2016–September 2017 and river flows measured at the time of sampling. The sampling stations were identified to represent loadings from areas of the catchment upstream of the main STW discharges (Glaven - Glandford and Stiffkey u/s Stiffkey STW) and catchment outlets downstream of these (Glaven - Windmill and Stiffkey - White Bridges). In the River Stiffkey, no difference was found in mean *E. coli* loadings between these stations (Table 5). In the River Glaven, the mean *E. coli* loadings in the upper catchment were 1 $\log_{10}$ higher than the loadings at the catchment outlet. The results also indicate that, on average, the River Stiffkey contributes bacterial loadings that are 1 $\log_{10}$ higher than the loadings from the River Glaven.

Table 5 Estimated *E. coli* loadings from the rivers Stiffkey and Glaven.

River	Number of samples	*E. coli* loading (cfu/day)		
		Minimum	Maximum	Mean
Stiffkey (u/s Stiffkey STW)	10	1.5×10^{10}	1.5×10^{12}	3.1×10^{11}
Stiffkey (White Bridges)	10	1.3×10^{10}	1.8×10^{12}	4.7×10^{11}
Glaven (Glandford)	8	2.1×10^{10}	8.0×10^{11}	2.3×10^{11}
Glaven (Windmill)	9	7×10^{9}	2.7×10^{11}	9.0×10^{10}

Table 6 presents a comparison of *E. coli* levels in freshwater samples collected at six sites in the River Stiffkey on surveys carried out during different weather conditions on 14/03/2017 and 25/07/2017. The results suggest that, during high levels of rainfall, the bacterial concentrations in the river elevate about 1 $\log_{10}$ relative to concentrations during low rainfall.

Table 6 Comparison of *E. coli* concentrations in freshwater collected on two occasions at six sites in the River Stiffkey.

Sampling site	Approximate distance (km) from headwaters at Saxlingham	Survey on 14/03/2017 (1.2 mm rain in the preceding week)	Survey on 25/07/2017 (20.9 mm rain in the preceding week)
d/s Langham STW	3.6	7,500	Not sampled
Binham Ford House	5.6	450	6,200
Wighton Bridge	12.2	250	6,400
d/s Warham STW	15.0	61	2,500
u/s Stiffkey STW	18.6	97	1,098
White Bridges	20.9	77	504

4.1.3 Faecal bacteria from wildlife

Blakeney Harbour provides a diversity of natural habitats for large populations of birds and seals. It has been hypothesised that bird and seal faeces can contribute very high concentrations of non-human faecal indicator bacteria to the waters in Blakeney Harbour (Cefas, 2010; Environment Agency, 2015). Low tide counts of breeding birds carried out by staff of the National Trust Blakeney Nature Reserve during the period 2006–2015 were used to estimate the loadings of faecal coliforms at two sites (Blakeney Point, Stiffkey Freshes) in Blakeney Harbour. For wildfowl and waders, early morning visits were made in May and June counting adults from a discrete distance. For passerines, early morning counts of signing males were undertaken in April–May. For Sandwich Terns and Black-headed Gulls, a nest count was undertaken in late May, marking individual nests to gain an accurate figure. For other terns, sitting birds were counted, and nest counts conducted where possible. Weekly visits were made in June and July to monitor young of all species (Tegala, 2015). Loading estimates were carried out for Blakeney Point (Buoy 8) and Stiffkey Freshes (Figure 3). In this assessment, it was assumed that the average concentration of faecal coliforms in bird faeces is 6.2×10^8 cfu/g. This is based on results obtained in samples of droppings from captive gulls (Gould and Fletcher, 1978). It was also assumed that the average excretion rate per bird is 25 g and that 25% of the faecal material reaches the tidal waters in Blakeney Harbour. At Blakeney Point, the average daily loadings were 3.5×10^{11} cfu/day while at Stiffkey Freshes the average loadings were 1.9×10^{10} cfu/day.

A similar assessment was carried out to estimate the potential contribution of seals to the total daily faecal coliform loading. Two species of seals are commonly found in Blakeney

Point: the common seal (*Phoca vitulina*) and the grey seal (*Halichoerus grypus*). This site is currently one of the largest seal colonies in England with over 2,000 pups born annually (The National Trust, 2016). Data on low tide seal counts carried out on 18 occasions around low tide during the period March–October 2015 around Blakeney Point were used (Tegala, 2015). In this assessment, an average concentration of faecal coliforms in seal faeces of 3.1 x 10^7 cfu/100 ml and a daily excretion rate of 375 g were assumed (Calambokidis et al. 1987). This faecal coliform concentration is similar to that found in untreated sewage (Kay et al. 2008). It was also assumed that 25% of faecal material would impact the harbour waters. This was considered a reasonable approximation because seals are not always in the water and a proportion of the colony spends long periods of time in the outer deeper reaches of the harbour where more water is available for dilution of the faecal matter. The results of this assessment indicate total average loadings of 4.6 x 10^{13} cfu/day from common seals and 1.2 x 10^{14} cfu/day from grey seals.

4.1.4 Faecal bacteria in seawater

In the field studies, 53 samples of seawater were collected at marine sites during the period November 2016–September 2017 and tested for *E. coli*. Table 7 presents the summary statistics of these data. Overall, concentrations of *E. coli* ranged from 1 cfu/100 ml to 4,600 cfu/100 ml. The sites with higher geometric mean levels of *E. coli* were inshore locations on the eastern part of the harbour (Blakeney Fresh Marshes and Blakeney Quay). Faecal contamination at Blakeney Fresh Marshes is likely to be associated with inputs from livestock grazing in the marshes and birds while contamination at Blakeney Quay is likely to be associated with urban sources.

The geometric means of *E. coli* at sites in the main harbour channel (Nature Reserve, Stiffkey Freshes and Tibby Head) are below the mean that is considered equivalent to the flesh standard of 300 *E. coli*/100 g of the Shellfish Water Protected Areas Directons (Kershaw et al. 2013). The highest *E. coli* concentration (1,000/100 ml) was found at Blakeney Quay which is approximately 4 km upstream of the edge of the classified shellfish production area in the main meandering channel on the eastern part of the harbour.

Most water samples were collected at or around high water and therefore there was insufficient data to assess the variation of *E. coli* over the tidal cycle.

Sediment samples were collected at Fresh Marshes on 08/11/16 and 21/11/16 and at Nature Reserve on 21/11/16 for *E. coli* testing. The results of these samples were 15, 80 and 4,600 cfu/100 ml, respectively. This high concentration could be associated with localised *E. coli* inputs from wildlife (seals, birds).

Table 7 Summary of *E. coli* concentrations in seawater samples collected at marine sites in Blakeney Harbour.

	Sampling site						
Statistic	Blakeney Fresh Marshes	Blakeney Quay (Hotel)	Morston Creek (Visitor Centre)	Mouth of Morston Creek	Nature Reserve North Side	Stiffkey Freshes	Tibby Head
Upper 95% CI (cfu/100 ml)	264	1,398	152	46	15	13	31
Lower 95% CI (cfu/100 ml)	207	50	25	3	1	2	2
Maximum (cfu/100 ml)	260	1,000	400	400	24	20	256
Minimum (cfu/100 ml)	210	22	4	1	1	1	1
Geometric mean (cfu/100 ml)	234	265	62	18	4	5	9
Number of samples	3	4	12	9	5	7	9

Results below the limit of quantification (<20) were adjusted to 19.

To evaluate the effect of *E. coli* decay across the harbour, data for 5 stations were chosen to represent a transect from Blakeney Quay at Cley next the Sea to the mouth of the harbour. Figure 6 shows the linear relationship obtained between bacterial levels in the water and fluvial distance.

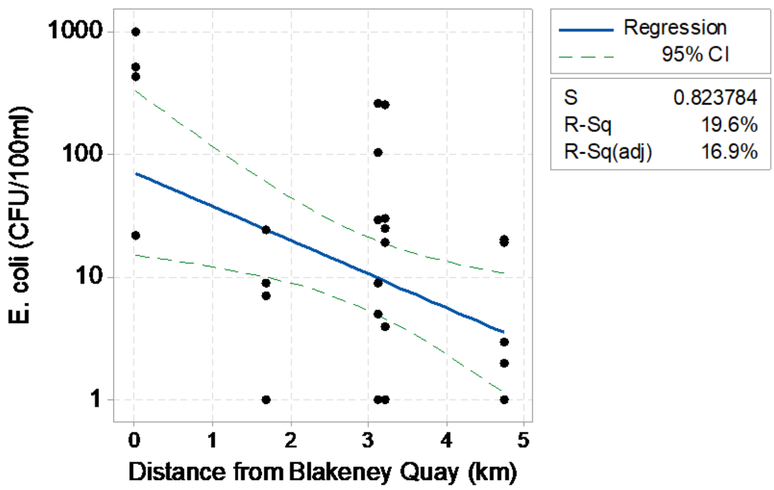


Figure 6 Linear relationship between concentrations of *E. coli* in seawater at 5 sites and fluvial distance in Blakeney Harbour. The regression equation is $\log_{10}$*E. coli* = 1.847-0.2736*Distance. Sewage dilution was assumed to increase with fluvial distance.

Although the relationship is statistically significant (p=0.011), fluvial distance explains only 17% of the spatial variability in *E. coli* concentrations in the harbour. This indicates that factors other than dilution alone (as suggested by fluvial distance) would explain the variation of faecal indicator bacteria in Blakeney Harbour. Other factors that are likely to influence bacterial abundance in seawater are UV radiation, SPM, turbidity and predation by protozoa and other microorganisms. The level of explained variance (adjusted R^2) of the model is lower than the variance observed in other harbours in England that receive larger volumes of wastewater (Campos et al. 2015).

What is *E. coli* and how does it relate to health risk?

Escherichia coli are a type of fecal coliform bacteria commonly found in the intestines of animals and humans. Most *E. coli* do not cause illness but if a person becomes sick from *E. coli*, the primary site of infection is the gastrointestinal tract. Symptoms can include nausea, vomiting, diarrhea and fever. Contaminated food and water are common ways to be exposed to these bacteria. There are specific types (strains) of *E. coli* that can cause disease and there are also harmless types.

Many studies have been conducted to assess the connection between water quality and health effects in people who come into contact with contaminated water through recreation (swimming, sailing, kayaking, etc.). These studies have demonstrated that *E. coli* concentrations are the best predictor of swimming-associated gastrointestinal illness (GI). In addition to GI, illnesses such as eye infections, skin irritations, ear, nose, throat infections, and respiratory illness are also common in people who have come into contact with water contaminated with faeces. Elevated levels of pollution during and following rainfall are associated with an increased risk of GI in swimmers/surfers when compared with those who swam/surfed in less polluted waters. There is also evidence of a significant dose response between faecal indicator organisms and gastrointestinal illness in freshwater bathers, i.e. the risk of illness increases with decreasing water quality. It is very difficult to relate actual *E. coli* levels to the probability of illness because the studies have been conducted in very different circumstances and there is lack of epidemiological data to confirm or disprove some of its findings (King et al. 2014). However, it is possible to relate the monitoring results with the standards of the Bathing Waters Directive shown in Table 8.

Table 8 *E. coli* upper limits used for classification of bathing waters under Annex I of the Bathing Waters Directive (European Parliament and Council of the European Union, 2006).

	Excellent	Good	Sufficient
Inland (fresh) waters	500[a]	1,000[a]	900[b]
Coastal and transitional (marine) waters	250[a]	500[a]	500[b]

[a] Calculated as 95th percentile; [b] Calculated as 90th percentile.

The River Stiffkey u/s STW site is used for water recreation in the summer and the *E. coli* results obtained during the study were used to verify the compliance of this site with the standards tabulated above. The results indicate a 90th percentile of 3,940 cfu/100 ml for this site (n=10) and therefore would exceed the limit for “Sufficient” classification. In this case, the site would be classified as "Poor" quality. To represent typical marine conditions, the results obtained for the mouth of Morston Creek were selected (n=12). At this site, the 95th percentile of *E. coli* levels is 367 cfu/100 ml and therefore the site would be classified as "Good" under the directive. On the basis of these results, it can be concluded that the risk of GI from bathing in the River Stiffkey is much higher than at Morston Creek.

4.1.5 Levels and seasonality of faecal bacteria in shellfish

At the time of writing, one shellfish production area (South Side) in Blakeney Harbour is classified for Pacific oysters (*C. gigas*) under Regulation (EC) No 854/2004. Until September 2017, common mussels (*Mytilus* spp.) were also classified. The classification standards are given in the protocol available on Cefas website. Currently, oysters are class B while mussels were class C at the time of declassification (Food Standards Agency, 2016). The geographical boundaries of the production area are shown in Appendix I. The classification is a public health measure and determines the sanitary quality of the production areas and the extent of processing required before shellfish can be placed on the market for human consumption. The classification categories are A, B, and C, with class A being the "cleanest". Class A shellfish require no treatment prior to consumption. Class B shellfish require treatment (typically depuration) whereas class C shellfish require more treatment still (typically relaying for a longer period or heat processing by an approved method). Production areas with levels of contamination greater than class C may be designated as Prohibited, where shellfish cannot be harvested or marketed for consumption at all.

In addition to these standards, the Shellfish Water Protected Areas (England and Wales) Directions 2016 stipulate a microbiological standard of 300 *E. coli* per 100 ml in shellfish flesh and intervalvular fluid in 75% of samples taken within any period of 12 months (Defra and Natural Resources Wales, 2016). The aim of this standard is to ensure that the environmental objectives of the WFD are achieved.

The summary statistics of levels of *E. coli* in shellfish for the period 2013–2015 presented in Table 9 indicate that mussels at Simpool Head are, on average, more contaminated that Pacific oysters at South Side. Maximum *E. coli* levels exceeding the class B threshold were detected in mussels but not in oysters. However, the results of compliance assessment indicate that 80% of the samples at Simpool Head and 72% of the samples at South Side did not comply with the *E. coli* standard of the SWPA Directions. The results also indicate that both mussels and oysters are more likely to align with B classification under Regulation (EC) No 854/2004 and therefore would require a post-harvest purification treatment before marketing for human consumption.

Table 9 Summary statistics of levels of *E. coli* in shellfish, January 2013–November 2015.

			E. coli (MPN/100 g)			Percentage of samples over			
Site	Species	n	GM	Minimum	Maximum	300 *E. coli*/100 g (SWPA standard)	230 *E. coli*/100 g (class A)	4,600 *E. coli*/100 g (class B)	46,000 *E. coli*/100 g (class C)
Simpool Head	Mussel	20	1,138	110	92,000	80.0	80.0	20.0	5.0
South Side	Pacific oyster	36	690	78	17,000	72.2	72.2	11.1	0.0

n - number of samples; GM - geometric mean; 230 *E. coli* - class A threshold; 4,600 *E. coli* - class B threshold; 46,000 *E. coli* - class C threshold.

The seasonality of *E. coli* results was investigated to understand if shellfish in Blakeney Harbour accumulate higher levels of contamination during certain seasons. In this assessment, the *E. coli* results were combined by season considering the following periods: spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). The results indicate that although geometric mean levels of *E. coli* in mussels are higher in the summer than in the winter, the 95% confidence intervals are within the range for class B. One-way analysis of variance tests did not provide evidence of significant differences in mean bacterial levels between seasons at both sites (Figure 7).

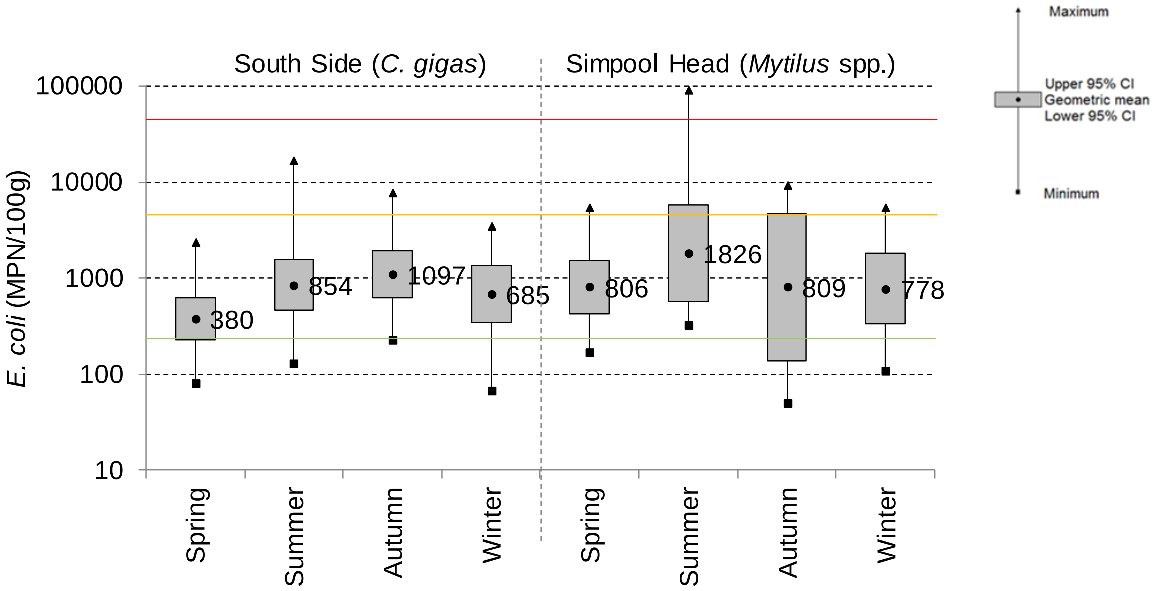


Figure 7 Box-and-whisker plots of seasonal variation of *E. coli* in shellfish at two sites in Blakeney Harbour, 2012–2016. Green line - class A threshold (230 *E. coli*/100 g); orange line - class B threshold (4,600 *E. coli*/100 g); red line - class C threshold (46,000 *E. coli*/100 g).

4.1.6 Relationships between E. coli in shellfish and river flows

Levels of *E. coli* in shellfish have been shown to increase several orders of magnitude during high flow conditions in the rivers (Campos et al. 2013). After cessation of stormflow conditions, bacterial concentrations in shellfish can remain high for more than 3 days (Campos et al. 2011). In general, the survival, mobilisation and transport of *E. coli* in rivers depends upon high connectivity between pollution sources and the rivers network and surface runoff - both of which are greater in less-permeable catchments. In contrast, slow soil seepage and groundwater flow will filter out *E. coli* and provide greater opportunities for bacterial die-off and predation, thereby reducing *E. coli* fluxes (Crowther et al. 2011). The geology of the Stiffkey catchment is mainly of chalk largely covered with Boulder Clay and therefore of high permeability (NRFA, 2017).

To investigate the effect of river flows on levels of contamination in bivalves, Pearson's correlation coefficient parametric test was carried out between daily total flows in the River Stiffkey at Warham gauging station and $\log_{10}$ transformed *E. coli* in shellfish at monitoring points in Blakeney Harbour. Concentrations of *E. coli* were compared with river flows occurring in discrete 24 h periods (days) up to 7 days prior to sampling and cumulative flows up to seven days prior to sampling. The correlation coefficients are shown in Table 10. No statistically significant correlations were found between flows in the River Stiffkey and *E. coli* levels in mussels and Pacific oysters at sampling points in Blakeney Harbour. This suggests that surface run-off is not associated with the transport of bacterial contamination in the catchment. The likely factors implicated would be local inputs from point sources and/or storage of bacteria in the rivers (Wilkinson et al. 1995).

Table 10 Results of Pearson correlation analysis between levels of *E. coli* in shellfish and flows in the River Stiffkey at Warham, January 2013–December 2015.

		B006S	B006U	B006T
	RMP name	Simpool Head	Simpool Pontoon	South Side
	Species	Mussels (*Mytilus* spp.)	Mussels (*Mytilus* spp.)	Pacific oysters (*M. gigas*)
	n	20	15	36
	Number of days			
24h periods prior to sampling	1	-0.230	-0.238	-0.195
	2	-0.222	-0.216	-0.176
	3	-0.243	-0.286	-0.112
	4	-0.253	-0.293	-0.097
	5	-0.248	-0.284	-0.048
	6	-0.294	-0.273	-0.018
	7	-0.403	-0.296	-0.114
Total prior to sampling over	2	-0.226	-0.227	-0.185
	3	-0.232	-0.247	-0.160
	4	-0.235	-0.259	-0.142
	5	-0.236	-0.265	-0.117
	6	-0.246	-0.267	-0.093
	7	-0.080	-0.212	0.059

Relationships that are significant at $p<0.05$ are in italics and bold.

4.3 Nutrients

4.3.1 Nutrients in freshwater and seawater

High inputs of nitrogen and phosphorus into the aquatic environment can cause excessive algal growth, which can reduce the aesthetic and recreational value of water and stress aquatic organisms, resulting from depleted dissolved-oxygen concentrations when algal blooms die. A total of 90 water samples were tested for nutrients during the field studies. Table 11 summarises the concentrations of total oxidised nitrogen (nitrate+nitrite), nitrite, phosphate, silicate and ammonium at riverine and marine sites. At riverine sites, mean concentrations of total oxidised Nitrogen ranged from 232.8 to 365 µmol/l. At marine sites, total oxidised nitrogen concentrations ranged from 5.3 to 151.4 µmol/l. The highest mean total oxidised nitrogen concentration was found in the River Stiffkey u/s STW (365 µmol/l). Mean total oxidised nitrogen concentrations at marine sites were relatively lower than at shoreline sites with the lowest concentration detected in the mouth of Morston Creek (5.3 µmol/l).

The highest mean concentration of nitrite was found in the River Glaven at Windmill (2.2 µmol/l). Marine (shoreline) stations had relatively higher nitrite concentrations than marine sites. However, there was little variation in concentrations between marine sites (Table 11).

At riverine sites, concentrations of phosphate in the River Stiffkey were lower than in the River Glaven. In the River Stiffkey, the mean phosphate concentration d/s STW was 3.8 µmol/l while u/s STW the mean concentration of this nutrient was 4.0 µmol/l. At marine sites, mean phosphate concentrations were 0.5 µmol/l at all stations (Table 11).

Concentrations of silicate at riverine sites ranged from 150 µmol/l in the River Glaven at Windmill to 157.9 µmol/l in the River Glaven at Glandford. At marine (shoreline) sites, mean silicate concentrations ranged from 58 µmol/l at Morston Creek at Visitor Centre to 133.8 µmol/l at Fresh Marshes. Much lower mean concentrations of silicate were found at marine sites with the lowest detected at Nature Reserve (3.1 µmol/l) and the highest (5.5 µmol/l) at the Mouth of Morston Creek (Table 11).

Mean concentrations of ammonium at riverine sites were lower than at marine sites. The highest mean concentration of ammonium was found at Blakeney Quay (9.4 µmol/l) and the lowest in the River Glaven at Glandford (1.2 µmol/l) (Table 11).

The Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015, stipulates ammonia standards in rivers which relate to total ammonia as nitrogen (mg/l) calculated as the 90th percentile. These standards are listed in the Appendix II. The river typology used for the Rivers Stiffkey and Glaven is “2 - lowland high alkalinity”. Table 12 summarises the compliance results for these rivers using the monitoring data obtained during the period November 2016–September 2017. The results indicate “high” status at the four riverine sites investigated and are consistent with the results obtained at 8 sites in this catchment regularly monitored by the Environment Agency (data for the period Jan 2013–Jan 2015).

Table 11 Summary of nutrient concentrations in water samples collected in the Rivers Stiffkey and Glaven and Blakeney Harbour.

Sampling station	ToxN (µmol/l)				NO_2 (µmol/l)				PO_4 (µmol/l)				SiO_4 (µmol/l)				NH_4 (µmol/l)			
	n	Min.	Max.	Mean	n	Min.	Max.	Mean	n	Min.	Max.	Mean	n	Min.	Max.	Mean	n	Min.	Max.	Mean
Riverine stations																				
River Stiffkey u/s STW	10	221.5	461.6	365.0	10	1.2	2.1	1.7	10	1.9	6.8	4.0	10	122.0	198.0	155.1	10	0.4	3.3	1.5
River Stiffkey d/s STW	10	208.0	473.0	349.0	10	0.8	2.6	1.5	10	2.0	4.9	3.8	10	108.0	195.0	150.3	10	0.4	3.0	1.5
River Glaven at Glandford	8	190.0	438.1	269.7	8	0.9	2.0	1.4	8	3.1	11.2	6.6	8	117.6	195.0	157.9	8	0.4	2.1	1.2
River Glaven at Windmill	10	19.8	393.8	232.8	10	0.9	4.0	2.2	10	1.4	8.4	6.4	10	55.0	202.2	150.0	10	1.1	11.3	4.7
Marine stations (shoreline)																				
Morston Creek (Visitor Centre)	15	0.6	771.1	151.4	15	0.06	3.5	1.3	15	0.1	2.2	1.2	15	3.0	160.1	58.0	15	0.1	20.2	8.3
Blakeney Quay	6	4.7	307.0	98.7	6	0.2	2.1	1.4	6	0.7	11.1	3.9	6	15.5	186.0	85.9	6	2.4	15.9	9.4
Fresh Marshes	8	102.9	348.4	31.1	8	0.8	2.1	1.5	8	2.2	5.4	3.6	8	46.5	185.3	133.8	8	0.9	11.1	4.3
Marine stations																				
Mouth of Morston Creek	5	0.1	27.7	5.3	5	0.01	0.6	0.2	5	0.2	0.8	0.5	5	1.40	11.4	5.5	5	0.5	7.5	3.0
Nature Reserve	5	0.9	27.4	9.2	6	0.01	0.7	0.3	6	0.02	1.5	0.5	5	0.4	7.0	3.1	6	0.5	9.5	3.9
Tiby Head	6	0.1	26.4	13.7	6	0.01	0.3	0.2	6	0.2	0.8	0.5	6	1.2	17.4	7.6	6	0.4	7.6	3.5
Stiffkey Freshes	7	0.1	31.2	11.9	7	0.01	0.6	0.2	7	0.1	0.9	0.5	7	1.0	16.6	5.4	7	0.4	7.8	2.9

ToxN-total oxidised Nitrogen (Nitrate+Nitrite); NO_2-Nitrite; PO_4-Phosphate; SiO_4-Silicate; NH_4-Ammonium; u/s-upstream; d/s-downstream; n-number of samples tested; Min.-minimum; Max.-maximum.

Table 12 Compliance of the rivers Stiffkey and Glaven with the Water Framework Directive standards for ammonia in rivers.

Sampling station	Ammonia (90th percentile) (mg/l N)	Class
River Stiffkey u/s STW	0.03	High
River Stiffkey d/s STW	0.04	High
River Glaven at Glandford	0.03	High
River Glaven at Windmill	0.15	High

For phosphate, the results obtained at the River Glaven u/s STW were also compared with the historical data provided by the Environment Agency for the same site (STF080). Here, the phosphate concentrations ranged from 0.019 to 0.069 mg/l P and are consistent with the “high status” classification given for this site by the Environment Agency (0.056 mg/l P).

Of the nutrients tested, nitrogen is of environmental concern, because when in excess it is responsible for eutrophication. Dissolved inorganic nitrogen (DIN), calculated as nitrate+nitrite+ammonium, is of particular interest because it is the most bioavailable form of nitrogen used by algae and, therefore, plays an important role in controlling the formation of algal blooms.

Figure 8 shows a reduction in the concentrations of DIN monitored by the Environment Agency at 6 marine sites in Blakeney Harbour as a function of the fluvial distance from Blakeney Quay. These sites (Blakeney Hotel; Watch House; Blakeney Pit; Simpool Head Buoy 9; Buoy 8; Buoy 3) were selected to represent an increasing gradient of dilution in the harbour. The coefficient of determination of the linear model indicates that distance from the quay accounts for ≈28% of the variation in DIN concentrations. The model provides good fit to the data (p=0.000). Large variability (≈1$\log_{10}$) in DIN concentrations is observed at Blakeney Quay. This variability reduces markedly at stations in the main harbour channel where DIN concentrations were mostly below 50 µmol/l).

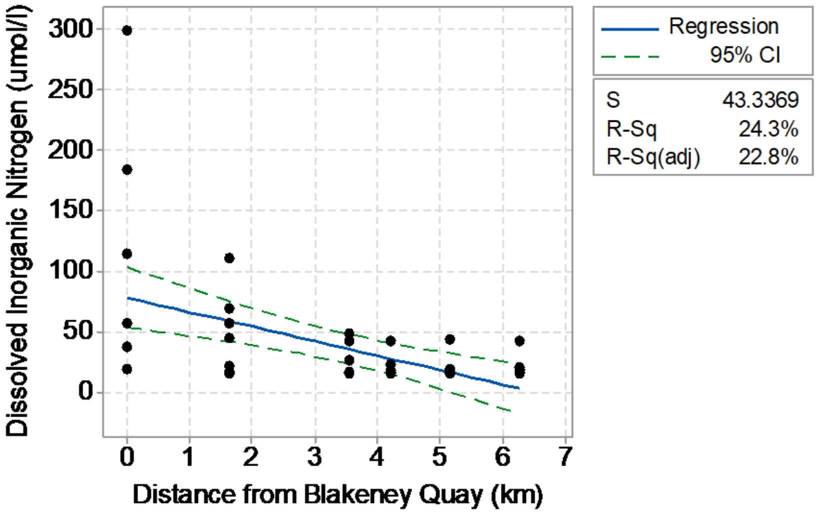


Figure 8 Linear relationship between concentrations of dissolved inorganic nitrogen at 6 sites and fluvial distance in Blakeney Harbour. Stations: 0 km - Blakeney Hotel; 1.63 km - Watch House; 3.56 km - Blakeney Pit; 4.22 km - Buoy 9; 5.15 km - Buoy 8; 6.27 km - Buoy 3. Regression equation: DIN=78.01-12.03*Distance. Nutrient concentrations were assumed to reduce with fluvial distance.

The Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015, sets out criteria for classifying turbidity levels in transitional waters according to the arithmetic mean concentration of DIN normalised at salinity of 25 for the period of 1 November–28 February (Defra and Natural Resources Wales, 2015). Figure 9 shows the relationship between DIN and salinity for water samples collected at marine sites in Blakeney Harbour in 2005–2006. The linear regression model explains 81% of the variability of DIN concentrations in surface waters and indicates a concentration of 90 µmol/l corresponding to 25 psu. These results are characteristic of waters with “good” environmental status and intermediate turbidity levels. It should be noted that winter nutrient concentrations are expected to vary according to surface water runoff volumes (Painting *et al*. 2005).

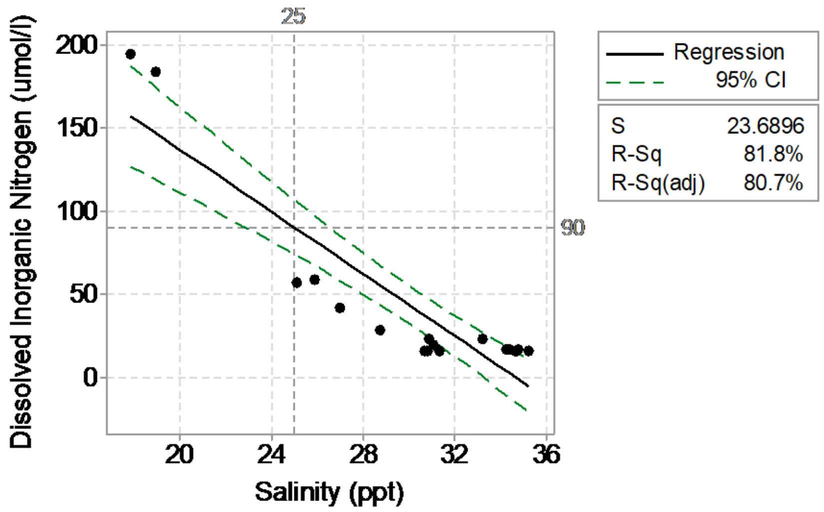


Figure 9 Relationship between dissolved inorganic nitrogen concentrations and salinity in Blakeney Harbour.

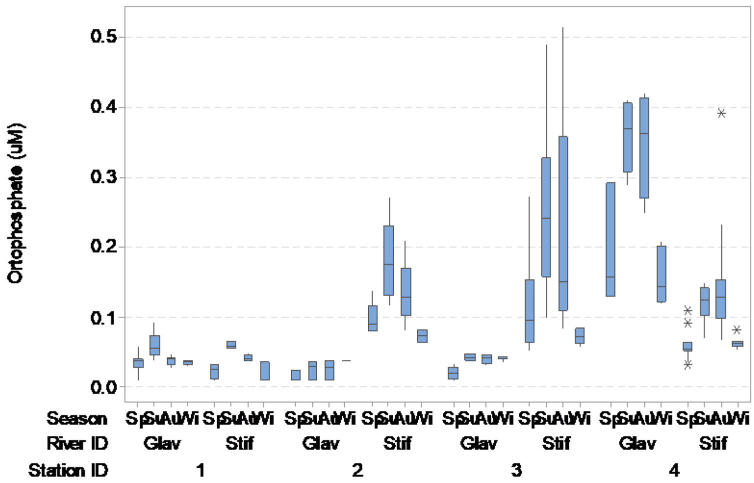
4.3.2 Seasonality of nutrients in freshwater

The seasonality of concentrations of nutrients was investigated to understand if the delivery of these water quality constituents is associated with climatic and/or human factors. In this assessment, the concentrations of orthophosphate, total oxidised nitrogen (nitrate+nitrite) and ammonia monitored at 8 sites in the Stiffkey and Glaven catchments were combined by season considering the following periods: spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). The results provide insight into the spatial variability of nutrient contamination and allow for comparisons between sites under similar environmental conditions. The highest concentrations of orthophosphate were found in the River Stiffkey at Binham Tributary, Stiffkey Bridge and Wighton Bridge; and in the River Glaven at Wiveton Bridge (Figure 10A). All of these sites had elevated orthophosphate concentrations in the summer-autumn period and lower concentrations in the winter-spring period. These results are consistent with results obtained in other catchments across England and Wales and indicate the significance of high winter rainfall and river flows diluting the total phosphorous load from the catchments (Bowman et al. 2012). The sites with lower orthophosphate concentrations were the River Glaven at Edgefield Bridge and Letherhingsett Mill, and in the River Stiffkey at Snoring Bridge.

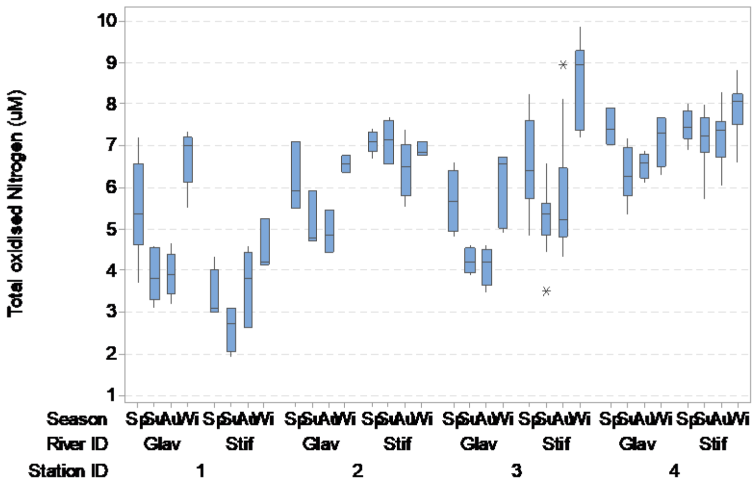
Higher concentrations of total oxidised nitrogen were found in the winter relative to those found in the summer in the River Stiffkey at Binham Tributary and Snoring Bridge, and in the River Glaven at Gunthorpe Stream and Letheringsett Mill (Figure 10B). No seasonality of total oxidised nitrogen was found in the River Stiffkey at Stiffkey Bridge and Wighton Bridge.

The distributions of concentrations of ammonia were very similar between seasons at most sites except in the River Glaven at Gunthorpe Stream, where summer concentrations were higher than the winter ones (Figure 10C). This could be associated with local inputs from sewage discharges.

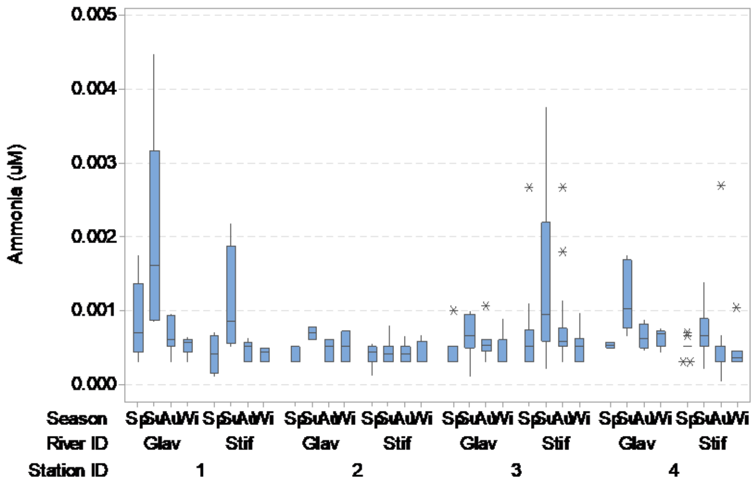
A


Ortophosphate (uM)
0.5
0.4
0.3
0.2
0.1
0.0
Season
River ID
Station ID
Glav
Stif
1
2
3
4

B


Total oxidised Nitrogen (uM)
10
9
8
7
6
5
4
3
2
1
Season
River ID
Station ID
Glav
Stif
1
2
3
4

C



◄ Upstream Downstream ►

Figure 10 Boxplots of seasonal concentrations of orthophosphate, total oxidised nitrogen and ammonia at 8 sites in the Rivers Stiffkey and Glaven. Sp-spring; Su-summer; Au-autumn; Wi-winter; Glav-Glaven; Stif-Stiffkey; Glav 1-Gunthorpe Stream (13.6 km); Glav2-Edgefield Bridge (14.7 km); Glav3-Letheringsett Mill (8.4 km); Glav4-Wiveton Bridge (3.7 km); Stif1-Great Snoring (23.4 km); Stif2-Wighton Bridge (11.2 km); Stif3-Binham Tributary (7.1 km); Stif4-Stiffkey Village (3.4 km).

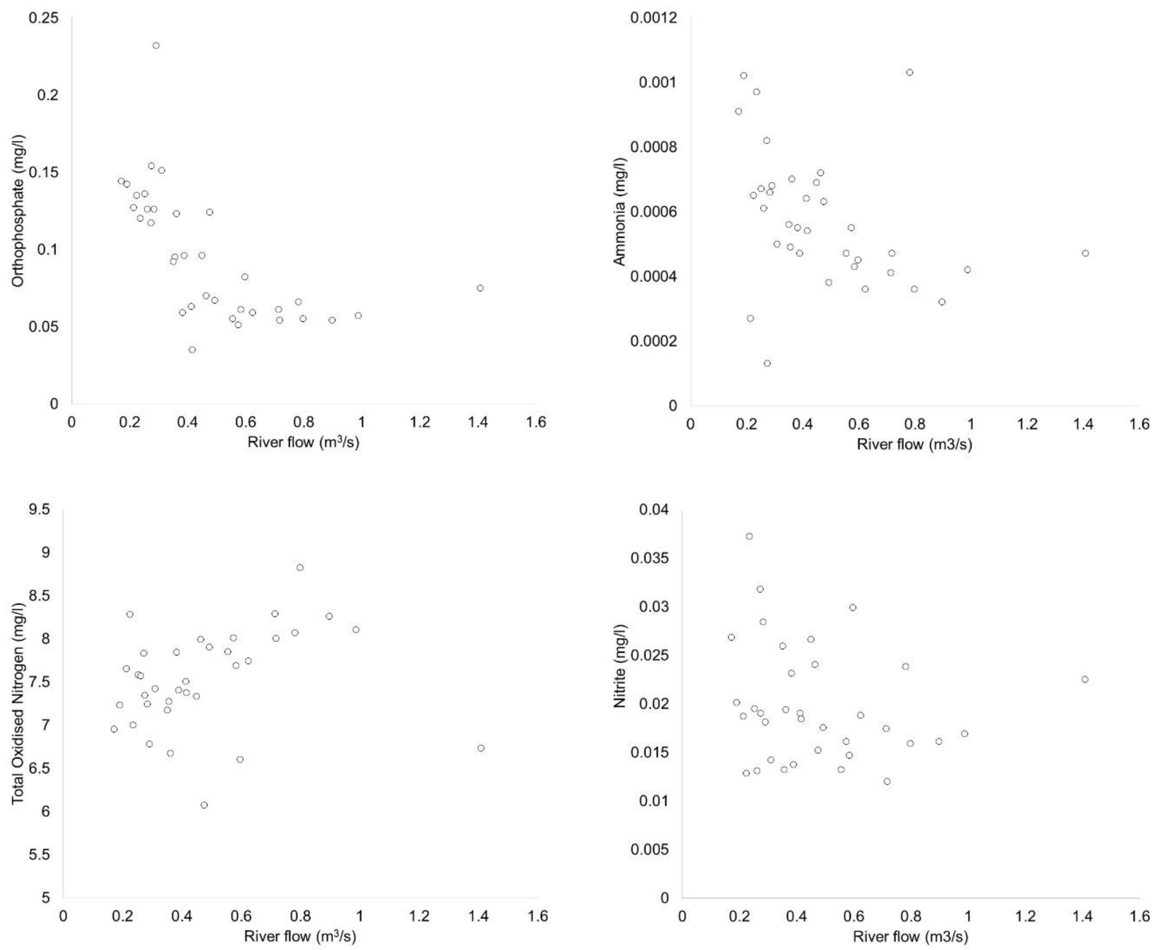
How do these concentrations of Ammonia relate to toxicity?

In one study conducted in the US, concentrations of un-ionidised ammonia (NH_3) ranging from 0.53 to 22.8 mg/l were shown to be acutely toxic to 19 freshwater invertebrates, while acute toxicity among 29 fish species ranged from 0.083 to 4.60 mg/l (USEPA, 1986). The tested fish include species of the genus Salmonidae. In the same study, chronic toxicity tests on two freshwater invertebrates (daphnids) showed effects at concentrations ranging from 0.340 to 1.2 mg/l. The ammonia concentrations monitored by the Environment Agency at 8 sites in the rivers Stiffkey and Glaven during the period 2012–2017 ranged from 0.00003 and 0.0087 mg/l and are therefore well below the toxic concentrations reported in the study.

4.3.3 Relationships between nutrients and river flows

Deterioration of water quality during high river flows can suggest runoff from fields or farm yards, sewer overflow discharges while deterioration during lower flows can suggest a constant background source such as landfills, surface water sewer misconnections or septic tanks. The relationships between concentrations of nutrients (orthophosphate, ammonia, total oxidised nitrogen, nitrite, nitrate) and flows in the River Stiffkey at Warham were investigated using the WFD compliance monitoring data for the period January 2013–December 2015 provided by the Environment Agency and measured river flow data available from the National River Flows Archive (2017).

In general, concentrations of orthophosphate and ammonia decreased with flows while concentrations of total oxidised nitrogen and nitrate increased with increasing flows (Figure 11). However, no evidence was found of statistically significant relationships between the variables, except for orthophosphate (p=0.000). This indicates that river flows are an important factor determining the dilution of orthophosphate in this part of the catchment. However, river flows explained only 36% of the variability of orthophosphate concentrations. Although inorganic phosphorous is used as fertiliser, it is probably strongly adsorbed to soils, rather than leached to watercourses (Neal et al. 1998). Higher concentrations of nitrogen at higher river flows could be associated with downstream sources of contamination (for example, sewage discharges) and/or mobilisation and entrainment of sediments in the rivers during high-flow conditions. The high degree of data scatter in the nitrogen-flow relationships may reflect temporal variations in the availability of particulate nitrogen for entrainment and delivery to the river and particulate euhaustion effects during storm events (Walling and Webb, 1982).



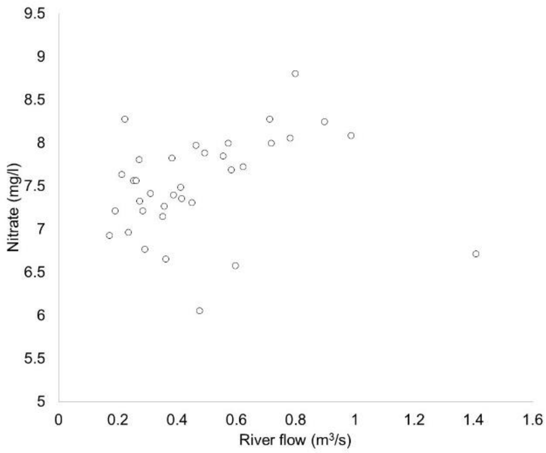


Figure 11 Scatterplots of concentrations of nutrients in freswater at Stiffkey u/s Stiffkey STW and flows in the River Stiffkey at Warham, January 2013–December 2015.

The distribution of the ratio of nitrate:ortophosphate was examined in more detail for the River Stiffkey. The seasonal differences in the relationship between this ratio and river flows were examined with samples assigned to one of two groups: growing season (April–September), when algal and other plant activity is highest, or dormant season (October–March). During the growing season, the variation in ratios was relatively larger than during the dormant season. The maximum ratio obtained for the growing season was 210, while the maximum ratio for the dormant season was 160. During the growing season, there was a stronger association with river flows (R^2=52%) than during the dormant season (R^2=24%). This is probably associated with greater mobilisation of nutrients in the growing season and probably the fact that the flow regime in the river is relatively stable during the year (groundwater-influenced regime).

4.3.4 Relationships between nutrients and physico-chemical parameters

Pearson correlation tests were carried out to investigate the associations between concentrations of nutrients and physico-chemical parameters in water samples collected at marine sites. The results summarised in Table 13 suggest the following correlations:

- Total oxidised nitrogen was strongly correlated with nitrite and phosphate; very strongly correlated with silicate; weakly correlated with chlorophyll; moderately correlated with phaeopigments; and strongly correlated with turbidity.
- Nitrite was strongly correlated with phosphate, silicate and turbidity; and moderately correlated with ammonium, chlorophyll and phaeopigments.
- Phosphate was very strongly correlated with silicate; weakly correlated with chlorophyll; moderately correlated with phaeopigments; and strongly correlated (negative correlation) with temperature.

- Silicate was weakly correlated with chlorophyll; moderately correlated with phaeopigments; strongly correlated (negative correlation) with oxygen; and very strongly correlated (negative correlation) with temperature.
- Ammonium was moderately correlated with chlorophyll and phaeopigments; and strongly correlated (negative correlation) with salinity.
- Suspended particulate matter was weakly correlated with phaeopigments and very strongly correlated with turbidity.
- Chlorophyll was strongly correlated with phaeopigments and turbidity; very strongly correlated with fluorescence; and strongly correlated (negative correlation) with salinity.
- Phaeopigments were very strongly correlated with turbidity and strongly correlated (negative correlation) with photosynthethically active radiation.
- Fluorescence was moderately correlated with turbidity and strongly correlated (negative correlation) with salinity.
- Turbidity was moderately correlated (negative correlation) with photosynthethically active radiation and temperature.
- Oxygen was strongly correlated with temperature.

A scatterplot of the relationship between nitrite and phosphate is shown in Figure 12 below. The concentrations of these nutrients at marine stations were very low and therefore the ratios are mostly within the lower ranges of the scatterplot. At the marine (shoreline) stations, the gap between the concentrations of these two nutrients widens indicating dilution of inputs from land-based sources. The higher concentrations of nitrite detected at low concentrations of phosphate could indicate the convertion of ammonia from sewage-related sources to nitrite in the estuarine waters.

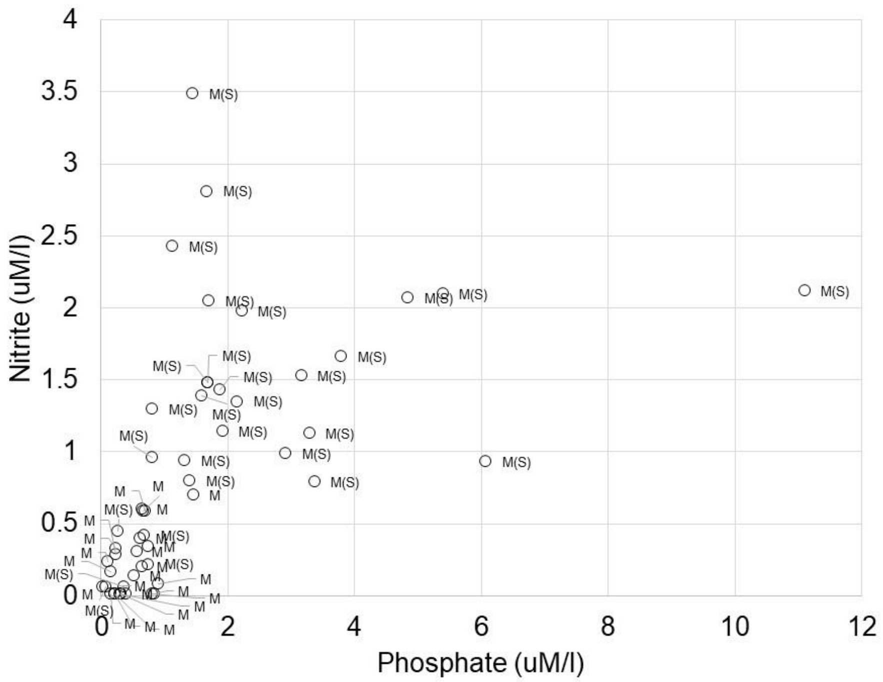


Figure 12 Scatterplot of concentrations of nitrite and phosphate in water samples collected at marine sites in Blakeney Harbour.

The WFD assessments for transitional waters include chlorophyll thresholds set against salinity normalised nutrients and comparing these with the nutrient risk assessments. For the chlorophyll multimetric, the assessment can be made for one or two salinity zones. If only one zone is assessed, the reference value is 5 µg/l while for two salinity zones the reference score is 10 µg/l (Devlin et al. 2009). Figure 13 presents the distributions of concentrations of chlorophyll measured during the period 2005–2007 grouped by two salinity zones in Blakeney Harbour: inner zone (salinity ≤25 ppt) and outer zone (salinity>25 ppt). The median concentrations obtained for both zones was similar (4 µg/l) and below the thresholds corresponding to inner and outer salinity zones used in WFD assessments. However, the outer zone shows a tendency for higher levels of chlorophyll as indicated by the larger data distribution in the third quartile (75% of the data are less than or equal to 15 µg/l). The median concentration of chlorophyll obtained in the field studies was also low (2 µg/l) and below the WFD thresholds.

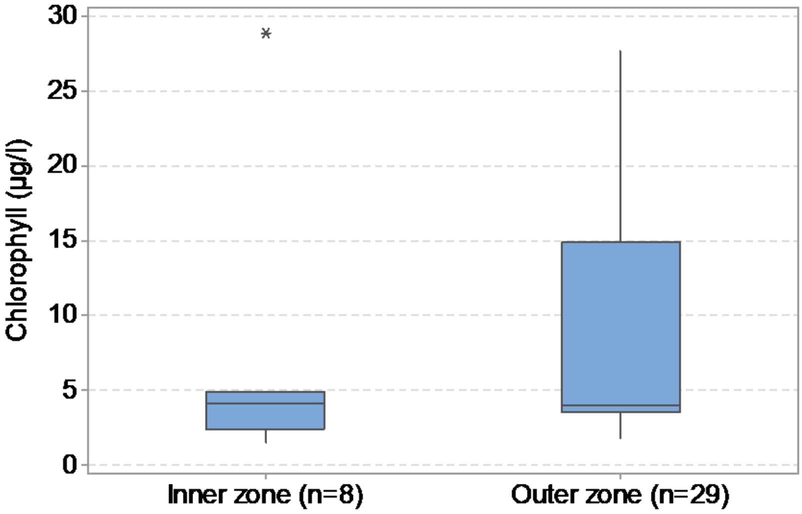


Figure 13 Distributions of chlorophyll data by two salinity zones in Blakeney Harbour, 2005–2007. Inner zone: salinity ≤25 ppt; outer zone: salinity>25 ppt.

Table 13 Results of Pearson correlation tests between concentrations of nutrients and physico-chemical parameters.

	TOxN	NO_2	PO_4	SiO_4	NH_4	SPM	Chl	Phae	Fluor	Turb	O_2	PAR	Sal	Temp
TOxN														
NO_2	**0.666 (0.000)													
PO_4	**0.735 (0.000)	**0.668 (0.000)												
SiO_4	**0.858 (0.000)	**0.646 (0.000)	**0.828 (0.000)											
NH_4	0.040 (0.779)	**0.545 (0.000)	0.183 (0.189)	0.151 (0.285)										
SPM	0.255 (0.068)	0.176 (0.209)	0.228 (0.101)	0.219 (0.119)	0.005 (0.972)									
Chl	*0.339 (0.014)	**0.575 (0.000)	*0.336 (0.014)	*0.321 (0.020)	*0.410 (0.002)	0.260 (0.060)								
Phae	*0.456 (0.001)	**0.525 (0.000)	*0.447 (0.001)	*0.437 (0.001)	*0.450 (0.001)	*0.386 (0.004)	**0.704 (0.000)							
Fluor	0.180 (0.521)	0.337 (0.201)	-0.352 (0.182)	-0.079 (0.780)	0.204 (0.449)	0.444 (0.085)	**0.886 (0.000)	0.460 (0.073)						
Turb	*0.775 (0.001)	*0.653 (0.008)	0.205 (0.465)	0.470 (0.090)	0.143 (0.611)	**0.818 (0.000)	*0.707 (0.003)	**0.853 (0.000)	*0.515 (0.049)					
O_2	-0.407 (0.317)	-0.234 (0.545)	-0.355 (0.348)	*-0.776 (0.024)	0.350 (0.356)	-0.068 (0.862)	-0.524 (0.147)	-0.460 (0.213)	-0.403 (0.282)	-0.567 (0.111)				
PAR	-0.468 (0.147)	-0.382 (0.221)	0.062 (0.848)	-0.109 (0.751)	-0.154 (0.633)	-0.563 (0.056)	-0.437 (0.156)	*-0.615 (0.033)	0.219 (0.493)	*-0.593 (0.042)	-0.090 (0.818)			
Sal	-0.073 (0.760)	-0.428 (0.053)	0.159 (0.492)	0.184 (0.438)	*-0.639 (0.002)	-0.358 (0.111)	*-0.674 (0.001)	-0.283 (0.215)	*-0.605 (0.013)	-0.410 (0.129)	-0.182 (0.639)	0.084 (0.796)		
Temp	-0.759 (0.972)	-0.259 (0.352)	*-0.664 (0.007)	**-0.848 (0.000)	0.254 (0.361)	-0.349 (0.202)	0.087 (0.758)	-0.277 (0.318)	0.227 (0.416)	*-0.554 (0.032)	*0.680 (0.044)	0.144 (0.655)	-0.082 (0.771)	

Pearson correlation coefficients (*r*) and level of significance in parenthesis are shown. * Statistically significant correlations at the 95% confidence level (*p*<0.050). ** Statistically significant correlations at the 99% confidence level (p<0.001). ToxN-total oxidised Nitrogen (Nitrate+Nitrite); NO_2-Nitrite; PO_4-Phosphate; SiO_4-Silicate; NH_4-Ammonium; SPM-suspended particulate matter; Chl-chlorophyll; Phae-phaeopigments; Fluor-fluorescence; Turb-turbidity; O_2-oxygen; PAR-photosyntetically active radiation; Sal-salinity; Temp-temperature.

Table 14 Summary statistics of chlorophyll (µg/l) in Blakeney Harbour.

Mean	4
Median	2
Percentage of samples <10 µg/l	81
Percentage of samples <20 µg/l	100

4.4 Phytoplankton

Phytoplankton of coastal and transitional waters are monitored routinely in the UK as an indicator of ecological and eutrophication status, as required by the Urban Waste Water Directive, the Oslo Paris Convention, and the WFD. The abundance and composition of the phytoplankton is one of the key tools in defining Ecological Quality Status for the WFD, particularly in relation to the impact on the ecology of coastal and transitional waters by anthropogenic inputs of nutrient (mainly inorganic nitrogen) (Devlin et al. 2014). The assessments relating to phytoplankton are required to encompass taxonomic composition, abundance, biomass and plankton blooms for the ecological classification of transitional and coastal waters. The primary biological response to nutrient enrichment in aquatic environments, given suitable environmental conditions (such as light availability and water temperatures), is the growth of phytoplankton and higher plants (Devlin et al. 2014).

In the field studies, a total of 24 were samples were collected at four sites (Nature Reserve, Mouth of Morston Creek, Pits Point, Stiffkey Freshes) in Blakeney Harbour for quantification of the abundance and composition of phytoplankton taxa. The five most abundant groups were *Phaeocystis* spp., microflagellates, *Chaetoceros* spp., cyanobacteria and *Pseudo-nitzschia* spp. Species of *Alexandrium* and *Dinophysis* were not recorded in any of the samples. *Karenia mikimotoi* was found in two samples at low concentrations (100 cells/l). The highest concentration of *Pseudo-nitzschia* spp. was 140,910 cells/l detected at the Mouth of Morston Creek on 08/06/2017. However, this concentration does not exceed the trigger level set at 150,000 cells/l.

Taxa identified at species level formed a relatively small community of less than 28 species (Table 15). At Nature Reserve and Mouth of Morston Creek sites, the largest species diversity was observed in the spring-summer period while at Pits Point and Stiffkey Freshes the largest diversity was found in the autumn-winter period.

Table 15 Summary of phytoplankton species observed at four sites in Blakeney Harbour.

Sampling site	Number of observed taxa (all data)	Number of species		
		Total	Spring-Summer	Autumn-Winter
Nature Reserve	71	28	24	23
Mouth of Morston Creek	54	21	18	14
Pits Point	71	25	16	23
Stiffkey Freshes	64	28	19	24

Analysis of historical phytoplankton monitoring data suggests that the use of commonly occurring species for ecological assessment of marine waters is potentially a valuable and easily communicated tool and that there are some common species within all the marine waters, and that it may be possible to have one or very few generic lists of species that should occur at a particular time of the year (Devlin et al. 2009). Table 16 shows the 20 most common species found in Blakeney Harbour. Of these, 13 are common in other parts of the coast of England and Wales (Devlin et al. 2009). All of the species listed are typical of marine habitats (Guiry and Guiry, 2017). It should be noted that very large datasets are needed to describe the phytoplankton community of a particular geographical area with confidence and that this assessment, whilst a useful comparison with reference conditions, must not be considered significant.

Table 16 List of the twenty species with the highest average counts at four sites in Blakeney Harbour.

Number	Species	Habitat
1	*Asterionellopsis glacialis*	Marine
2	*Dactyliosolen fragilissimus*	Marine
3	*Guinardia delicatula* (+)	Marine
4	*Leptocylindrus* cf. *minimus* (+)	Marine (harmful species)
5	*Guinardia striata* (+)	Marine
6	*Thalassionema nitzschioides* (+)	Marine
7	*Paralia sulcata* (+)	Marine
8	*Nitzschia closterium* (+)	Marine

9	*Rhizosolenia setigera* (+)	Marine
10	*Leptocylindrus danicus* (+)	Marine
11	*Lauderia annulata* (+)	Marine
12	*Guinardia flaccida* (+)	Marine
13	*Rhizosolenia imbricate* (+)	Marine
14	*Helicotheca tamesis*	Marine
15	*Prorocentrum micans* (+)	Marine. Species capable of forming blooms, but it is usually considered harmless. Incidents involving shellfish mortality have been associated with this species
16	*Rhizosolenia styliformis*	Marine
17	*Ceratium minutum*	Marine
18	*Dictyocha speculum* (+)	Marine
19	*Mesodinium rubrum*	Marine
20	*Rhizosolenia hebetata*	Marine

(+) Listed in the top 20 most common species in the UK, based on data from a single reference site (Devlin et al. 2009).

The temporal variation of *Pseudo-nitzschia* spp. was assessed in relation to the variation of nutrient ratios to understand if there was a relationship between anthropogenic nutrient enrichment and HABs. This taxonomic group was selected because it contains species capable of producing the neurotoxin domoic acid, which is responsible for the neurological disorder known as amnesic shellfish poisoning. Historically, blooms of *Pseudo-nitzschia* spp. have been recorded on the coast of North Norfolk as exemplified by the bloom recorded by satellite imagery on 26 June 2013 (Figure 14). This bloom had a cell count at the shellfish representative monitoring point in Blakeney Harbour of 3,013,000 cells/l and caused ASP toxicity above the regulatory limits in mussels farmed at Pits Point.

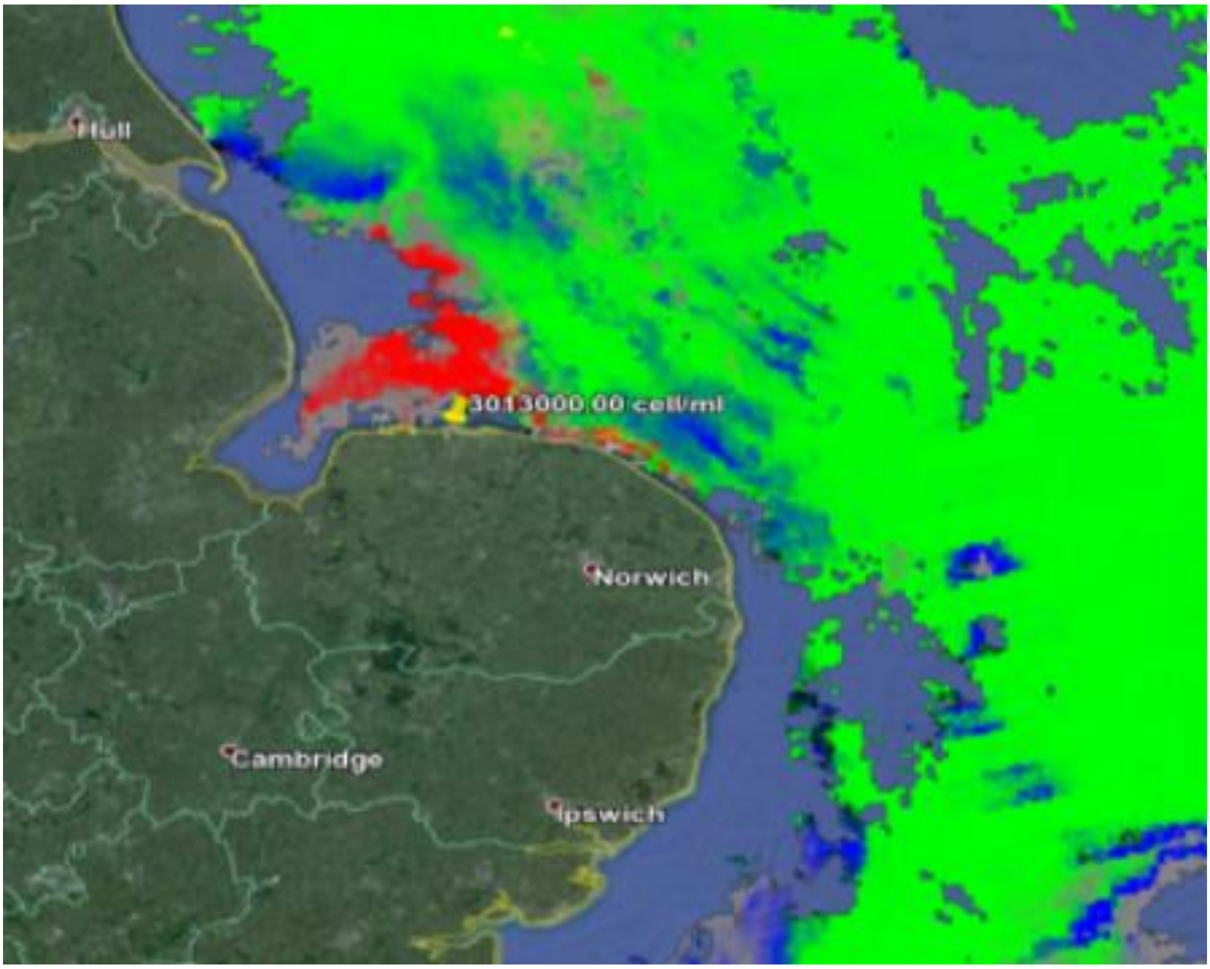


Figure 14 Satellite image showing a bloom of *Pseudo-nitzschia* spp. off the North Norfolk coast on 26 June 2013. Image provided by Dr. Andrey Kurekin, Plymouth Marine Laboratory.

The results indicate that elevated concentrations of these diatoms do not always coincide with elevated nutrient ratios suggesting no evidence of an association between the abundance of *Pseudo-nitzschia* and nutrient levels in Blakeney Harbour (Figure 15).

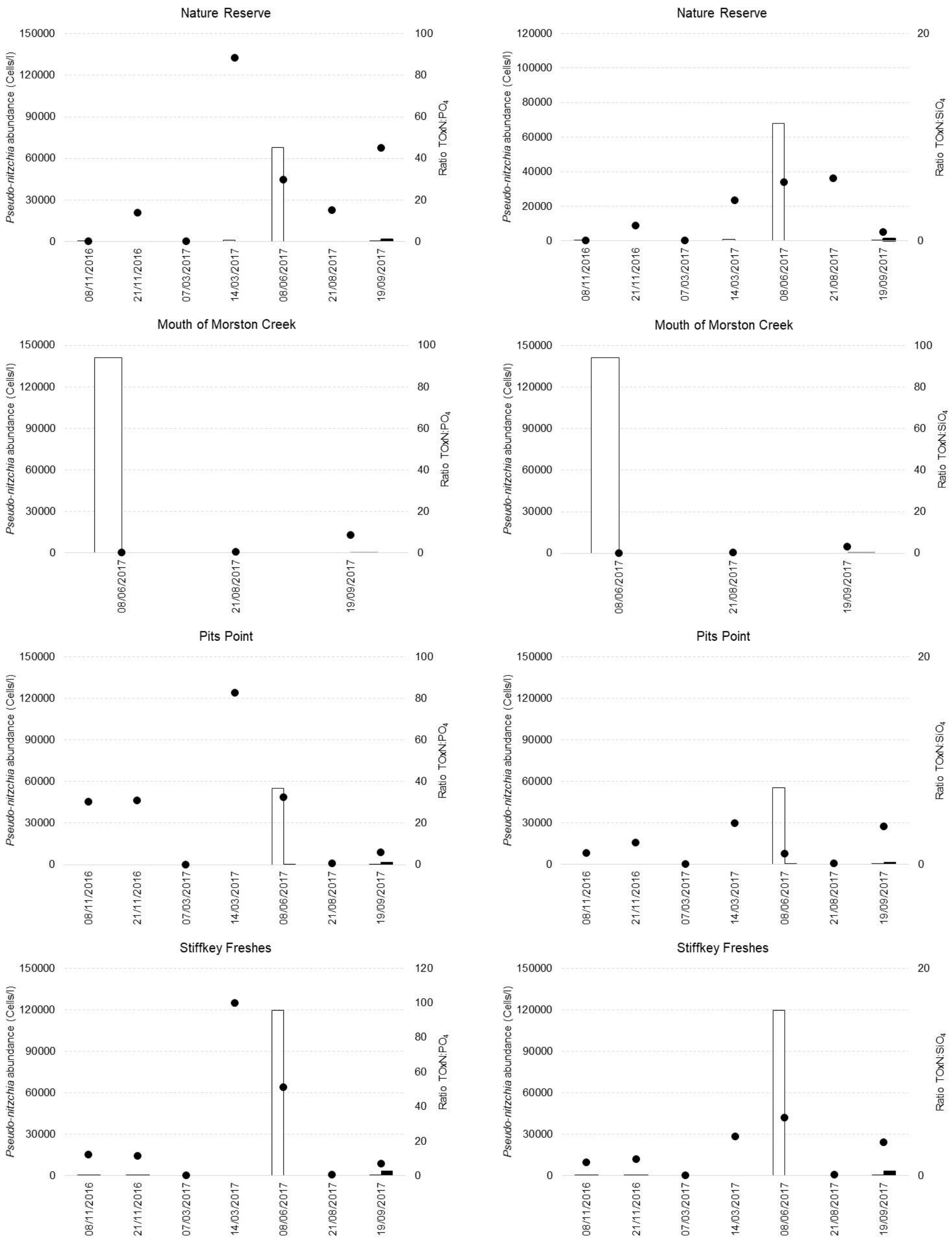


Figure 15 Abundance of *Pseudo-nitzschia* spp. and nutrient ratios at four sites in Blakeney Harbour.
White bars - cells ≤ 4.9 µm; black bars - cells ≥ 5 µm.

The classification status of the Stiffkey and Glaven transitional waters on phytoplankton was downgraded from “poor” in the 2014 cycle 1 evaluation to “bad” in the 2014 cycle 2 evaluation (Figure 16). Analysis of phytoplankton data (24 samples) obtained at four sampling sites indicated that, during the monitoring period, the single cell counts ranged from 40 to 495,930 and the total taxa counts ranged from 40 to 3,601,000 (Table 17). The the top 10 species are listed in Table 16 above. The sample collected at Morston Creek on 08/06/2017 exceeded the 10^6 cells/l threshold for microflagellates and Phaeocystis. As per thresholds set for WFD (which use longer-term monitoring results), the data collected suggests that the cell counts obtained would be consistent with “high” classification.

Table 17 Summary of single and total taxa counts obtained at four sites in the Stiffkey and Glaven transitional waters.

		Nature Reserve	Mouth of Morston Creek	Pits Point	Stiffkey Freshes
Single taxa count	Minimum	40	100	40	40
	Maximum	296,840	495,930	113,125	396,390
Total taxa count	Minimum	40	100	40	40
	Maximum	1,156,000	3,601,000	25,190	1,370,170

Water body classification

Select year: 2014 Cycle 1 Select year: 2016 Cycle 2

	2014 Cycle 1	2016 Cycle 2	Objectives
Overall Water Body	Poor	Bad	Good by 2027
Ecological	Poor	Bad	Good by 2027
Biological quality elements	Poor	Bad	Good by 2027
Angiosperms	-	Good	Good by 2015
Invertebrates	-	Moderate	Good by 2027
Macroalgae	Good	High	Good by 2015
Phytoplankton	Poor	Bad	Good by 2027

Figure 16 Classification status of Stiffkey and Glaven transitional waters for biological quality elements under the Water Framework Directive.

5. Discussion

Cefas and Norfolk Rivers Trust conducted a collaborative study to evaluate water quality in the catchments of the Rivers Glaven and Stiffkey and in Blakeney Harbour, an environmentally sensitive area that supports economically important fisheries and tourism activities. This study comprised field surveys carried out during the period November 2016–September 2017 to obtain new data on levels of faecal indicator bacteria (*E. coli*), nutrients and other water quality constituents (suspended particulate matter, chlorophyll, phaeopigments, temperature, salinity, fluorescence, turbidity, oxygen, photosyntetically active radiation) and characterisation of phytoplankton communities, and re-analyses of historical monitoring data for the same water quality constituents collected as part of the WFD and shellfish hygiene monitoring programmes. The results provide insight into the variability of water quality in the rivers, identify areas of the catchments that may be of particular water quality concern, and add information concerning contributions from point and non-point sources of contamination to the total loadings impacting the waters in Blakeney Harbour.

5.1 Faecal indicator bacteria

Faecal indicator bacteria can originate from different animal sources in rural catchments, including agricultural livestock, wildlife and humans. In the UK, improved grassland and associated livestock are the key sources of *E. coli* during high river flow conditions. During base flow conditions, when there is little or no runoff from agricultural land, urban (i.e. sewerage-related) sources contribute larger concentrations of *E. coli* (Kay et al. 2010). High concentrations of faecal indicator bacteria indicate that exposure to pathogenic (disease-causing) microorganisms can occur during swimming or other water-based activities through ingestion, inhalation or direct contact with contaminated water. Consumption of raw or lightly cooked shellfish contaminated with *E. coli* may also pose a human health risk.

In 2007, ADAS, CREH and IGER published results of a source apportionment modelling study which quantified the percentage of faecal coliform loadings from rural and urban sources of pollution during low flow and high flow conditions for a selection of catchments in England. The source apportionment estimates were produced for the bathing season (May–September) only. The hypothesis of this assessment was that the major driver of coliform loadings to rivers would be the overall livestock density (particularly dairy cows because these animals graze outside during the summer months and the large quantity of manure produced and the number of potential routes by which faecal bacteria may enter watercourses via runoff from grazed fields), excreta voided into streams or uncontained runoff from hardstandings. In the Stiffkey and Glaven catchments, contributions of microbiological contamination from beef or pig farms were expected to be higher than those from sheep or dairy farms[4]. The model predicted that 63% of the faecal coliform loading to Blakeney Harbour is delivered during high river flows (Appendix IV). The remaining 37% of the loading is delivered during low flows. During these flow conditions, the predicted mean

[4] The total livestock density assumed for this catchment is one of the lowest among the selected catchments because 79% of its surface area is arable land and only 12% is grassland.

concentrations of faecal coliforms from urban sources were ≈15,000 cfu/100 ml while the concentrations from rural sources were ≈5,000 cfu/100 ml. The model also predicted that urban sources contribute the majority (77%) of the total coliform loading delivered, irrespective of the flow conditions. Rural sources were predicted to contribute only 23% of the loading.

The present study estimated faecal coliform loadings from the main sewage-related sources in the Stiffkey and Glaven catchments for "average conditions" using generic data on concentrations of coliforms in final effluents and consented dry weather flows. The results indicate higher bacterial loadings in the upper reaches of the rivers (just downstream of the STW which discharge secondary-treated sewage) than in the lower reaches of the rivers. In particular, in the Stiffkey catchment, the estimated average coliform loadings from Great Walsingham STW were 2 $\log_{10}$ higher than the loadings from Stiffkey STW. In the Glaven catchment, the estimated coliform loadings from Holt STW were 3 $\log_{10}$ higher than loadings from Cley next the Sea STW. A review of the microbiological monitoring carried out by Anglian Water on the efficacy of the UV treatment system operating at this plant indicates that the UV disinfection has been consistently effective with concentrations in the final effluent consistent with those found in other UV treatment systems across the UK (Kay et al. 2008). Bacterial loadings were also estimated for sewer overflows. However, according to information provided by the water company these sources are unlikely to significantly impact water quality in Blakeney Harbour.

Once discharged to the rivers, coliform bacteria are subject to environmental decay which is determined by many factors, including light, turbidity, temperature, pH, competition and predation by other microbes and nutrients. It was felt appropriate to quantify bacterial loadings in the mouths of the rivers Stiffkey and Glaven to contextualise the STW loading estimates. These estimates are based on the monitoring data obtained in the field surveys (November 2016–September 2017). The results indicate that, on average, the River Stiffkey contributes bacterial loadings that are 1 $\log_{10}$ higher than the loadings from the River Glaven. In the River Stiffkey, no difference was found in mean *E. coli* loadings between sites while in the River Glaven, the mean *E. coli* loadings in the upper catchment were 1 $\log_{10}$ higher than the loadings at the river mouth. Together, these results suggest lower levels of bacterial die off in the River Stiffkey and that the faecal inputs from this river are likely to be primarily from sewage-related sources while the relatively lower inputs from the River Glaven are likely to be from a combination of sewage-related and diffuse sources. This conclusion is supported by results of previous studies carried out by the University of Essex which also found higher levels of *E. coli* in the River Stiffkey (Ball and Smith, 2008). Locally significant sources of this contamination would be septic tank discharges in the Stiffkey catchment, as suggested by the Environment Agency Shellfish Water Action Plan (Environment Agency, 2015).

Concerning levels of bacterial contamination in the harbour, a qualitative assessment carried out by the Environment Agency (2015) concluded that *E. coli* inputs from wildlife are of high significance relative to bacterial loadings from agricultural land and sewage discharges. In the present study, *E. coli* loadings from bird and seal populations around Blakeney Point were estimated using generic data on low tide counts, bacterial concentrations and excretion rates published the literature. For both groups of animals, it was assumed that 25% of the faecal matter impacts the tidal waters at the nearest WFD compliance point. At Blakeney Point, the average daily *E. coli* loadings from birds were 3.5×10^{11} cfu/day while at Blakeney

Freshes the average loadings were 1.9 x 10^{10} cfu/day. These loadings are similar to those quantified in freshwater discharges from the rivers Stiffkey and Glaven. The source apportionment estimates for seals indicate total average loadings of 4.6 x 10^{13} cfu/day from common seals and 1.2 x 10^{14} cfu/day from grey seals. These results indicate that the *E. coli* loadings from seals are 2–3 $\log_{10}$ higher than the loadings from catchment sources.

In the main channel of the harbour, mean concentrations of *E. coli* in the water decreased as distance from the shoreline at Blakeney increased. At sampling sites in the harbour entrance, mean *E. coli* concentrations were below the equivalent standard in shellfish flesh of the Shellfish Water Protected Areas (England and Wales) Directions 2016. Bacterial decay in this area would be associated with physical (sedimentation, dilution, exposure to ultraviolet radiation) and biological (for example, zooplankton grazing) factors. High percentage of shellfish samples were found to contain *E. coli* levels that exceed the class A standard. However, this is common in England where the largest proportion of shellfish production areas are class B (Food Standards Agency, 2017). The results of correlation analyses indicate that although concentrations of *E. coli* in the rivers are likely to increase significantly during wet-weather, the bacterial concentrations in shellfish are not associated with river flows. This indicates that surface run-off is not significantly associated with the levels of *E. coli* accumulated by the shellfish. Other factors likely to influence the levels of accumulation and clearance of FIB by the shellfish and thus compliance with regulatory standards are the physiological status of the animals, the location of the monitoring points and/or the sampling regime.

The intertidal mussel stocks in Blakeney Harbour have traditionally provided a valuable resource for the local fishing industry and also provide an essential food resource for the internationally important communities of birds that reside locally. In recent years, mussel stocks have been suffering high mortalities and mussel beds in Simpool Head were declassified at the last review (Food Standards Agency, 2017). Members of the industry have raised concerns about the state of the mussels and suggested that poor settlement of mussel spat could be associated with changes in sediment types (Eastern Daily Press, 2014). Although it is outside the scope of this project to investigate the causes of mussel mortalities, the monitoring data analysed in this study suggests that water quality is unlikely to be a significant factor in inhibiting mussel settlement on intertidal areas in Blakeney Harbour. Future studies on the recruitment ecology of mussel spat could provide additional evidence that can be used to underpin the management of a sustainable fishery in Blakeney Harbour.

5.2 Nutrients

The Rivers Stiffkey and Glaven are listed in the RBMP as being at risk of excessive nitrogen and phosphorous concentrations (Defra and Environment Agency, 2016). High concentrations of these nutrients are considered the main cause of eutrophication in freshwater, estuarine and coastal waters. Eutrophication is the enrichment of waters by nutrients causing excess plant/algal growth and leading to undesirable effects on the ecology, quality and uses of the water. Eutrophication adversely impacts on a range of water uses, including drinking water abstraction and treatment, water contact sports, angling, wildlife and conservation interest, livestock watering, general amenity and tourism (Environment Agency, 2015a). In standing fresh waters, blue-green algal blooms can occur; many such blooms are toxic and pose a hazard to humans involved in water sports and to animals that drink the water. Major sources of these nutrients include point discharges such as sewage discharges in and around the main urban settlements in the catchments (Stapleton et al. 2000; Rothwell et al. 2010). Non-point discharges include agricultural activities such as the application of synthetic fertilizers and the pasturing and feeding of livestock (Rothwell et al. 2010). Because of the predominant agricultural use of the Stiffkey and Glaven catchments (approximately 80% is arable land), non-point sources were assumed to contribute higher levels of nutrients than point sources.

The field surveys carried out in this project provided additional data (n=90) on levels of total oxidised nitrogen, nitrite, phosphate, silicate and ammonium across a freshwater and to seawater gradient and complement the existing WFD monitoring and outcomes. Overall, the concentrations of these nutrients detected at the monitoring sites were low. Nitrate concentrations are generally greatest in the drier, arable-dominated southern and eastern areas of England, where communities are very dependent upon groundwater for public water supply. The Stiffkey and Glaven catchments are representative of these conditions. In the present study, the highest mean concentration of total oxidised nitrogen was found in the River Stiffkey u/s Stiffkey STW (365 µmol/l or 22.6 mg/l) and the highest maximum (473 µmol/l or 29.32 mg/l) in the River Stiffkey d/s STW. These results compare with a reference mean concentration in Anglian catchments of 39 mg/l (1999–2004 data) (ADAS, 2007).

Analysis of compliance of the ammonia results with the standards in rivers under the Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015 indicate “high” status at the four riverine sites investigated and are consistent with the results obtained at 8 sites in this catchment regularly monitored by the Environment Agency (data for the period Jan 2013–Jan 2015).

Areas of the catchment with the highest concentrations of orthophosphate were identified using the historical WFD monitoring data. These are the River Stiffkey at Binham Tributary, Stiffkey Bridge and Wighton Bridge; and in the River Glaven at Wiveton Bridge. Results at these sites indicate elevated concentrations of orthophosphate in the summer-autumn and lower concentrations in the winter-spring. For total oxidised nitrogen, the highest concentrations were found in the River Stiffkey at Binham Tributary and Snoring Bridge, and in the River Glaven at Gunthorpe Stream and Letheringsett Mill during the winter. These are the areas of the catchments where interventions to reduce diffuse pollution from agricultural land are more likely to result in better WFD compliance. In addition, during the field studies, elevated concentrations of Phosphate were found in the River Glaven (11.2 µmol/l) at Glandford and at Blakeney Quay (11.1 µmol/l). The sources of these could be associated with concentrations of livestock upstream of Glandford and a duck pond near Blakeney Quay.

Levels of nitrate are lost from land mainly during winter and early spring because this is when land is fully wetted and drains flow. During the early part of the winter, nitrate concentrations in water draining from agricultural land are relatively high. This is period when nitrate concentrations in surface waters are most likely to exceed 50 mg/l, and it is at this time of year that water from land dominates river flows. The variation of the ratio of nitrate:ortophosphate and flows in the River Stiffkey were compared for the growing season (April–September) and the dormant season (October–March). Larger variation of ratios and stronger association (R^2=52%) with flows were observed during the growing season. The maximum ratio obtained for the growing season was 210, while the maximum ratio for the dormant season was 160. These results indicate greater mobilisation of nutrients in the growing season and is probably associated wit the fact that the flow regime in the River Stiffkey is relatively stable throughout the year.

Modelling using linear regression indicated a reduction in the concentrations of dissolved inorganic nitrogen (calculated as nitrate+nitrite+ammonium) in seawater as the distance between Blakeney Quay and the sampling points increased. The model suggests that ≈28% of the variation in DIN concentrations in the harbour is explained by the distance from land-based sources. Similarly to that observed for *E. coli* levels, the variation of DIN reduced to levels below 50 µmol/l at sites in the main harbour channel. Linear modelling also indicated a DIN concentration of 90 µmol/l equivalent to salinity of 25 psu which is characteristic of waters with "good" status and intermediate turbidity. Based on the results obtained, gradients of mean contamination were established:

- Total oxidised nitrogen: riverine > marine (shoreline) > marine
- Nitrate: riverine ≈ marine (shoreline) > marine
- Phosphate: riverine > marine (shoreline) > marine
- Silicate: riverine > marine (shoreline) > marine
- Ammonium: marine (shoreline) > marine > riverine

5.3 Phytoplankton

Phytoplankton utilise sunlight energy and dissolved nutrients converting these into organic materials which are consumed by higher life forms such as fish. Populations of individual species are very dynamic in coastal waters and, in many cases, are highly seasonal. Most species of phytoplankton typically reproduce by binary division and consequently the number of cells grows exponentially over a few days. Under certain circumstances, the abundance of phytoplankton as a whole or of one or more species in particular, can increase rapidly. These occurrences are often referred to as "blooms". Phytoplankton blooms are discrete events which can occur at any time during the production season and many, such as the spring bloom in temperate waters, are natural events. However, some blooms can have a negative impact on the ecosystem and/or restrict the human use of the ecosystem. These "Harmful Algal Blooms" (HABs) can cause the closure of shellfish harvesting areas because of elevated abundance of toxin-producing phytoplankton in the shellfish.

The results of the phytoplankton monitoring carried out in Blakeney Harbour indicated a relatively small diversity of species recorded compared to that in other parts of the UK coast (Devlin et al. 2009). The most abundant groups of species observed were *Phaeocystis* spp., microflagellates, *Chaetoceros* spp., cyanobacteria and *Pseudo-nitzschia* spp. Some of the toxin-producing algal genera of regulatory interest (*Alexandrium* spp. and *Dinophysis* spp.) were not recorded in any of the samples. Species of *Pseudo-nitzschia* were recorded with the highest concentration (140,910 cells/l) below the trigger level of 150,000 cells/l. The 20 most common species were identified and, of these, 13 are common in other parts of the coast of England and Wales (Devlin et al. 2009). The assessment against single cell counts and total taxa counts indicated that, according to the thresholds set for WFD, the data collected would align with "high" classification status. Furthermore, chlorophyll measurements taken in the mixing (salinity≤25 ppt) and coastal (salinity>25 ppt) zones did not exceed the thresholds considered in the multimetric assessment under WFD. These results constrast with the "bad" classification status given as a result of the monitoring carried out for WFD compliance, which uses longer-term monitoring data.

Enrichment of nutrients in coastal waters caused by human activity has been associated with the occurrence of HABs in many parts of the world. This association has led to the view that the occurrence of HABs diagnoses the undesirable occurrence of eutrophication in the waters. However, a literature review has questioned the relationship between anthropogenic nutrient enrichment and HABs in UK coastal waters (Gowen et al. 2009). In the present study, the variation of the abundance of *Pseudo-nitzschia* spp. in water samples collected at four sites in Blakeney Harbour was assessed in relation to nutrient ratios to understand if the monitoring data support a nutrient enrichment - HABs relationship. This genus was selected because it contains species capable of producing the neurotoxin domoic acid, which is responsible for the neurological disorder known as amnesic shellfish poisoning. The results indicated no evidence of a relationship between nutrient ratios and the abundance of *Pseudo-nitzschia* spp. suggesting that other factors determine the occurrence of HABs in the study area. Such factors can be associated with the hydrodynamic conditions of the harbour and the adaptations of particular species to these conditions.

6. Recommendations to improve water quality in the catchments

Based on the results obtained, it is recommended that:

1. Fertilisers are applied taking into account soil reserves and organic manure supply as recommended by best practice on nutrient management systems (e.g. PLANET - Planning Land Applications of Nutrients for Efficiency and the environmenT). This would help reduce diffuse pollution to surface waters by planning crop nutrient requirements and spreading no more inorganic and organic fertilisers than a crop needs. The results of this study indicate that this measure should be considered at sub-catchment level. Within the River Stiffkey sub-catchment, the most appropriate areas for this type of intervention would be Binham, Stiffkey Bridge and Wighton Bridge. Within the Glaven sub-catchment, the most appropriate area for intervention would be Wighton Bridge. All of these areas showed elevated concentrations of orthophosphate.

2. Fertilisers or manures are not spread in high risk areas and at high risk times, avoiding periods of rainfall when nutrients are rapidly transferred to surface runoff or drains. This should help reduce pollution by not applying fertilisers where pollutants can be easily and rapidly transferred to surface waters. This assessment demonstrated that nutrient levels increase with flows in the river Stiffkey. Therefore, the upper reaches of the catchments with higher slope gradients would be more vulnerable to runoff contamination.

3. Animal manures and slurry are applied to land after extended storage and without addition of fresh manures. This would help reduce concentrations of FIB in manures.

4. Livestock feeders are not positioned within 10 metres of a surface water or wetland. This measure would reduce pollution by stopping animals poaching and excreting close to rivers or wetlands.

5. Livestock is kept away from watercourses through streambank fencing or bridging of streams. This measure would help reduce pollution by stopping excreta dropping into rivers. It also reduces the erosion of river banks. This measure could be considered across the catchments. Areas for prioritisation would be The Entries, to the east of the Stiffkey village, which drains to Freshes Creek and is close to the WFD compliance point in Blakeney Harbour and Cley Marshes.

6. Feed planning systems are used to match the nutrient content of diets to livestock feeding requirements. This reduces pollution by matching livestock diet to livestock needs to reduce nitrogen and phosphorus concentrations in livestock waste.

7. Owners of septic tanks or small package sewage treatment plants ensure that their systems are performing well and not causing groundwater or surface water pollution and comply with the new regulatory regime implemented in January 2015. Priority should be given to the Stiffkey catchment where there is a large number of properties not connected to the public sewerage system. Further information can be found here:

   https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/367016/ssd-reform-further-info-201410.pdf

8. Boat owners are encouraged to adopt the recommendations of the RYA/British Marine Federation *Love where you sail* campaign

   http://www.rya.org.uk/newsevents/news/Pages/Lovewhereyousail.aspx. Awareness raising campaigns could be carried out, including the provision of advisory leaflets with information on the location of pump out facilities at boat hiring facilities and sailing clubs. It is also recommended that the cost-effectiveness of these campaigns is monitored.

9. Awareness raising campaigns are carried out specifically to address the effects of misconnections, washing products, waste disposal and septic tank best practice on surface water quality.

10. A detailed study is carried out to describe the dispersion and dilution of nutrient and FIB contamination in Blakeney Harbour and assess if the current monitoring arrangements adequately represent the levels of contamination in the harbour.

7. Literature cited

ADAS, 2007. Nitrates in water – the current status in England (2006). ADAS report to Defra – supporting paper D1 for the consultation on implementation of the Nitrates Directive in England.

ADAS, CREH and IGER, 2007. Application of the FIO-SA model to failing bathing waters and shellfish waters. Report WT0713 to Defra.

Ball, A.S., Smith, D. 2008. Assessment of the importance and origin of faecal contamination of Blakeney Point.

Blakeney Parish Council, 2015. Minutes of a meeting of the Joint Dinghy Park Management Committee held on Wednesday 25th November 2015. http://www.blakeneyparishcouncil.co.uk/wp-content/uploads/2012/06/Wednesday-25th-November-2015.pdf.

Bowman, A., Ferguson, C., Lee, D., Magdalina, A.-M., Scott, E.M. 2012. Spatiotemporal modelling of nitrate and phosphorous for river catchments. Environment Agency report SC080041/R.

Calambokidis, J., McLaughin, B., Ma, G.J., Wetzler, T.F., Welch, J., Banks, B. 1987. Harbor seal populations and their contributions to fecal coliform pollution in Quilcene Bay, Washington. Report prepared for Jefferson County and Washington Departmenr of Ecology.

Campos, C.J.A., Avant, J., Gustar, N., Lowther, J., Powell, A., Stockley, L., Lees, D.N. 2015. Fate of human noroviruses in shellfish and water impacted by frequent sewage pollution events. *Environmental Science and Technology* 49(14): 8377–8385.

Campos, C.J.A., Avant, J., Lowther, J., Till, D., Lees, D. 2013. Levels of norovirus and *E. coli* in untreated, biologically treated and UV-disinfected sewage effluent discharged to a shellfish water. *Journal of Water Resources and Protection* 5: 978–982.

Campos, C.J.A., Kershaw, S.R., Lee, R.J. 2013. Environmental influences the levels of faecal indicator organisms in coastal waters and their accumulation in bivalve molluscan shellfish. *Estuaries and Coasts* 36: 834–853.

Campos, C.J.A., Kershaw, S., Lee, R.J., Morgan, O.C., Hargin, K. 2011. Rainfall and river flows are predictors for β-Glucuronidase positive *Escherichia coli* accumulation in mussels and Pacific oysters from the Dart Estuary (England). *Journal of Water and Health* 09.2: 368–381.

Cefas, 2010. Sanitary survey of Blakeney (Norfolk). Cefas report on behalf of the Food Standards Agency, to demonstrate compliance with the requirements for classification of bivalve mollusc production areas in England and Wales under Regulation (EC) No 854/2004.

Crowther, J., Kay, D., Campos, C.J.A., Morgan, O.C. 2011. Sanitary profiles of selected shellfish water catchments pre- and post-improvements in sewerage infrastructure. CREH/Cefas contract report to Defra, Project WT1001: Factors affecting the microbial quality of shellfish.

Defra and Environment Agency, 2016. Anglian river basin district river basin management plan: 2009. https://www.gov.uk/government/publications/anglian-district-river-basin-management-plan.

Defra and Natural Resources Wales, 2015. The Shellfish Water Protected Areas (England and Wales) Directions 2016.

Devlin, M., Barry, J., Painting, S., Best, M. 2009. Extending the phytoplankton tool kit for the UK Water Framework Directive: indicators of phytoplankton community structure. *Hydrobiologia* 633: 151–168.

Devlin, M., Best, M., Bresnan, E., Scanlan, C., Baptie, M. 2014. Water Framework Directive: the development and status of phytoplankton tools for ecological assessment of coastal and transitional waters. United Kingdom. Water Framework Directive – United Kingdom Technical Advisory Group (WFD-UKTAG).

Eastern Daily Press, 2014. Historical part of fishing industry set to disappear. Published 09:22, 26 October 2014. http://www.edp24.co.uk/news/historical-part-of-fishing-industry-set-to-disappear-1-3819574.

Environment Agency, 2015. Shellfish Water Action Plan.

Environment Agency, 2015a. Supporting information: pressure narrative: Phosphorous and freshwater eutrophication. Updated river basin management plans. October 2015.

European Communities, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* L327, 22.12.2000: 1–72.

European Parliament and Council of the European Union, 2006. Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC. *Official Journal of the European Union* L64, 4.3.2006: 37–51.

Food Standards Agency, 2017. Designated bivalve production areas in England and Wales. https://www.food.gov.uk/sites/default/files/shellfish-classification-list-2016-17.pdf.

Gould, D.J., Fletcher, M.R. 1978. Gull droppings and their effects on water quality. *Water Research* 12: 665–672.

Gowen, R., Tett, P., Bresnan, E., Davidson, K., Gordon, A., McKinney, A., Milligan, S., Mills, D., Silke, J., Crooks, A.M. 2009. Anthropogenic nutrient enrichment and blooms of harmful micro-algae. Report prepared for Defra, September 2009.

Guiry, M.D., Guiry, G.M. 2017. AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. http://www.algaebase.org.

Hulme. P. Rukin, N. 2015. Tidal Ribble water bodies. Report to Defra and the Environment Agency for the evidence and measures project.

Kay, D., Anthony, S., Crowther, J., Chambers, B.J., Nicholson, F.A., Chadwick, D., Stapleton, C.M., Wyer, M.D. 2010. Microbial water pollution: a screening tool for initial catchment-scale assessment and source apportionment. *Science of the Total Environment* 408: 5649–5656.

Kay, D., Crowther, J., Stapleton, C.M., Wyer, M.D., Fewtrell, L., Edwards, A., Francis, C.A., McDonald, A.T., Watkins, J., Wilkinson, J. 2008. Faecal indicator organism concentrations in sewage and treated effluents. *Water Research* 42: 442–454.

Kershaw, S., Campos, C.J.A., Reese, A., Mitchard, N., Kay, D., Wyer, M. 2013. Impact of chronic microbial pollution on shellfish. Cefas report to Defra.

King, S., Exley, J., Winpenny, E., Alves, L., Henham, M.-L., Larkin, J. 2014. The health risks of bathing in recreational waters. A rapid evidence assessment of water quality and gastrointestinal illness. A report of research carried out by RAND Europe, on behalf of the Department for Environment, Food and Rural Affairs.

Neal, C., Robson, A.J., Wass, P., 1998. Major, minor, trace element and suspended sediment variations in the River Derwent: results of the LOIS core monitoring programme. *Science of the Total Environment* 210/211: 163–172.

Norfolk Environmental Waste Services Ltd, 2012. Edgefield landfill. Landscape management and aftercare plan.

NRFA, 2017. National River Flow Archive. http://nrfa.ceh.ac.uk/data/search.

Painting, S.J., Devlin, M.J., Rogers, S.I., Mills, D.K., Parker, E.R., Rees, H.L. 2005. Assessing the suitability of OSPAR EcoQOs for eutrophication vs ICES criteria for England and Wales. *Marine Pollution Bulletin* 50(12): 1569–1584.

Rothwell, J.J., Dise, N.B., Taylor, K.G., Allott, T.E.H., Scholefield, P., Davies, H., Neal, C. 2010. A spatial and seasonal assessment of river water chemistry across North West of England. *Science of the Total Environment* 408: 841–855.

Seal Analytical, 1996. Nitrate and Nitrite in water and seawater; total Nitrogen in perisulfate digests. Method No. G-172-96, Rev. 13 (Multitest MT 19).

Seal Analytical, 1996a. Nitrite in water and seawater. Method No. G-173-96, Rev. 9 (Multitest MT 18).

Seal Analytical, 1996b. Silicate in water and seawater. Method No. G-177-96, Rev. 10 (Multitest MT 19).

Seal Analytical, 1996c. Phosphate in water or Bray soil extracts. Method No. G-297-03, Rev. 5 (Multitest MT 19).

Seal Analytical, 1996d. Ammonia in water and seawater. Method No. G-327-05, Rev. 6.

Stapleton, C.M., Kay, D., Jackson, G.F., Wyer, M.D. 2000. Estimated inorganic nutrient inputs to the coastal waters of Jersey from catchment and waste water sources. *Water Research* 34(3): 787–796.

Standing Committee of Analysts, 2009. blue books. Environmental management guidance. Retrieved 16 February 2016. https://www.gov.uk/government/publications/standing-committee-of-analysts-sca-blue-books.

Tegala, A. 2015. Blakeney National Nature Reserve. Breeding bird report, 2015. http://www.cleybirdclub.org.uk/cbc/content/files/2015_blakeney_nnr_breeding_bird_report_73238.pdf.

Tett, P. 1987. The ecophysiology of exceptional blooms. Rapports et Proces-Verbaux des Reunions Conseil International pour l'Exploration de la Mer 187: 47–60.

The National Trust, 2016. Seals on Blakeney Point. https://www.nationaltrust.org.uk/blakeney-national-nature-reserve/documents/blakeney-seal-leaflet-2016.pdf.

The Norfolk Rivers Trust, 2014. The River Stiffkey. A Water Framework Directive Local Catchment Plan. NRT, EA, The Rivers Trust and Defra.

USEPA, 1986. Quality criteria for water, 1986: US Environmental Protection Agency Report 440/5-86-001.

Walling, D.E., Webb, B.W. 1982. Sediment availability and prediction of storm period sediment yields. IAHS Publication 137: 327–337.

WFD-UKTAG, 2014. Transitional Water Phytoplankton Tool. UKTAG Transitional Water Assessment Method. Phytoplankton.

White, P.J., Hammond, J.P. 2006. Updating the estimate of the sources of phosphorous in UK waters. Defra funded project WT0701CSF.

Wild Trout Trust, 2010. River Glaven, Wiveton, North Norfolk, Advisory visit, 4 August 2010.

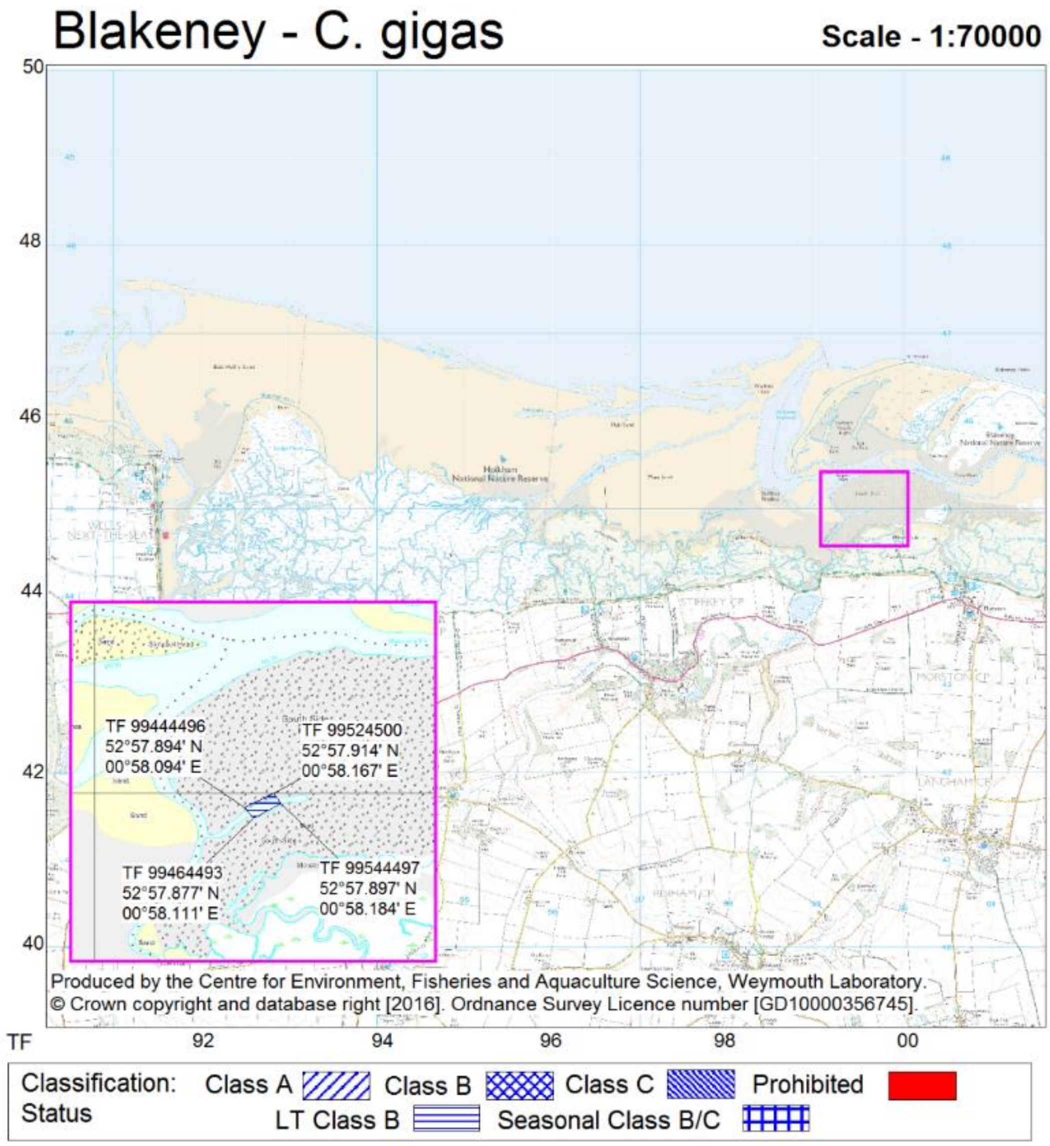
Wilkinson, J., Jenkins, A., Wyer, M., Kay, D. 1995. Modelling faecal coliform concentrations in streams. Institute of Hydrology Report No 127.

Wilson, T.R.S. 1981. Conductometry, Marine Electrochemistry. Institute of Oceanography Sciences, Wormley, Godalming, Surrey, UK. Edited by M. Whitefield and D. Jagner. John Wiley & Sons Ltd.

Yeats, P.A., Brügmann, L. 1990. Suspended particulate matter: collection methods for gravimetric and trace metal analysis. ICES Techniques in Marine Environmental Sciences 7.

Appendices

Appendix I Shellfish production area in Blakeney Harbour classified under Regulation (EC) No 854/2004.



<u>Classification of Bivalve Mollusc Production Areas: Effective from 1 September 2016</u>

The areas delineated above are those classified as bivalve mollusc production areas under EU Regulation 854/2004.

Further details on the classified species and the areas may be obtained from the responsible Food Authority. Enquiries regarding the maps should be directed to: Shellfish Microbiology, CEFAS Weymouth Laboratory, Barrack Road, The Nothe, Weymouth, Dorset DT4 8UB. (Tel: 01305 206600 Fax: 01305 206601)

N.B. Lat/Longs quoted are WGS84

Unless otherwise stated, non-straight line boundaries between co-ordinates follow the OS 1:25,000 mean high water line.

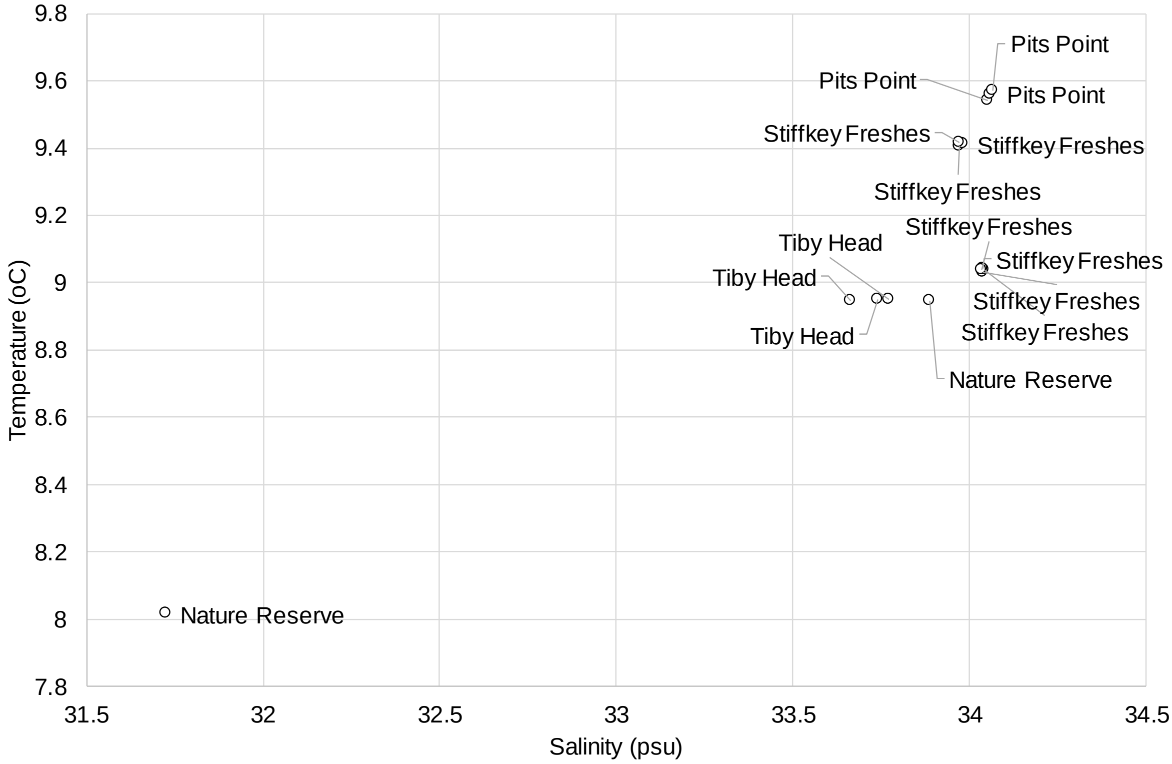
Separate map available for Mytilus spp. for Blakeney

Food Authority: North Norfolk District Council

Appendix II Water Framework Directive physico-chemical standards that apply to the Stiffkey and Glaven.

Element	Statistic	Typology	HIGH	GOOD	MODERATE	POOR	BAD
BOD (mg/l O)	90%ile	1 = Upland, low alkalinity or Lowland high alkalinity site in salmonid WB	3	4	6	7.5	>7.5
Ammonia (mg/l N)	90%ile	2 = Lowland high alkalinity	0.3	0.6	1.1	2.5	>2.5
Dissolved oxygen (% sat)		1 = Upland, low alkalinity or Lowland high alkalinity site in salmonid WB	80	75	64	50	<50
Phosphate (mg/l P)		Site specific standards apply.	The site specific phosphate standards for the Glaven and Stiffkey are shown in the table below:				
pH	High-Good: 5 & 95%ile; Mod-Poor 10%ile	All waters	> 6 & < 9	> 6 & < 9	4.7	4.2	<4.2
Temperature (°C)		S = Rivers in salmonid water bodies	20	23	28	30	>30
Acid Neutralising Capacity (ANC)		Clear Waters	80	40	15	-10	<-10

Appendix III Temperature-salinity diagram for marine sites in Blakeney Harbour.



Appendix IV Percentage of the total faecal coliform loading delivered from the Stiffkey and Glaven catchment to Blakeney Harbour during high flow and low flow from urban and rural sources of pollution. Estimates of the ADAS, CREH and IGER (2007) source apportionment study.

	High flow			Low flow		
Catchment area (km^2)	Urban	Rural	Total	Urban	Rural	Total
249	46	17	63	31	6	37

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