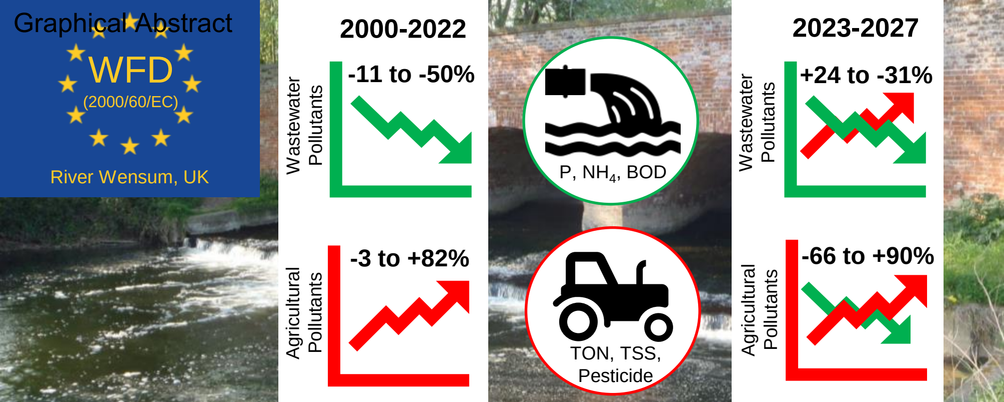
Graphical Abstract
WFD
(2000/60/EC)
River Wensum, UK
2000-2022
Wastewater Pollutants
-11 to -50%
Agricultural Pollutants
-3 to +82%
P, NH4, BOD
TON, TSS, Pesticide
2023-2027
Wastewater Pollutants
+24 to -31%
Agricultural Pollutants
-66 to +90%

Highlights

- 22-year dataset of 10,950 water quality samples compiled for the River Wensum
- Wastewater pollution indicators have reduced by 11–50% since early 2000s
- Agricultural pollution indicators have been stable or increasing (-3% to +82%)
- ‘*Good’* WFD status just 46% for phosphorus and 1.8% for nitrate in 2022
- WFD compliance unlikely to be achieved by 2027 due to legacy nitrogen enrichment

Two decades of the EU Water Framework Directive: evidence of success and failure from a lowland arable catchment (River Wensum, UK)

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Abstract

The EU Water Framework Directive (WFD) is widely regarded as a seminal piece of environmental legislation. However, two decades since its inception, many European waterbodies are failing to meet its ambitious goal to ensure ‘good’ quantitative and qualitative status. Here, we investigate the impact of the WFD upon the environmentally sensitive yet heavily impacted River Wensum, a lowland arable catchment in eastern England. Compiling a dataset of 10,950 water quality samples collected from 57 sites across the catchment at approximately monthly intervals during 2000–2022, we assess the spatio-temporal dynamics of 12 priority pollutants, identify the major drivers of water quality change, and evaluate current and future compliance with WFD goals. Our analysis reveals improvements in wastewater treatment initiated significant declines (11–50%) in the concentration of key sewage pollution indicators (phosphorus, ammonium, biological oxygen demand (BOD)) during the early 2000s. Conversely, agricultural pollution indicators (nitrogen, suspended solids, pesticides) displayed either limited change or a deterioration in water quality, with oxidised nitrogen concentrations in particular having increased 23% during 2015–2022. Concentration spikes of organic chemical contaminants in recent years (propyzamide, tetrachloroethylene) raise concerns about increased riverine pollution from hazardous substances. Similarly, changes in winter (+13%) and summer (-7%) discharge over the past two decades have increased the risk of diffuse pollution mobilisation and reduced the dilution of point source pollutants, respectively. By 2022, ‘good’ or ‘high’ water quality status for organic matter pollution indicators (dissolved oxygen, BOD, ammonium) was achieved for >98% of samples, however WFD compliance fell to just 46% for phosphorus and 1.8% for nitrogen. Projections to the end of the 3rd river basin management planning cycle (2027) reveal that whilst phosphorus compliance is likely to improve, nitrogen compliance failure will persist due to the existence of catchment legacy stores and climate change induced impacts on nitrogen mobilisation.

Keywords: Europe; water quality; nutrients; sewage; agriculture; pollution.

1. Introduction

At the time of its adoption in the year 2000, the EU Water Framework Directive (2000/60/EC) was considered a seminal piece of legislation with an ambitious target to ensure that all waterbodies within EU member states achieved ‘good’ qualitative and quantitative status by 2015 (Hering et al., 2010). Many of the major drivers of freshwater degradation were already widely known: agricultural fertilisers (Grizzetti et al., 2011; Withers et al., 2014) and pesticides (Ccanccapa et al., 2016; Massei et al., 2018), industrial wastewater (Thevenon et al., 2011), urban runoff (Beasley and Kneale, 2002; Even et al., 2007), excess sediment (Dethier et al., 2022; Wohl, 2015), invasive species (Harvey et al., 2014; Leuven et al., 2009), over abstraction (Acreman and Ferguson, 2010), loss of hydromorphological complexity (Palmer and Ruhi, 2019), artificial barriers (Belletti et al., 2020), atmospheric deposition of sulphur and nitrogen compounds (Garmo et al., 2014), and a cocktail of chemicals released in sewage effluent (Godfray et al., 2019; Jarvie et al., 2006; Schröder et al., 2016). Attention therefore turned to the development and implementation of mitigation measures to tackle these drivers of degradation, such as the adoption of conservation agriculture (Cooper et al., 2020a; Kassam et al., 2019), sustainable drainage systems (Cotterill and Bracken, 2020; Gimenez-Maranges et al., 2020) and improved wastewater treatment technologies (Bowes et al., 2011; Bunce et al., 2018). This was accompanied by various legislative drivers, often derived from pre-existing legislation, to penalise polluters, place restrictions on polluting activities and financially incentivise more sustainable practices (Giakoumis and Voulvoulis, 2018). Measures included, amongst other things, the creation of Nitrate Vulnerability Zones (Nitrates Directive (91/676/EEC)), stricter pollution limits for urban wastewater discharge (Urban Wastewater Treatment Directive (91/271/EEC)), establishment of ‘best available techniques’ to control industrial pollution (Integrated Pollution Prevention and Control Directive (2008/1/EC)), and restrictions on the chemical content of household cleaning products (Detergents Regulation (648/2004/EEC)).

However, by 2015, only 53% of waterbodies across the EU and 17% in England were achieving ‘good’ ecological status and many member states consequently applied for extensions to the end of the second (2015–2021) and third (2021–2027) river basin management plan (RBMP) cycles in order to achieve WFD goals (Environment Agency, 2021; Voulvoulis et al., 2017). Despite extending the deadline for compliance, current evidence suggests that there has been limited improvement in freshwater quality across the EU in recent years (Blaas and Kroeze, 2016; Giakoumis and Voulvoulis, 2019). The percentage of both EU and English surface waterbodies achieving ‘good’ ecological status has stagnated over the past two decades, with hydromorphological pressures, diffuse pollution and water abstraction identified as the main reasons for compliance failure (EEA, 2019). Similarly, just 38% of surface waterbodies in the EU and 0% in England were achieving ‘good’ chemical status by 2020, primarily due to diffuse nutrient pollution and the presence of ubiquitous, persistent, bioaccumulative, toxic substances (uPBTs), which include pesticides, industrial chemicals, heavy metals, polyaromatic hydrocarbons, flame retardants and plasticizers (EEA, 2019; Environment Agency, 2021).

The lack of progress towards meeting EU wide targets, set two decades ago, emphasises that further research is urgently required to better understand both the reasons behind compliance failure and how mitigation measures and policy mechanisms can be applied at scale to yield meaningful and sustained improvements in freshwater quality over the coming years

(Carvalho et al., 2019). This in turn will require detailed catchment-level understanding of the current physico-chemical status of waterbodies and the catchment-specific drivers of degradation.

In the above regard, taking the River Wensum as a case study of an environmentally sensitive yet heavily degraded lowland arable catchment, common to large parts of Europe, the overarching aim of this research was to determine whether the implementation of the EU WFD has resulted in significant improvements in water quality over the past two decades and, if not, to identify the reasons for compliance failure. Thus, the main objectives were to:

- **i.** Compile a comprehensive record of water quality parameters from across the River Wensum catchment since implementation of the WFD (2000–2022).
- **ii.** Assess the short-term (monthly) and long-term (decadal) temporal dynamics of a range of physico-chemical metrics and priority riverine pollutants.
- **iii.** Assess the spatial variability in water quality across the River Wensum catchment, considering the impacts of land use, geology and point sources of pollution.
- **iv.** Quantify the changes in water quality over the past two decades and identify the major drivers behind these changes.
- **v.** Evaluate current and projected future compliance with WFD legislation and identify the key areas for improvement.

2. Material and Methods

2.1 Study Location

The River Wensum, UK, is a 78 km length, lowland (2–75 m above sea-level), groundwater-dominated calcareous river that drains an area of 660 km^2 and has a mean annual discharge of 4.36 m^3 s^{-1} (208 mm) near its outlet (Figure 1). The catchment is underlain by Cretaceous White Chalk bedrock which is unconfined in the upper catchment and along sections of the river valley, with an annual baseflow index (BFI) of 0.7–0.9 (Cooper et al., 2018). Over much of the rest of the catchment, the Chalk is confined by superficial deposits of Mid-Pleistocene diamicton glacial tills principally comprising chalky, flint-rich boulder clays of the Sheringham Cliffs (~0.2–10 m depth) and Lowestoft (~10–20 m depth) Formations. These are interspersed with layers of glaciofluvial and glaciolacustrine sands and gravels where the BFI is 0.5–0.7 (Cooper et al., 2018). Climatologically, the catchment experiences a temperate maritime climate, with a mean annual temperature of 10.7°C and a mean annual precipitation total of 647 mm (2000–2021) evenly distributed throughout the year (Met Office, 2022).

The main river channel is designated a Site of Special Scientific Interest (SSSI) and a European Special Area of Conservation (SAC) due to the diversity of its internationally important flora and invertebrate fauna and in recognition of it being one of the best examples of a lowland calcareous river in the world. However, the majority of the river habitat is in an unfavourable and declining state due to a combination of sedimentation, eutrophication, presence of organic contaminants (e.g. pesticides), and degraded hydromorphology resulting from historic dredging and land drainage (Cooper et al., 2020c; Giakoumis and Voulvoulis, 2019). Arable agriculture (wheat, barley, sugar beet, oilseed rape) dominates the land use (73%) and is extensively under drained, with the rest of the catchment comprising improved grassland (14%), urban development (7%) and mixed woodland (5%). The catchment population was ~258,000 people in 2020, an increase of ~14% since 2001 (Norfolk County Council, 2022). There are 21 water company owned wastewater treatment plants (WWTPs) across the catchment, with the seven largest facilities currently having tertiary phosphorus stripping treatment to reduce phosphorus discharge. Most of the phosphorus stripping infrastructure was installed in the late 1990s and early 2000s at facilities serving population equivalents (p.e.) >1000. In addition, there are ~1800 properties served by domestic septic tank systems.

2.2 Datasets

Two pre-existing River Wensum datasets were compiled for this study:

Dataset 1: Environment Agency (EA) – The Environment Agency is a statutory body responsible for environmental protection in England. As part of its remit, the EA routinely analyses riverine hydrochemistry at weekly-monthly resolution across England and stores the data in an open-access online water quality archive (environment.data.gov.uk/water-quality). From this archive, we extracted data for 9737 water samples collected from 36 locations across the River Wensum catchment between January 2000 and August 2022 (Table SM1). In total, 513 different water quality parameters were measured covering a wide range of organic and inorganic contaminants, however not all parameters were measured at all sites for the full monitoring period. As such, we focussed our analysis on the 13 parameters with the longest records across the greatest number of sites. These included total oxidised nitrogen (TON; NO_3 + NO_2), ammonium (NH_4^+), total phosphorus (TP), total reactive phosphorus (TRP), total suspended solids (TSS), dissolved oxygen (DO), biological oxygen demand (BOD), pH, water temperature, dissolved copper (Cu), faecal indicator organisms (FIOs), propyzamide (herbicide) and tetrachloroethylene (TCE).

Dataset 2: River Wensum Demonstration Test Catchment (DTC) – The River Wensum DTC platform was established in 2010 by the UK Government to evaluate the extent to which on-farm mitigation measures could cost-effectively reduce the impacts of agricultural water pollution on river ecology whilst maintaining food production capacity (McGonigle et al., 2014). As part of this initiative, 1213 river water samples were collected from 21 sites across the catchment at approximately monthly intervals between October 2010 and September 2019 (Table SM1). All water was grab sampled from the centre of the river channel in 1 L acid pre-washed polypropylene bottles, transported in cool boxes, and returned to cold storage (4°C) within 5 h to minimise biological degradation. Subsequent laboratory analysis was conducted by the University of East Anglia's Science Analytical Facilities for 31 water quality parameters. For the purposes of this study, we focused our analysis on TON, NH_4^+, TP, TRP, TSS and pH. Further details on the field and laboratory stages of the DTC data collection can be found in (Cooper et al., 2020c, 2022).

Separately to these two datasets, river discharge data (2000–2021) were obtained for the lower River Wensum from the open-access National River Flow Archive (UKCEH, 2022).

2.3 Data Analysis

All data processing was conducted in R Studio v4.1.3 (R Core Team, 2022) and all spatial analysis was conducted in ArcGIS Pro 3.0.

The individual EA and DTC datasets were combined into a single master dataset and, from this, composite water quality records for the entire River Wensum were derived for 12 parameters based on the monthly average values across all 57 sampling locations. Annual smoothing of the composite water quality records was then conducted using a 12-month Savitzky-Golay first order filter using the R '*signal*' package. To minimise temporal bias in the resulting composite records, all individual location data were initially averaged by month prior to merging to ensure that sites with higher frequency data (i.e. weekly) did not disproportionately weigh upon the composite record. To minimise spatial bias and ensure the composite records were representative of the entire catchment, the composite dataset contained data from five main river channel locations spanning the upper, middle, and lower catchment, each of which consisted of >700 samples, encompassed the full 2000-2022 monitoring period, and collectively accounted for 43% of all samples. Additionally, when considering individual location data, only monitoring sites with >30 samples and >4 years of monitoring were included to minimise the impact of atypical short-term variability.

All parameters were initially inspected (histograms) for normality prior to further analysis. Seven parameters displayed normal distributions (TON, NH_4^+, TP, TRP, DO, pH, copper), five displayed a degree of positive skewness (TSS, BOD, propyzamide, TCE, FIOs), and no parameters displayed multimodal distributions. Large sample sizes meant there was little difference between mean and median values for most parameters. Linear interpolation was used to fill any gaps in the datasets. Statistically significant temporal trends in the data were determined using the Mann-Kendall Trend Test ('*Kendall*' package), with further time series analysis conducted via seasonal trend decomposition using the '*stl*' function. Long-term changes in most parameters are reported by comparison of mean concentrations during the first 5 years (2000–2005) and last 6 years (2016–2022) of the record, with the latter extended to take account of limited sampling during 2020–21 due to the COVID-19 pandemic. Water quality data were evaluated in the context of the EU WFD environmental quality standards (EQS) (Table 1). Note, the overall waterbody classification under the WFD is based on a 'one out, all out' approach, whereby all water quality parameters are assessed collectively and the lowest performing parameter defines the overall status of the waterbody.

Future water quality projections for 2027, the deadline for achieving 'good*'* status by the end of the 3rd RBMP cycle, were derived via linear regression forecasting on mean monthly concentration data for the most recent period of data (2016–2022 for NO_3, NH_4^+, TRP, TSS, DO, copper; 2010–2021 for BOD; 2011–2017 for propyzamide; 2010–2020 for TCE). The resulting estimates can be viewed as semi-quantitative as they assume a business-as-usual scenario for the sources, pathways and cycling of pollutants. Other regressions were tested (exponential, power, logarithmic), but did not provide a significantly better fit.

3. Results

3.1 River Discharge

Over the past two decades, long-term mean annual River Wensum discharge remained relatively stable, declining by just 2% between 2000–2005 (4.49 $m^3 s^{-1}$) and 2016–2021 (4.41 $m^3 s^{-1}$). However, this masks much larger long-term seasonal changes. Mean summer (JJAS) discharge declined by 7% between 2000–2005 (2.66 $m^3 s^{-1}$) and 2016–2021 (2.48 $m^3 s^{-1}$), with mean summer precipitation declining 11% during this period, in line with wider national-scale climate change projections for warmer and drier summers in England (Watts et al., 2015). Conversely, mean winter (DJFM) discharge increased by 13% between 2000–2005 (6.09 $m^3 s^{-1}$) and 2016–2021 (6.87 $m^3 s^{-1}$), with mean winter precipitation increasing 17% during this time, again in line with national-scale projections for warmer and wetter winters (Watts et al., 2015). At annual timescales, notably dry calendar years with substantially below average discharge were recorded in 2006 and 2011, whilst notably wet years with substantially above average discharge were recorded in 2007, 2008 and 2021 (Figure 2 & SM1).

3.2 Total Oxidised Nitrogen

There has been no significant (*p* = 0.398) reduction in mean total oxidised nitrogen (TON) concentrations over the past 22 years since implementation of the WFD, with mean concentrations during the period 2016–2022 (7.20 mg N L^{-1}) only 0.7% lower than the period 2000–2005 (7.25 mg N L^{-1}) (Figure 3). Concerningly, after the lowest mean annual concentrations were recorded in 2015 (6.26 mg N L^{-1}) there has since been a steady increase in TON concentrations of 0.24 mg N L^{-1} $year^{-1}$, with the highest mean annual concentrations observed in the last 12 months of the record (7.70 mg N L^{-1}). Intra-annual variability is superimposed on these long-term trends, with a pronounced seasonal cycle of significantly (p <0.05) higher mean TON concentrations during the winter (7.81 mg N L^{-1}) and lower during the summer (6.12 mg N L^{-1}) (Table 2). Such a cycle reflects increased leaching of residual nitrate fertiliser from agricultural soils during the winter months (enhanced by preferential shallow soil throughflow in artificial drainage networks), followed by reduced summer nitrate leaching due to increased crop uptake of soil nitrogen and biological uptake in the river (Dupas et al., 2016; Outram et al., 2016). Spatially, TON concentrations were highest in the upper part of the catchment where mean concentrations widely exceeded 8.00 mg N L^{-1} and locally reached 11.32 mg N L^{-1}, whereas lower down the catchment mean concentrations were typically <7.00 mg N L^{-1} (Figure 4). This difference can be explained by the high BFI (0.7–0.9) in the upper catchment leading to the dominance of nitrate-rich groundwater, coupled with downstream denitrification within the hyporheic zone (Wexler et al., 2011).

3.3 Ammonium

In contrast to TON, there has been significant (p <0.001) reductions in mean ammonium (NH_4^+) concentrations over the past two decades, with mean concentrations 50% lower during 2016–2022 (0.042 mg N L^{-1}) than 2000–2005 (0.084 mg N L^{-1}) (Figure 3). Most of this reduction occurred during a pronounced decline in NH_4^+ concentrations between 2002 and 2007. Except for a notable concentration spike in January 2010, since 2008 there has been very little change in NH_4^+ concentrations. Seasonally, NH_4^+ concentrations were significantly (p <0.05) highest during the winter and lowest during the late summer and early autumn (Table 2), matching the trends observed for TON. This indicates increased summer nitrification coupled with increased winter leaching of ammonium nitrate fertiliser from agricultural soils as the dominant drivers of NH_4^+ variability at seasonal timescales, outweighing the impact of ammoniacal-N release in sewage effluent that would typically be concentrated during low summer river discharge (Romero et al., 2016). Spatially, the highest NH_4^+ concentrations were typically to be observed downstream of WWTPs, especially on the Wendling Beck and River Tud tributaries, reflecting point source effluent input of ammoniacal-N (Figure 4).

3.4 Total Phosphorus

Like ammonium, there has been significant (p <0.001) reductions in mean total phosphorus concentrations since WFD implementation, with mean concentrations 44% lower during 2016–2022 (0.080 mg P L^{-1}) than 2000–2005 (0.143 mg P L^{-1}). Most of this reduction again occurred between 2004 and 2007, and since 2012 there has continued to be a steady decline in TP concentrations at the rate of ~0.003 mg L^{-1} $year^{-1}$. Seasonally, TP concentrations were significantly (p <0.05) higher during the ecologically sensitive summer/autumn compared to winter/spring (Table 2). This likely reflects a concentration of phosphorus-rich sewage effluent during the period of lowest river discharge, coupled with in-situ production of organic phosphorus, the consequence of which is heightened eutrophication risk (Bowes et al., 2015; Yates and Johnes, 2013). Spatially, TP concentrations were highest downstream of WWTPs which reflects point source effluent input (Figure 4), an observation recorded previously in this catchment (Cooper et al., 2022). The River Tud tributary in the south of the catchment was particularly impacted, with mean TP concentrations in the headwaters reaching 0.720 mg P L^{-1} and high concentrations persisting downstream until merging with the main River Wensum.

3.5 Total Suspended Solids

There has been no significant (p = 0.780) reduction in mean total suspended solids (TSS) concentrations since 2000, with mean concentrations during 2016–2022 (7.52 mg N L^{-1}) only 3% lower than during 2000–2005 (7.76 mg L^{-1}) (Figure 3). Mean annual concentrations were largely stable throughout the record, varying between 5–10 mg L^{-1}, although there was significant seasonal variability (Table 2). Higher mean concentrations recorded during the winter (10.89 mg L^{-1}) compared to the summer (5.13 mg L^{-1}) indicate both increased soil erosion and mobilisation of riverbed sediments during higher winter flows (Halliday et al., 2014). Spatially, TSS concentrations were variable across the whole catchment with no single area contributing most to TSS input. This likely reflects the uniform dominance of arable land use across the catchment and thus the potential for tillage induced soil erosion to occur widely.

3.6 Biological Oxygen Demand

In common with TP and NH_4^+ concentrations, biological oxygen demand (BOD) experienced a pronounced decline after 2005, with mean BOD reducing significantly (p = 0.004) by 11% between 2000–2005 (1.45 mg O_2 L^{-1}) and 2006–2015 (1.30 mg O_2 L^{-1}) when routine monitoring ended (Figure 3). However, a corresponding increase was not apparent in dissolved oxygen (DO) concentrations which remained relatively stable throughout the record at ~92% mean saturation, albeit with a slight reduction in concentration variability after 2005. Seasonally, mean BOD was significantly higher during the spring (1.57 mg L^{-1}) and lowest during the autumn (1.24 mg L^{-1}), a patten also observed in dissolved oxygen concentrations (Table 2) and seen in other UK catchments (Sharma et al., 2021). This pattern reflects an increase in microbial activity and algal driven photosynthesis early in the growing season as water temperatures and solar radiation increase, whilst elevated ammonium concentrations in early spring increase nitrification driven oxygen demand (Halliday et al., 2015).

3.7 Pesticides

Of the large number of pesticides detected in the River Wensum (>100 compounds), propyzamide was the most commonly detected and is used here as a general indicator of pesticide pollution (Figure 3). As a systematic herbicide used to control both grass and broadleaved weeds in arable crops, especially oilseed rape, propyzamide was the 10th most extensively used pesticide in the UK in 2020 (253,000 kg) (Ridley et al., 2022). Like other diffuse agricultural pollutants (e.g., TON), mean propyzamide concentrations consistently peaked during the winter months (0.078 µg L^{-1}) throughout the entire record, with these peaks often above the 0.1 µg L^{-1} safe drinking water threshold. During the summer months, concentrations where predominantly below the limit of detection (0.005 µg L^{-1}), revealing propyzamide is largely mobilised from arable fields post-application by winter leaching through the soil profile and subsequent transport into the river network via artificial drainage networks (Holvoet et al., 2007). Although limited sampling prior to 2007 and after 2017 make reliable assessment of long-term trends difficult, mean concentrations were observed to increase by 82% between 2006–2010 (0.022 µg L^{-1}) and 2011–2017 (0.040 µg L^{-1}), although this trend was not significant ($p = 0.208$).

3.8 Heavy Metals

As the most routinely measured metal within the datasets, dissolved copper concentrations were taken as a general indicator of heavy metal contamination. Copper is naturally present at low levels within soils and geological deposits across the catchment, but is also derived from a variety of diffuse and point sources including agricultural fungicides, pig manure, household plumbing, urban road runoff contaminated with vehicle brake dust and tyre rubber, and from sewage sludge application to land (Cowan et al., 2021; Panagos et al., 2018; Whelan et al., 2022). Figure 3 reveals there has been a significant (p <0.001) 35% reduction in dissolved copper concentrations over the past 22 years, with mean concentrations reducing from 2.00 µg L^{-1} (2000–2005) to 1.31 µg L^{-1} (2016–2022). There has also been a substantial reduction in the variability of copper concentrations, although limited monitoring of dissolved metals post-2014 (occurring at just a single site near the catchment outlet) makes it difficult to draw any robust conclusions on catchment-wide copper concentrations since this time. There was no apparent seasonality in copper concentrations, with similar mean concentrations recorded throughout the year (Table 2). The pronounced increase in copper concentrations during 2008–2009 could reflect an increased application of sewage sludge or pig manure to arable fields across the catchment at this time.

3.9 Tetrachloroethylene

Tetrachloroethylene (TCE), also known as perchloroethylene (PCE), is a widely used solvent in the engineering and dry-cleaning industries and is used here as an indicator of a hazardous volatile organic compound (VOC) (Akita et al., 2007). As a likely carcinogen, tetrachloroethylene has been monitored in European waterbodies for several decades as it is known to be discharged into rivers via wastewater effluent (Nikolaou et al., 2002; Wittlingerová et al., 2016). However, sporadic sampling in the River Wensum over the past 22 years makes robust assessment of temporal trends difficult (Figure 3). Nevertheless, there has been a significant (p <0.001) increase in concentrations over time, with the highest monthly mean concentrations (peaking at 7 µg L^{-1}) having all been observed since 2015, whilst concentrations prior to 2010 were largely below the limit of detection (0.1 µg L^{-1}). The distinctly ‘spikey’ concentration profile reflects the sporadic point source nature of TCE discharge into the environment from wastewater.

3.10 Faecal Indicator Organisms

There was no consistent monitoring of faecal indicator organisms (FIOs) across the Wensum catchment following WFD implementation. However, faecal coliform counts were recorded between 2000 and 2007 at three locations, with a mean concentration of 635 counts/100 mL (Figure 3). Further specific monitoring of *E. coli* (2016–2020) occurred at a single location on the River Tud tributary, with mean concentrations of 1648 counts/100 mL. In both cases, mean coliform counts were higher than the 200 counts/100 mL limit for bathing waters, although none of the locations monitored were designated as such. Coliform counts were highest during the summer, likely reflecting the higher concentrations of sewage effluent under lower river flows (Reder et al., 2015; Vilanova et al., 2002) (Table 2).

4. Discussion

4.1 Long-term Trends in Wastewater Pollution Indicators

The greatest long-term improvements in water quality since WFD implementation were in total phosphorus (-44%) and ammonium (-50%) concentrations, with both experiencing pronounced step changes between 2004 and 2007. Reductions in these pollutants, which are found in high concentrations in raw or partially treated sewage effluent (Neal et al., 2005; Yates et al., 2019), principally reflect improvements in wastewater treatment processes during the early 2000s in response to the implementation of the Urban Wastewater Treatment Directive (91/271/EEC; UWWTD) a decade earlier (Demars et al., 2005). The UWWTD helped drive investment in improved secondary (organic matter removal) and tertiary (nutrient removal) sewage treatment processes across Europe, with secondary treatment mandatory by 2005 for WWTPs serving >2000 p.e. and tertiary treatment mandatory by 2000 for WWTPs serving >15,000 p.e. In particular, this resulted in the increased adoption of phosphorus-stripping (e.g., ferric chloride dosing) and ammonia oxidation (e.g., nitrifying sand filters) treatments at larger WWTPs. This investment has resulted in comparable widespread declines in phosphorus and ammonium concentrations across 33 EU states since the late 1990s and early 2000s (Bowes et al., 2018, 2011; Civan et al., 2018; EEA, 2019; Romero et al., 2013). Additionally, the EU Detergents Regulation (648/2004), which came into force in October 2005, permitted member states to place restrictions on the amount of inorganic phosphate in domestic laundry detergents. In the UK, this restriction was set to no more than 0.4% w/w, whilst a later EU-wide amendment in 2012 (259/2012) placed a limit of 0.3% w/w phosphate in dishwasher detergents and 0.5% w/w in laundry detergents, further driving down phosphorus concentrations in wastewater discharge (Romero et al., 2016).

The continued steady decline in TP concentrations in the Wensum catchment throughout the 2010s has occurred despite a 14% increase in the catchment population (and thus wastewater production) since 2000, and may reflect a gradual readjustment of the riverbed sediments to lower phosphate exposure in the overlying water column (Roberts and Cooper, 2018).

Although not directly measured here, the evidence presented suggests that improvements in wastewater treatment (e.g. installation of trickling filters and activated sludge treatment) also reduced the concentration of organic matter in effluent discharge during the early 2000s, resulting in reduced instream microbial respiration (Johnson et al., 2019; Worrall et al., 2019). This, combined with a reduction in ammonium resulting in lower rates of nitrification, can be seen in the step change towards lower BOD around 2005 (-11%), an observation also made across other European rivers at this time (EEA, 2019; Vigiak et al., 2019). Whilst such a reduction in BOD would have reduced the risk of hypoxia across the Wensum catchment, this is not reflected in any simultaneous increase in dissolved oxygen concentrations as these were already close to saturation and remained so over the two decades of monitoring.

Improved wastewater treatment can also partly be detected in the decline in copper concentrations (-35%), with potentially large amounts of copper entering the sewage system through storm drains that channel heavy metal-laden road runoff during precipitation events. Heavy metals are readily removed at WWTPs through binding with organic matter that accumulates in sewage sludge (Whelan 2022), a process that is enhanced through the increased adoption of activated sludge treatment.

4.2 Long-term Trends in Agricultural Pollution Indicators

Whilst improvements in wastewater treatment have reduced eutrophication risk over the past two decades, oxidised nitrogen concentrations in the River Wensum have not significantly reduced since WFD implementation, in common with many other European studies (EEA, 2019; Grizzetti et al., 2011; Minaudo et al., 2015; Romero et al., 2016). Instead, concentrations have been increasing in recent years. The primary source of oxidised nitrogen is the leaching of nitrate fertilisers from the intensive arable agriculture which dominates catchment land use. Data on fertiliser usage across Great Britain reveals average nitrogen application rates to tillage crops declined by 10% between 2000 (149 kg ha^{-1}) and 2021 (130 kg ha^{-1}), having already fallen from highs of ~230 kg ha^{-1} in the mid-1990s (DEFRA, 2022a), thus significantly reducing nitrogen surplus in agricultural soils (Bouraoui and Grizzetti, 2011). This highlights improved fertiliser usage efficiency and has in part been driven by most of the River Wensum catchment being designated a Nitrate Vulnerability Zone (NVZ) to protect the underlying Chalk groundwater by placing restrictions on nitrogen fertiliser application rates. Whilst this could explain the 15% decrease in TON concentrations observed between 2000 and 2015, the 23% increase post-2015 is less clear and troubling. Potentially, this could be due to climate change induced increases in winter precipitation (+17%) which have been recorded over the past two decades and which would likely have increased rates of winter nitrate leaching across the catchment in recent years. Higher winter temperatures (DJF), which have increased 0.26^{o}C between 2000–2005 and 2016–2021 (Met Office, 2022), would also have increased rates of soil nitrogen mineralisation thus making more nitrate available for leaching (Jeppesen et al., 2011). Alternatively, it could also be due to an increase in the cultivation of spring crops leaving more bare soils exposed over winter and vulnerable to leaching. This is most notably the case with spring barley, which accounted for ~15% of total combinable cropping area in eastern England in 2021 and which has seen a threefold increase in cultivated area between 2002 and 2020 (DEFRA, 2022b).

Similar to nitrogen, there is also limited evidence of any long-term improvement in the other key agricultural pollution indicators. Whilst total suspended solids (soil erosion indicator) have remained largely consistent over the past two decades, pesticide concentrations have been trending upwards with an increase in winter peak concentrations observed since 2010. Although average pesticide usage in the UK fell significantly from 5.8 kg ha^{-1} in 2001 to 2.7 kg

ha^{-1} by 2011, usage has since increased to 3.1 kg ha^{-1} by 2020 (Ridley et al., 2022; Roser and Rosado, 2019). The highest propyzamide concentrations observed in the Wensum catchment were in 2008, 2013 and 2016, years in which the area of oilseed rape cultivation (the main crop to which propyzamide is applied) was 6%, 30% and 4% above the 2002–2022 average, respectively (DEFRA, 2022b), thus signalling a land use driven water quality decline. The area of UK oilseed rape cultivation fell sharply by ~40% during 2020–2022 due to restrictions on the use of neonicotinoid insecticides and consequent concerns about flea beetle damage. Hence, lower riverine propyzamide concentrations may have been expected at this time had monitoring been conducted.

Although referred to above as a sewage pollution indicator, the long-term decline in copper concentrations could also reflect changes in agricultural pollution. Legislation driven declines in the use of copper-based fungicides over recent years (EU regulation 2018/1981), combined with improved management of sewage sludge and pig manure application to land, will likely have lowered copper fluxes into rivers draining arable catchments such as the Wensum (Tamm et al., 2022).

4.3 Compliance with WFD Goals

Overall, the evidence presented here reveals a mixed picture for the River Wensum with regards to meeting the original WFD goal of achieving 'good' qualitative and quantitative status by 2015 (Figure 5). Whilst dissolved oxygen, biological oxygen demand, ammonium and pH (not shown) recorded 'high' EQS status for >96% of samples during 2000–2005 and continued to record 'high' status for >98% of samples during 2016–2022, nutrient enrichment remains a significant cause for concern across the catchment.

For nitrate, which accounts for ~99.5% of TON and ~82% of total nitrogen across the Wensum catchment (Cooper et al., 2022), concentrations were recorded as 'good' status or higher for only 1.6% of samples during 2000–2005, rising to just 1.8% during 2016–2022. Whilst the proportion of samples recorded as 'poor' or 'bad' status did fall from 87% (2000–2005) to 73%

(2016-2022), there remains a significant challenge to achieving ‘good’ nitrogen status across the whole catchment. In fact, the increases in TON concentration observed since 2015 indicate that the situation is deteriorating not improving (Figure 3). For total reactive phosphorus, which accounts for ~65% of total phosphorus across the catchment (Cooper et al., 2022), whilst there has been a notable improvement in the proportion of samples achieving ‘good’ status or higher, rising from 25% (2000–2005) to 46% (2016–2022), 54% of samples still failed to meet the ‘good’ status target for surface water.

For pesticides, >90% of propyzamide samples recorded concentrations below the target 0.1 µg L^{-1} for ‘good’ status, however there was a slight increase in the proportion of samples recording ‘bad’ status, rising from 5% (2000–2010) to 8% (2011–2017). A lack of monitoring post-2017 means it is not possible to determine definitively whether this trend towards poorer water quality has continued to the present. Similarly, for TCE, whilst 100% of samples recorded ‘good’ status across the entire record, numerous high concentration spikes approaching the 10 µg L^{-1} ‘bad’ status threshold observed since 2015 are a cause for concern for future compliance.

For FIOs (not shown in Figure 5), inconsistent monitoring makes reliable assessment of compliance difficult, however taking all samples together over the entire monitoring period (2000–2019) reveals that 80% of samples were classified as ‘bad’ status making this the worst performing water quality indicator.

4.4 Future Projections

Linear regression forecasting was used to project recent water quality trends forward to 2027 to provide a semi-quantitative indication of which water quality parameters are likely to achieve the WFD ‘good’ status goal by the end of the 3rd RBMP cycle (Figure 6). Continued steady declines in the sewage pollution indicators ammonium (-21%), copper (-27%) and TRP (-31%) result in mean concentrations potentially falling within ‘good’ or higher status by 2027, whilst

BOD (+24%) and DO (-2%) are still projected to achieve ‘high’ status despite current trends towards a slight deterioration.

Conversely, concentrations of nitrate, the dominant agricultural pollution indicator, are projected to continue to deteriorate (+18%) with mean concentrations in 2027 falling within the ‘poor’ EQS category. Despite the introduction of the Nitrates Directive over 30 years ago, riverine nitrate concentrations remain at historically high levels across many parts of Europe (Frollini et al., 2021; Romero et al., 2016) and southern England in particular (Whelan et al., 2022), with records extending back more than 100 years revealing sustained high concentrations since the widespread adoption of inorganic ammonium nitrate fertilizers in the 1970s (Howden et al., 2010). This is in large part due to the nitrate ‘time bomb’ effect in groundwater-dominated catchments, whereby historic contamination of the underlying aquifer is coupled with decade-long time lags in soil and groundwater movement. These time lags result in legacy stores of nitrate that sustain high riverine nitrate concentrations for decades after the pollution source has been curtailed (Ehrhardt et al., 2021; Wang et al., 2016). Given the time lag in groundwater systems, and the fact that the nitrate trend in the River Wensum is deteriorating, it is unlikely that the ‘good’ water quality status goal will be achieved for several decades. Indeed, previous modelling of nitrate transport in English chalk stream catchments revealed nitrate concentrations may fail to achieve WFD goals this century (Jackson et al., 2008).

Reducing nitrogen pollution is clearly a key priority for the River Wensum, yet at the same time the river is a phosphorus limited system. Mean dissolved N:P mass ratios of 23:1 – 175:1 have been recorded across the catchment (Cooper et al., 2022), values substantially greater than the Redfield mass ratio of 7.3:1. Such high mass ratios imply that phosphorus remains the dominant control on eutrophication. Whilst sustained reductions in phosphorus concentrations have been recorded over the past 22 years due to improvements in sewage treatment at larger WWTPs, smaller rural WWTPs (<1000 p.e.) with limited secondary and tertiary treatment remain a major point source of nutrient-rich effluent, with 14 such facilities across the catchment serving a combined population of ~6000 people. The installation of integrated constructed wetlands at these small WWTPs could provide an efficient, cost-effective, nature-based solution to tackle this problem (Cooper et al., 2020b).

Alongside nitrogen, organic chemical contaminants are also a growing cause for concern. The mean concentration of propyzamide is projected to increase by 90% to 0.076 µg L^{-1} by 2027 based on the current trajectory (2011–2017), whilst the mean concentration of TCE is projected to increase by 402% based on 2010–2020 trends. These projected increases will elevate the risk of breaching the safe drinking water standard for pesticides (0.1 µg L^{-1}) especially during winter leaching events, and supports European-wide concerns about the rise of emerging contaminants in waterbodies (Brack et al., 2015). These concerns are particularly relevant to uPBTs such as pesticides, plasticizers, pharmaceuticals and perfluoroalkyl substances (PFAS). The long-term exposure impacts of these substances upon human health and the natural environment are currently poorly understood and not routinely monitored (EEA, 2019; Jones et al., 2015; Loos et al., 2017).

Adding to the impacts from agricultural land management and WWTPs, climate change driven changes to the hydrological cycle are also expected to negatively impact upon water quantity and quality over the coming decades (Schneider et al., 2013; Whitehead et al., 2009). Mean summer (JJAS) discharge in the River Wensum has already declined 7% over the past two decades, with lower summer flows reducing the potential for pollution dilution, especially from continuous point source effluent releases at WWTPs. Thus, increasing pollutant concentrations are likely to increase BOD and reduce dissolved oxygen concentrations, thereby offsetting some of the water quality improvement gains made during the early 2000s. Conversely, mean winter (DJFM) discharge in the River Wensum has already increased by 13% since 2000, with increased winter rainfall likely to increase leaching of nitrogen and pesticides from agricultural soils, whilst also increasing the risk of soil erosion, urban surface runoff and the activation of sewer storm overflows (Jeppesen et al., 2011; Miller and Hutchins, 2017). Hence, increased precipitation could potentially lead to increased riverine pollution with heavy metals, petrochemicals, pharmaceuticals, and other emerging contaminants such as microplastics over the coming decades.

Finally, of specific importance to the UK following its exit from the European Union, national UK legislation is beginning to diverge from EU environmental policy and as such the UK will no longer be tied to WFD targets. However, in recognising the pressures from agriculture and wastewater, the UK government recently passed the Environment Act (2021). This Act has the intention to apply a target reduction in nitrogen, phosphorus and sediment pollution loading from agriculture to the water environment by 40% by 2037 and an 80% reduction in phosphorus from wastewater by 2037 against a 2020 baseline (DEFRA, 2022c). It remains to be seen how effective this legislation will be in improving freshwater quality across the UK.

Conclusions

The key findings of this research are summarised as follows:

1. Wastewater pollution indicators (phosphorus, ammonium, BOD) in the River Wensum have declined by 11–50% since the implementation of the EU WFD, driven primarily by improvements in tertiary treatment at WWTPs during the early 2000s.

2. Agricultural pollution indicators (nitrogen, TSS, pesticides) have either remained stable or increased (-3% to +82%) since WFD implementation, with oxidised nitrogen concentrations in particular having increased by 23% between 2015 and 2022.

3. Spikes in the concentrations of certain organic chemical contaminants in recent years (propyzamide, tetrachloroethylene) raise concerns about increased riverine pollution by ubiquitous, persistent, bioaccumulative and toxic substances (uPBTs) and it is recommended that these compounds should be a priority focus for future monitoring and mitigation efforts.

4. Climate change pressures upon water resources are evident, with the mean River Wensum summer discharge declining by 7% over the past two decades, whilst mean

winter discharge has increased by 13%. These changes will reduce the dilution of riverine pollutants during the summer and increase the risk of pollution mobilisation in surface runoff and soil leachate during the winter, respectively.

5. ‘Good’ or ‘high’ water quality status was achieved by 2022 for >98% of samples for organic matter pollution indicators (DO, BOD, NH_4^+), however WFD compliance was just 46% for phosphorus and 1.8% for nitrate.
6. Future projections to the end of the 3rd WFD management cycle reveal that whilst phosphorus concentrations are likely to continue to decline and reach ‘good’ status compliance by 2027, nitrate enrichment will continue to increase due to a combination of soil and groundwater nitrogen legacy stores and climate change induced impacts upon nitrogen mobilisation. Renewed effort in the Wensum catchment and more widely in lowland agricultural catchments in England to reduce nitrogen inputs and leaching losses (e.g., winter cover cropping) is required if the current trend in nitrate concentrations is to be reversed in the coming decades.
7. Finally, most of the water quality improvements observed across the River Wensum catchment occurred prior to 2010 following water company investment in WWTP upgrades during the late 1990s and early 2000s. With the catchment population increasing, achieving further progress towards meeting ‘good’ water quality status over the coming decades will require water companies to increase their level of investment in wastewater treatment infrastructure once again, especially at smaller rural WWTPs which currently lack nutrient stripping capability. Further catchment modelling research (e.g., SWAT modelling) to specifically quantify the extent of WWTP upgrades and agricultural mitigation measures required to achieve ‘good’ water quality status in the River Wensum catchment would be highly beneficial.

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Figure Captions

Figure 1: The River Wensum catchment showing land use and sampling locations for the two water quality datasets used in this study. Letters refer to photograph locations. Point C also refers to the location of the river discharge gauging station dataset west of Norwich.

Figure 2: **(a)** Annual hydrograph for the lower River Wensum during the period 2000-2021 derived from gauged daily flow data (UKCEH, 2022). Central lines represent mean discharge during the stated periods. Blue and red shading represents the highest and lowest discharge recorded during the period 2000–2021. **(b)** Deviation in mean annual discharge from the 2000–2021 average.

Figure 3: Temporal variability in the monthly mean concentrations of 10 water quality parameters for the composite River Wensum record during the period 2000–2022. Shading represents ± 1 standard deviation. Black lines are 12-month Savitzky-Golay smoothing filters. Filters are not applied to datasets where concentrations are commonly below the limit of detection. Sample numbers represented by dark grey bars at the top of the plots.

Figure 4: Spatial variability in mean **(a)** total oxidised nitrogen (TON), **(b)** ammonium (NH_4^+), **(c)** total phosphorus (TP) and **(d)** total suspended solids (TSS) concentrations across the River Wensum catchment during the period 2000–2022.

Figure 5: Environmental Quality Standards (EQS) status for the composite River Wensum record during the periods 2000–2005 and 2016–2022. Different classification periods are applied for the following: ^{a}2010–2021; ^{b}2000–2010 and 2011–2017; ^{c}2010–2020.

Figure 6: Projected future (2027) water quality for the River Wensum derived via linear regression forecasting over the most recent data period (2016–2022 for NO_3, NH_4^+, TRP, TSS, DO, copper; 2010–2021 for BOD; 2011–2017 for propyzamide; 2010–2020 for TCE). Shading around the regression line is the 95% confidence interval. Percentage change refers to the central concentration estimate for 2027 compared to the regression period. Note: The EQS

for copper refers to ‘bioavailable copper’ rather than the ‘dissolved copper’ measured here, thus the EQS status is only indicative.

Tables

Table 1: EU Water Framework Directive environmental quality standards (EQS) applied to the River Wensum (WISE-Freshwater, 2022).

Parameter	Legislation	Units	Environmental Quality Standard (EQS)				
			Bad	**Poor**	**Moderate**	**Good**	**High**
Nitrate	1	mg N L^{-1}	>11.3	11.3 – 5.6	5.6 – 3.6	3.6 – 0.8	<0.8
Ammonium	2	mg N L^{-1}	>2.5	2.5 – 1.1	1.1 – 0.6	0.6 – 0.3	<0.3
Reactive phosphorus	3	mg P L^{-1}	>1.003	1.003 – 0.173	0.173 – 0.069	0.069 – 0.036	<0.036
Dissolved oxygen	2	%	<45	45 – 54	55 – 60	61 – 70	>70
BOD	2	mg L^{-1}	>9	9 – 6.5	6.5 – 5	5 – 4	<4
pH	2	-	<4.89	4.89 – 5.44	5.44 – 5.95	5.95 – 6.60	>6.60
Water temperature	2	°C	>30	30 – 28	28 – 23	23 – 20	<20
TSS	4	mg L^{-1}	-	>25	-	<25	-
Copper (bioavailable)	2	µg L^{-1}	-	>1	-	<1	-
Propyzamide	5	µg L^{-1}	-	>0.1	-	<0.1	-
Tetrachloroethylene	2	µg L^{-1}	-	>10	-	-	-
Faecal coliforms	6	Count 100 mL^{-1}	-	>200	-	<200	-

[1] The UK does not formally assign an EQS for riverine nitrate and thus the thresholds used here reflect typical values applied in other EU member states under the EU Nitrates Directive (91/676/EEC)

[2] The Water Framework Directive Standards and Classification Directions for England and Wales (2015)

[3] UK Technical Advisory Group (UKTAG) Recommendations on Phosphorus Standards for Rivers (2013)

[4] EU Freshwater Fish Directive (2006/44/EC)

[5] EU Drinking Water Directive (98/83/EC)

[6] EU Bathing Water Directive (2006/7/EC)

Table 2: Summary water quality statistics for the composite River Wensum record over the full monitoring period (2000–2022). Percentage of individual monitoring sites displaying increasing or decreasing trends over the full duration of the record were derived from site specific linear regressions.

Parameter	**Units**	***n* measurements**	***n* sites**	**Mean Concentration (1 standard deviation)**					**Increasing Trend (% of sites)**	**Decreasing Trend (% of sites)**
				Annual	**Spring**	**Summer**	**Autumn**	**Winter**		
Total oxidised nitrogen	mg N L^{-1}	10,480	57	6.91 (2.02)	7.21 (1.81)	6.12 (2.07)	6.63 (1.97)	7.81 (1.82)	46%	54%
Ammonium	mg N L^{-1}	10,255	57	0.051 (0.079)	0.050 (0.072)	0.047 (0.084)	0.044 (0.078)	0.064 (0.081)	33%	67%
Total phosphorus	mg P L^{-1}	9981	54	0.112 (0.107)	0.091 (0.082)	0.122 (0.115)	0.122 (0.128)	0.111 (0.091)	20%	80%
Total reactive phosphorus	mg P L^{-1}	7218	34	0.086 (0.058)	0.069 (0.051)	0.094 (0.061)	0.094 (0.062)	0.087 (0.050)	33%	67%
Water Temperature	ºC	9692	43	11.04 (4.40)	10.18 (3.13)	16.08 (2.25)	11.13 (2.81)	5.80 (1.84)	63%	37%
Total suspended solids	mg L^{-1}	8734	50	7.53 (12.04)	8.13 (13.58)	5.13 (5.45)	6.47 (9.28)	10.89 (16.88)	56%	44%
Dissolved oxygen	%	5240	36	92.2 (18.1)	99.5 (29.0)	91.9 (14.9)	86.7 (10.5)	92.3 (9.3)	31%	69%
pH	-	3889	36	7.97 (0.25)	8.00 (0.24)	7.98 (0.25)	7.94 (0.26)	7.96 (0.22)	33%	67%
Biological oxygen demand	mg O_2 L^{-1}	2596	27	1.34 (0.88)	1.57 (0.64)	1.33 (1.13)	1.24 (0.56)	1.44 (1.05)	15%	85%
Propyzamide	µg L^{-1}	1180	11	0.032 (0.153)	0.024 (0.103)	0.006 (0.002)	0.018 (0.058)	0.078 (0.277)	91%	9%
Copper	µg L^{-1}	1163	13	1.89 (1.03)	1.96 (1.03)	1.80 (0.98)	1.90 (1.14)	1.89 (0.93)	9%	91%
Coliforms	Count/100 mL	326	9	1172 (2108)	729 (1339)	1710 (3224)	889 (919)	1275 (1863)	60%	40%
Tetrachloroethylene	µg L^{-1}	115	4	0.345 (0.885)	0.452 (1.252)	0.378 (0.692)	0.196 (0.334)	0.342 (0.985)	100%	0%

Figure 1

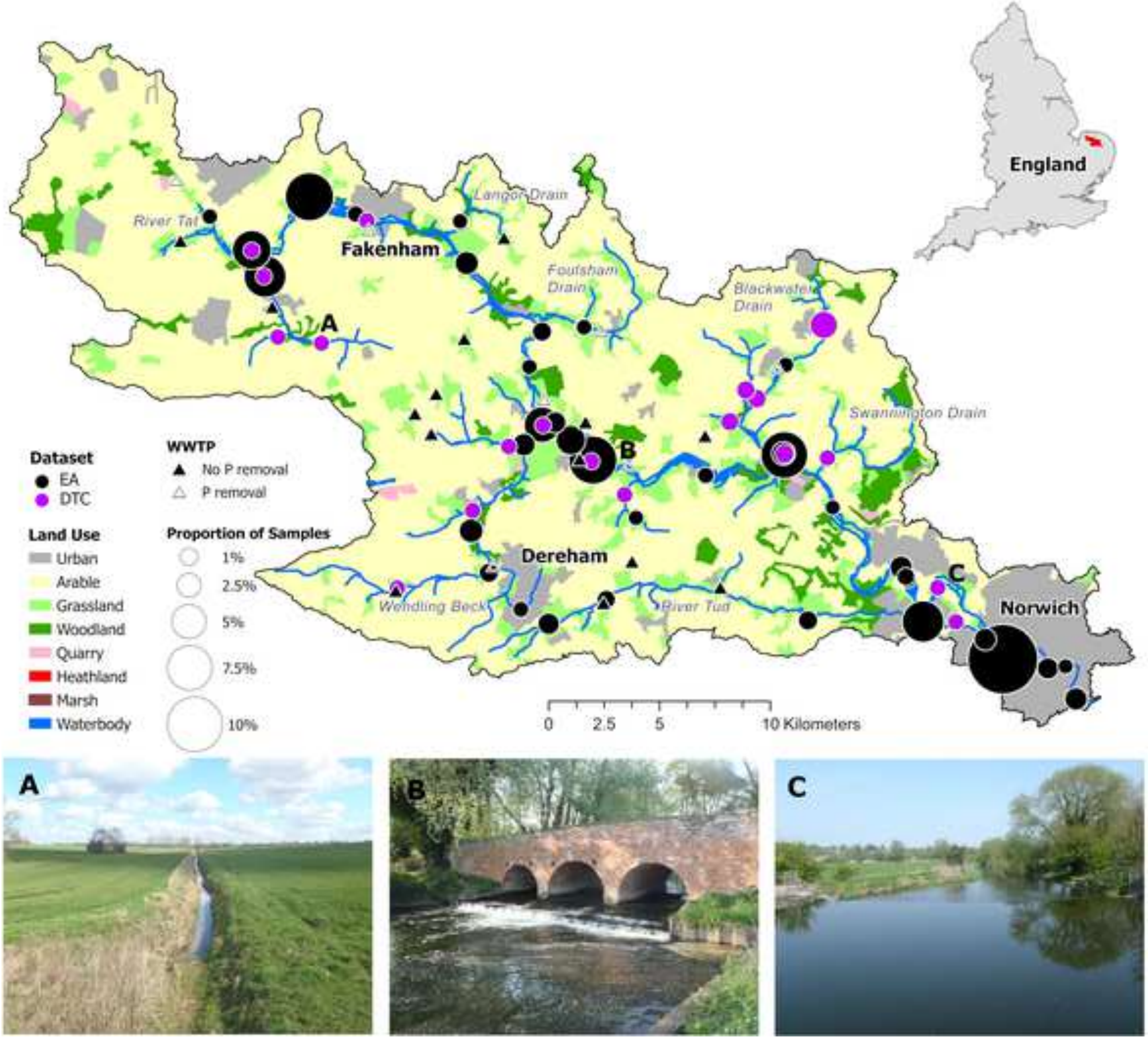

England
River Tat
Langor Drain
Fakenham
Foulsham Drain
Blackwater Drain
Swannington Drain
Dereham
Wendling Beck
River Tud
Norwich
A
B
C
Dataset
● EA
● DTC
Land Use
Urban
Arable
Grassland
Woodland
Quarry
Heathland
Marsh
Waterbody
WWTP
▲ No P removal
△ P removal
Proportion of Samples
1%
2.5%
5%
7.5%
10%
0
2.5
5
10 Kilometers
A
B
C

Figure 2

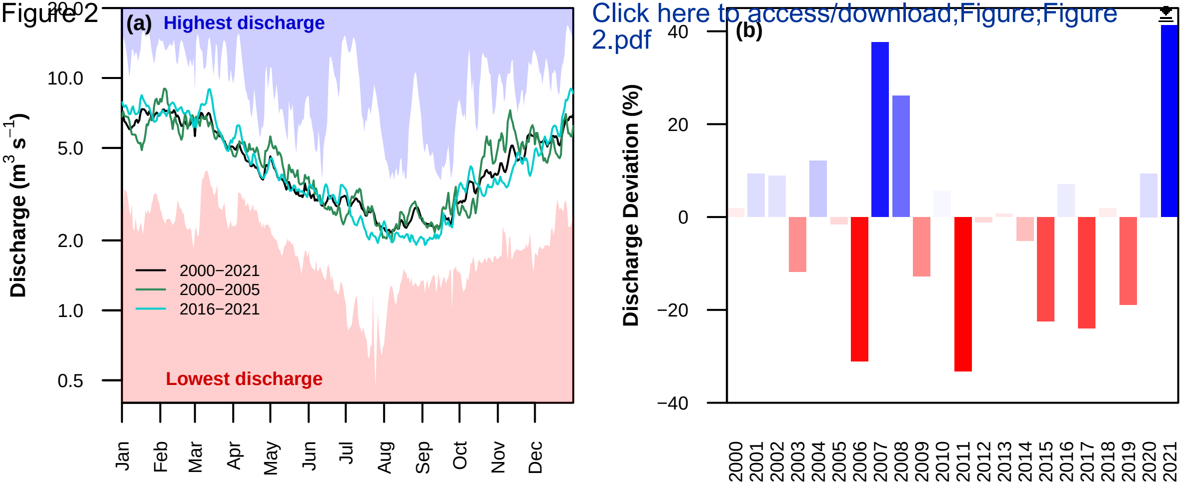

(a) Highest discharge
Lowest discharge
Discharge ($m^3 s^{-1}$)
20.0
10.0
5.0
2.0
1.0
0.5
2000–2021
2000–2005
2016–2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
(b)
Discharge Deviation (%)
40
20
0
−20
−40
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

Figure 3

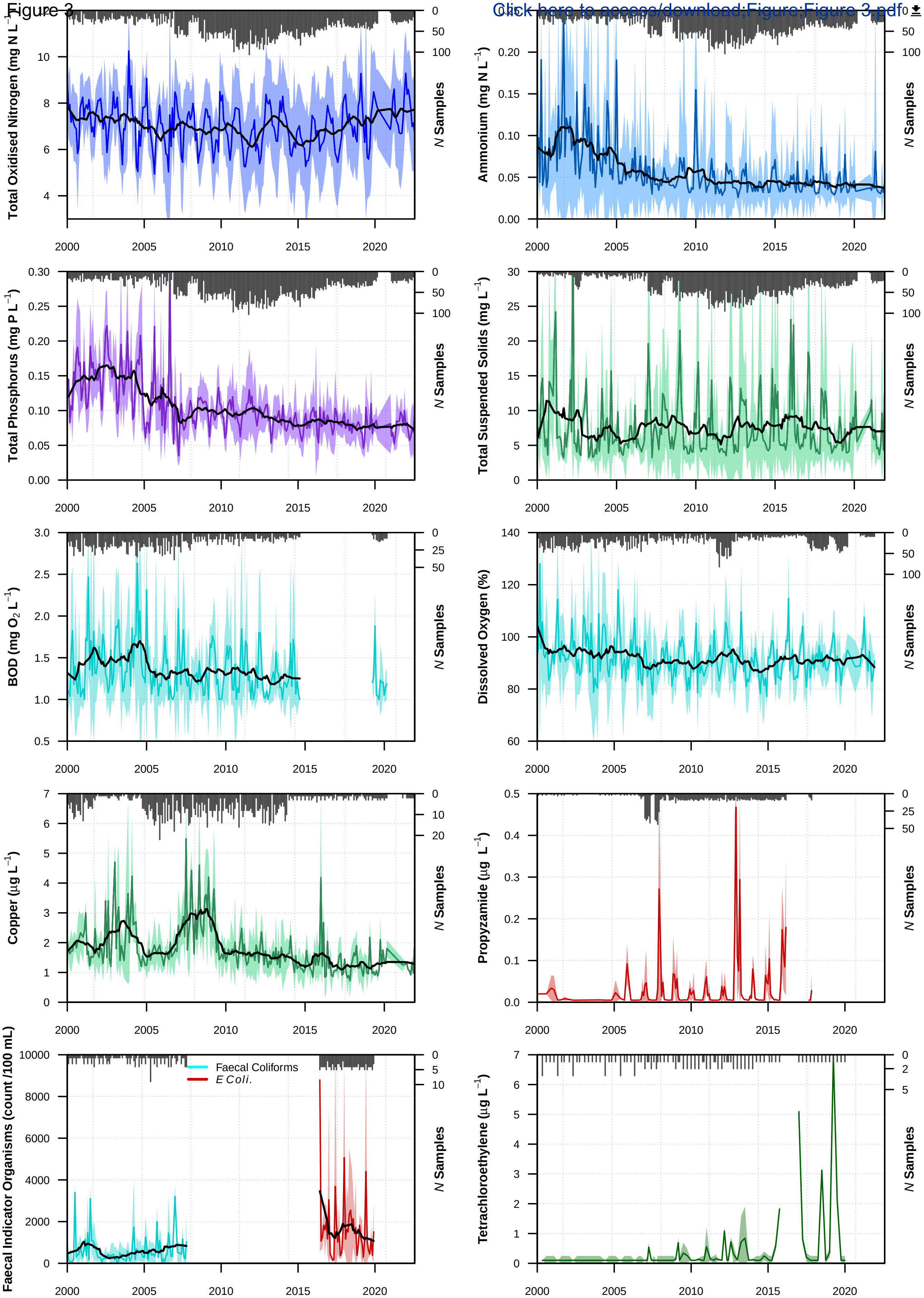

Total Oxidised Nitrogen (mg N L^{-1})
Ammonium (mg N L^{-1})
Total Phosphorus (mg P L^{-1})
Total Suspended Solids (mg L^{-1})
BOD (mg O$_2$ L^{-1})
Dissolved Oxygen (%)
Copper (µg L^{-1})
Propyzamide (µg L^{-1})
Faecal Indicator Organisms (count /100 mL)
Tetrachloroethylene (µg L^{-1})
N Samples
Faecal Coliforms
E Coli.
2000
2005
2010
2015
2020

Figure 4

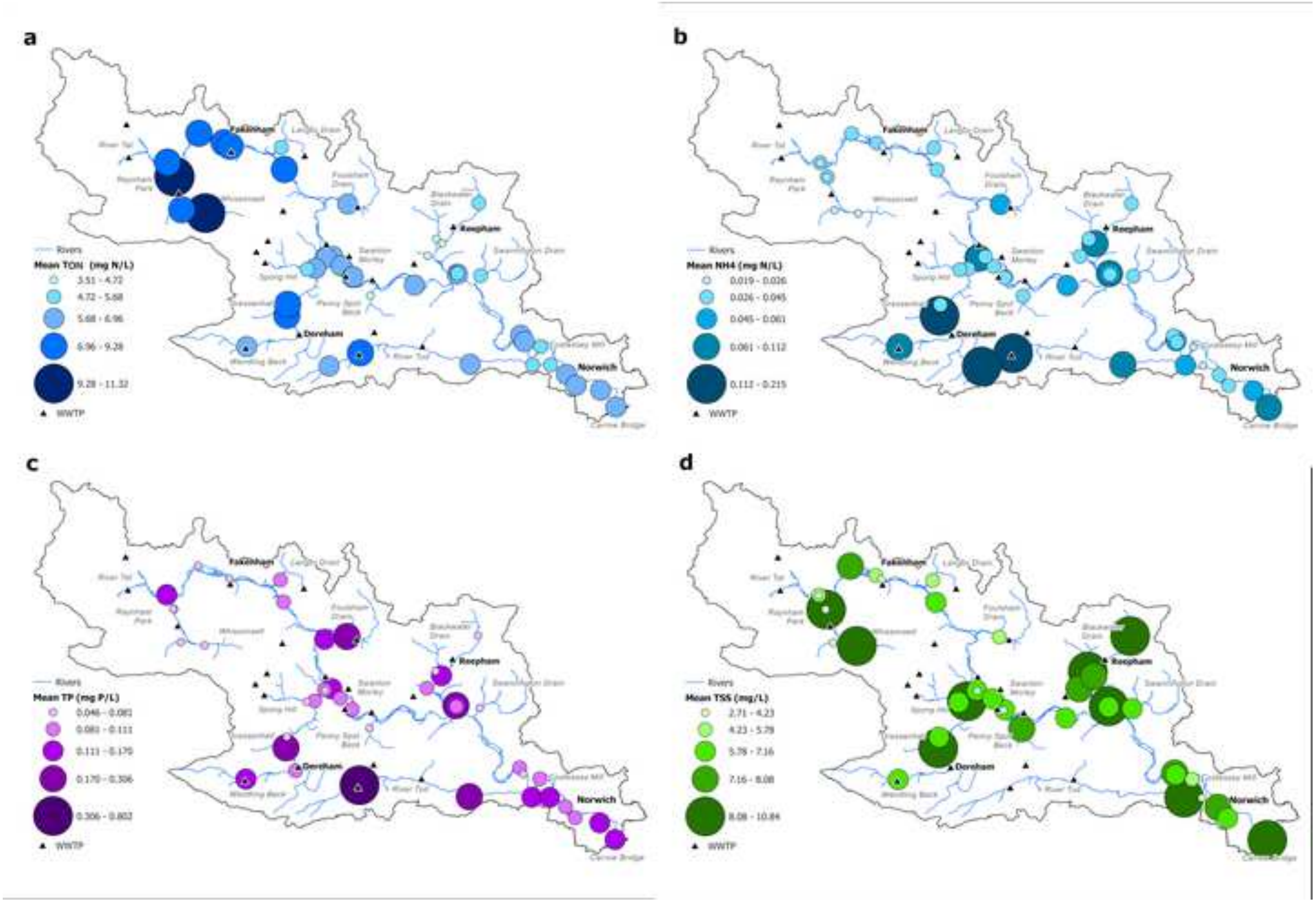

a
Fakenham
Reepham
Dereham
Norwich
River Tat
Raynham Park
Swanton Morley
Wendling Beck
River Tud
Costessey Mill
Rivers
Mean TON (mg N/L)
3.51 - 4.72
4.72 - 5.68
5.68 - 6.96
6.96 - 9.28
9.28 - 11.32
WWTP
b
Fakenham
Reepham
Dereham
Norwich
Rivers
Mean NH4 (mg N/L)
0.019 - 0.026
0.026 - 0.045
0.045 - 0.061
0.061 - 0.112
0.112 - 0.215
WWTP
c
Fakenham
Reepham
Dereham
Norwich
Rivers
Mean TP (mg P/L)
0.046 - 0.081
0.081 - 0.111
0.111 - 0.170
0.170 - 0.306
0.306 - 0.802
WWTP
d
Fakenham
Reepham
Dereham
Norwich
Rivers
Mean TSS (mg/L)
2.71 - 4.23
4.23 - 5.79
5.79 - 7.16
7.16 - 8.08
8.08 - 10.84
WWTP

Figure 5

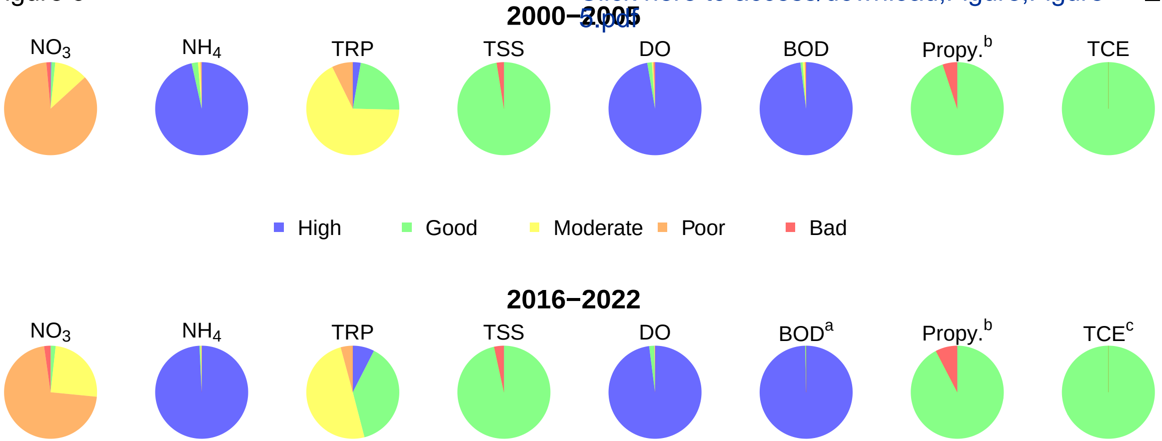
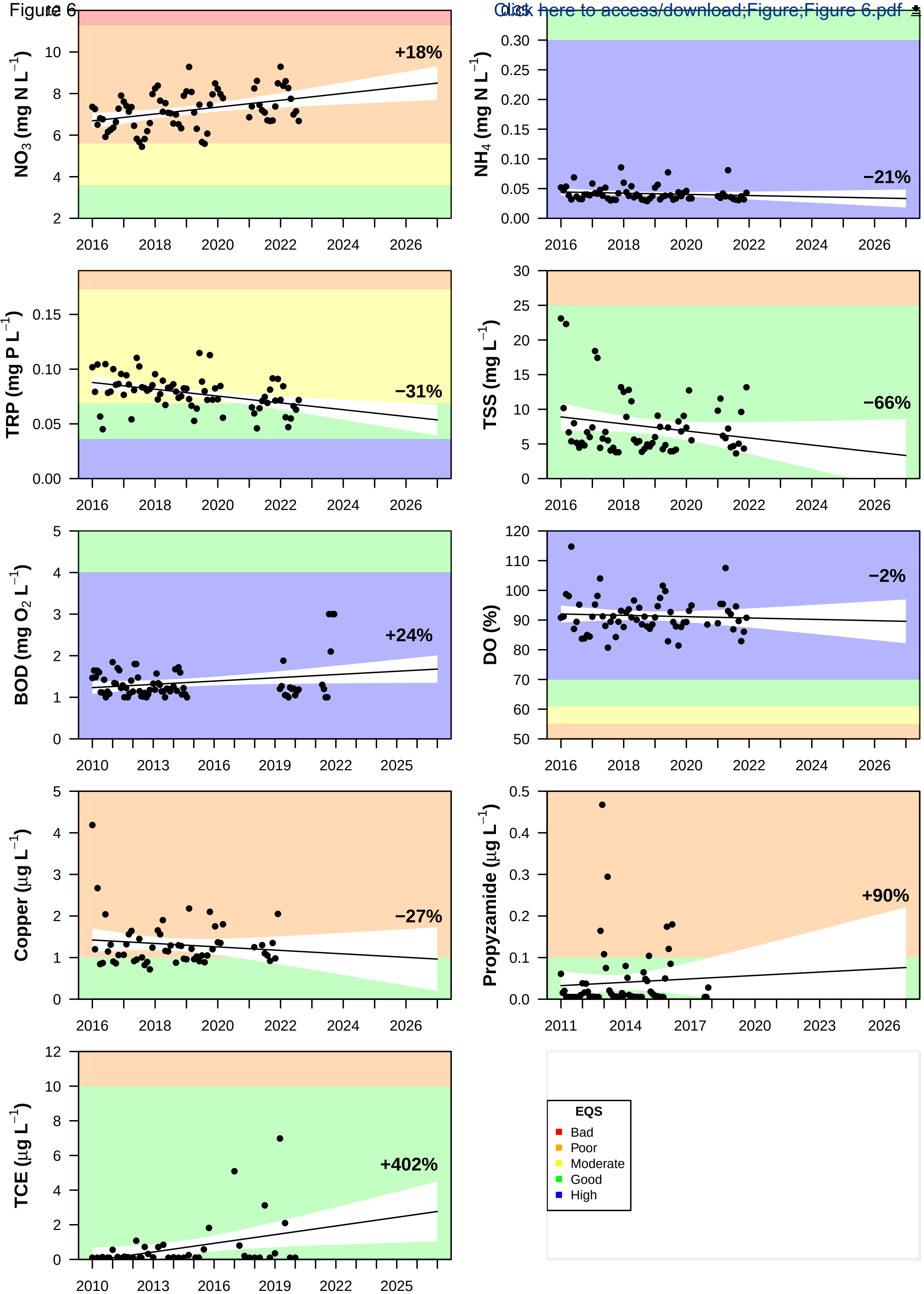

2000−2005
NO3
NH4
TRP
TSS
DO
BOD
Propy.b
TCE
High
Good
Moderate
Poor
Bad
2016−2022
NO3
NH4
TRP
TSS
DO
BODa
Propy.b
TCEc

Figure 6


NO$_3$ (mg N L^{-1})
2
4
6
8
10
12
+18%
2016
2018
2020
2022
2024
2026
NH$_4$ (mg N L^{-1})
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
−21%
2016
2018
2020
2022
2024
2026
TRP (mg P L^{-1})
0.00
0.05
0.10
0.15
−31%
2016
2018
2020
2022
2024
2026
TSS (mg L^{-1})
0
5
10
15
20
25
30
−66%
2016
2018
2020
2022
2024
2026
BOD (mg O$_2$ L^{-1})
0
1
2
3
4
5
+24%
2010
2013
2016
2019
2022
2025
DO (%)
50
60
70
80
90
100
110
120
−2%
2016
2018
2020
2022
2024
2026
Copper (µg L^{-1})
0
1
2
3
4
5
−27%
2016
2018
2020
2022
2024
2026
Propyzamide (µg L^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
+90%
2011
2014
2017
2020
2023
2026
TCE (µg L^{-1})
0
2
4
6
8
10
12
+402%
2010
2013
2016
2019
2022
2025
EQS
Bad
Poor
Moderate
Good
High