Marine Pollution Bulletin 186 (2023) 114450

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

The impact of an annual major recreational boating event on water quality in the Solent Strait

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ARTICLE INFO

Keywords:
Marine water quality
Shellfisheries
Pollution
Scrubber
Shipping
Recreational boating

ABSTRACT

A long-term historical analysis of the impacts of recreational boating on marine surface water quality during a regatta (Cowes Week) in an internationally crucial waterway, the Solent Strait (Hampshire, UK) is presented. Water quality indicators studied included nitrogen concentration, bacterial indicators, and oxygen saturation, at three sampling sites at/near Cowes during 2001–2019. Findings include that sewage discharge from recreational boats is the key contributor to localised faecal contamination of marine surface waters, putting bathers and shellfisheries at risk. Bathing water quality monitoring and pollution warning systems should be strengthened prior to and during this type of regatta and access to bathing water areas may need to be restricted. These findings have implications for the regulation, future monitoring and management strategies for discharges from recreational boats during extended regattas. Adequate and affordable local facilities for recovering sewage wastewater from recreational boats should be provided alongside appropriate mechanisms for communication to sailors.

1. Introduction

England's Solent Strait is a large, semi-enclosed water body that is heavily trafficked by commercial, naval, and public transport vessels. It has a complex tidal pattern that provides a “double high tide” that extends the tidal window during which deep-draught ships can be handled. The Solent economy, which incorporates two major cities (Southampton and Portsmouth) has a population of >1 million, >50,000 businesses and a local GVA of £25 billion. The area is of great ecological and landscape importance; much of it is internationally designated and it is bordered by and forms a part of a number of nationally important protected landscapes.

The Solent Strait is bordered by agricultural land and urban areas with wastewater treatment plants (WWTPs), with consequent adverse impacts on marine water quality. The impact of emissions from agriculture and discharges from WWTPs on the Solent's water quality is well-established and an ongoing cause of concern, with monitoring systems in place (Solent Forum, 2022, Cefas, 2013). A desk-based study by Carcinus Ltd. (2021) concluded that the existing capacity of Solent's wastewater treatment network “is sufficient to capture the summer increase in the population of the catchment” (due to tourism). The impact that vessels have had on this marine environment has been acknowledged since the 1980s, including the effects of petroleum pollution (Knap et al., 1982; Houston et al., 1983), anti-fouling paint particulates (APPs) (Gough et al., 1994; Bray et al., 2011), and volatile organic compounds (VOCs) (Bianchi and Varney, 1998). The Solent also contains a network of coastal and marine sites which are internationally protected for nature conservation, shellfisheries and bathing waters (Solent Marine Sites, 2022). The Solent waterway is part of the Baltic and North Sea Sulphur Emission Control Areas (SECA) and thus ships inside must be equipped with scrubber systems in exhausts or switch to fuel containing regulated amounts of sulphur. The potential impacts of the use of exhaust gas cleaning systems (EGCSs) on Solent water quality and ecosystems is the subject of an ongoing EU-funded case study (EMERGE, 2021). Having a baseline for water quality is essential for measuring changing conditions in marine waterways to enable greater understanding about what may be contributing to any changes.

However, there have been very few studies on environmental impacts of recreational boating, particularly in the Solent. Carcinus Ltd. (2021) flagged that the Solent Strait hosts a significant number of pleasure craft, with peak numbers during the summer months, and several marinas with pump-out facilities throughout the area. It is well-

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https://doi.org/10.1016/j.marpolbul.2022.114450
Received 20 July 2022; Received in revised form 24 November 2022; Accepted 26 November 2022
Available online 8 December 2022

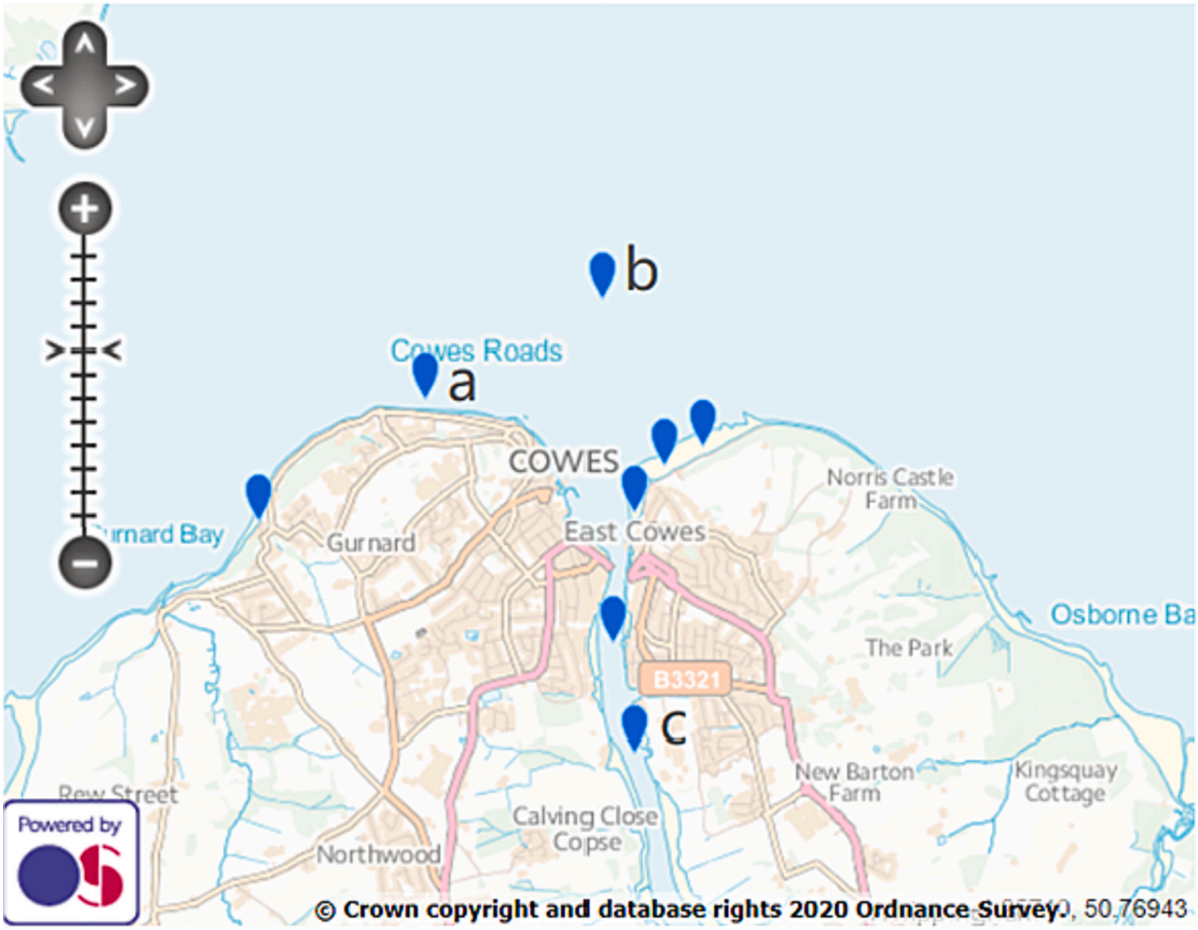

Fig. 1. Sample sites around Cowes selected for study; a) Cowes b) Cowes shellfishery c) Medina shellfishery.

established that larger recreational vessels (yachts, cabin cruisers and fishing vessels) with onboard toilets may make occasional overboard discharges, especially when moored overnight away from marinas or when transiting through principal navigational channels (Cefas, 2013). Research has shown that recreational boating has physical, chemical and biological effects on marine water quality, and flora and fauna (Lloret et al., 2008; Burgin and Hardiman, 2011), as well as being a major vector contributing to the spread of alien invasive species. Such studies have tended to focus on short-term environmental effects. Any potential increase in risk to human or ecological health as a consequence of discharges from recreational boating has thus not been established, although Cefas (2013) flagged that estuaries and harbours (such as the Medina which joins the Solent Strait at Cowes on the Isle of Wight) are at most risk in this regard.

Cowes Week is one of the most famous and long-running regattas in the United Kingdom. The event is named after its venue, Cowes, a port town at the northernmost of the Isle of Wight, an island close to the busy ports of Southampton and Portsmouth. Cowes Week started in 1826 with only seven boats competing. Since then, it has grown in scale with recreational boating worldwide. Now, each year (around the end of July or the start of August), Cowes Week welcomes >8000 sailors and >100,000 visitors for sailing competitions and other recreational activities (Cowes Week Limited, 2020). Visitors watch the competitions and tour their boats around the Solent area, generating increased emissions and wastewater. Annex IV of MARPOL 73/78 and the UK Merchant Shipping (Prevention of Pollution by Sewage and Garbage from Ships) Regulations 2008 stipulate that ships carrying 400 GT or above, or certificated to carry >15 passengers, must be equipped with wastewater storage or treatment facilities, and cannot discharge wastewater directly into the sea. However, there are no compulsory requirements for wastewater discharge for small recreational boats that carry <15 people, although some countries have stronger regulations. During Cowes Week, the increased number of small recreational boats has the potential to lead to a sudden increase in untreated wastewater discharge. Although each recreational boat only discharges a small amount of wastewater, the aggregated quantities may be significant. Discharge is high-strength wastewater with higher biochemical oxygen demand (BOD) and chemical oxygen demand (COD) than normal municipal wastewater (Kersh et al., 2020; Milliken and Lee, 1990). This kind of wastewater consumes dissolved oxygen and affects marine organisms when it enters seawater in large quantities in a short time. The other key pollutants from recreational boat discharges are nutrients, such as nitrate, ammoniacal nitrogen, and sulphate. Nitrate is the most abundant form of nitrogen in water, and is biologically active in the marine environment, whereas nitrite is less rich in the water yet also bioactive (Sharp, 1983). High concentrations of nutrients may lead to the overgrowth of microorganisms that consume more oxygen from the water and form algal blooms. In one of the few papers on this topic, Leon and Warnken (2008) studied the sewage discharge of ~10,000 recreational boats (>6 m overall) in Queensland and found that they were releasing ~1.17 tonnes of nitrogen into the sea each year, alongside copper (from Cu-based antifouling paints), human faecal matter, and urine.

Wastewater from recreational boats is also contaminated with pathogens such as salmonella, coliforms, viruses and streptococcus (Sinclair et al., 2009; Sobsey et al., 2003). The source of wastewater from boats includes sewage (blackwater) and non-sewage water (greywater) (Lindgren et al., 2016). Blackwater is flush water from human

Table 1
Details of sampling points (labelled a, b and c in Fig. 1) around Cowes.

Sampling point label on Fig. 1	Name	Location	Type	Parameters
(a)	Cowes	50.76784, −1.309366	Designated bathing beaches	Number of FC, FS, EC, and IE
(b)	Cowes-Shellfish Water	50.773588, −1.293114	Designated shellfisheries	Nitrite, nitrate, oxygen saturation
(c)	Medina-Shellfish Water	50.746953, −1.290538	Designated shellfisheries	Nitrite, nitrate, oxygen saturation

excretion whilst greywater is wastewater from washing and cleaning apart from toilet water (Tilley, 2014). Pathogens from human faeces are released into seawater from these releases. As these pollutants spread, beaches and shellfisheries may be severely affected, raising public health concerns if people swim or consume shellfish from affected areas. Note that pathogenic (faecal) contamination in estuarine areas such as mudflats, reedbeds, grazing marshland and shingle beaches from waterbirds is likely to be either i) diffuse or ii) highly localised and only possible during the overwintering periods when bird counts are relatively high (Cefas, 2013).

Current reports on pollution in the Solent Strait mainly focus on APPs, VOCs, nutrients, and petroleum pollution, with ongoing research focussing on contaminants associated with exhaust gas cleaning systems (EGCS). An overarching water quality study focussing on contaminants associated with recreational boats for this busy coastal area does not yet exist. Hence, the goal of this study was to critically analyse and review the impacts of wastewater discharges from small recreational boat activity on the Solent's water quality, with a focus on Cowes Week.

For multiple practical and logistical reasons, direct measurements of wastewater emissions from recreational boats are seldom taken. Indirect measurements at carefully selected sites must therefore be used to enable impacts on water quality to be estimated. Selected pollutant concentrations in the Solent's waters adjacent to, and at beaches in, Cowes before, during and after Cowes Week, focussing on wastewater-related pollutants from 2001 to 2019, were studied. The purpose was to identify any trends and to critically evaluate and highlight any issues.

2. Methods

As well as recreational boating, commercial fishing is crucial for the economy of the Solent area. The Solent Strait is a mixed marine fishery boasting mainly shellfish and some finned fish, such as sea bass (*Serranidae*). Shellfish fishing is one of the main types of fisheries (Solent Forum, 2020) but issues with overfishing, pollution, disease, habitat loss and other pressures have led to fishery closures with a regional restoration project ongoing (Blue Marine Foundation, 2019). As a crucial location for recreation and shellfishing, the water quality around Cowes should be the focus of monitoring and research.

Hence the study area was selected as Cowes harbour, located on the Isle of Wight off the south coast of England. Cowes harbour is one of the most attractive sailing destinations in the UK. It is at the centre of the Solent, an international site for boating and other water recreations, such as sea fishing, diving, and swimming (Fletcher et al., 2007). According to the latest report on the economic contribution of recreational boaters by Royal Yachting Association (2014, p. 8), 72 % of the UK's coastal berths (about 37,000) are in England, of which 25 % are situated

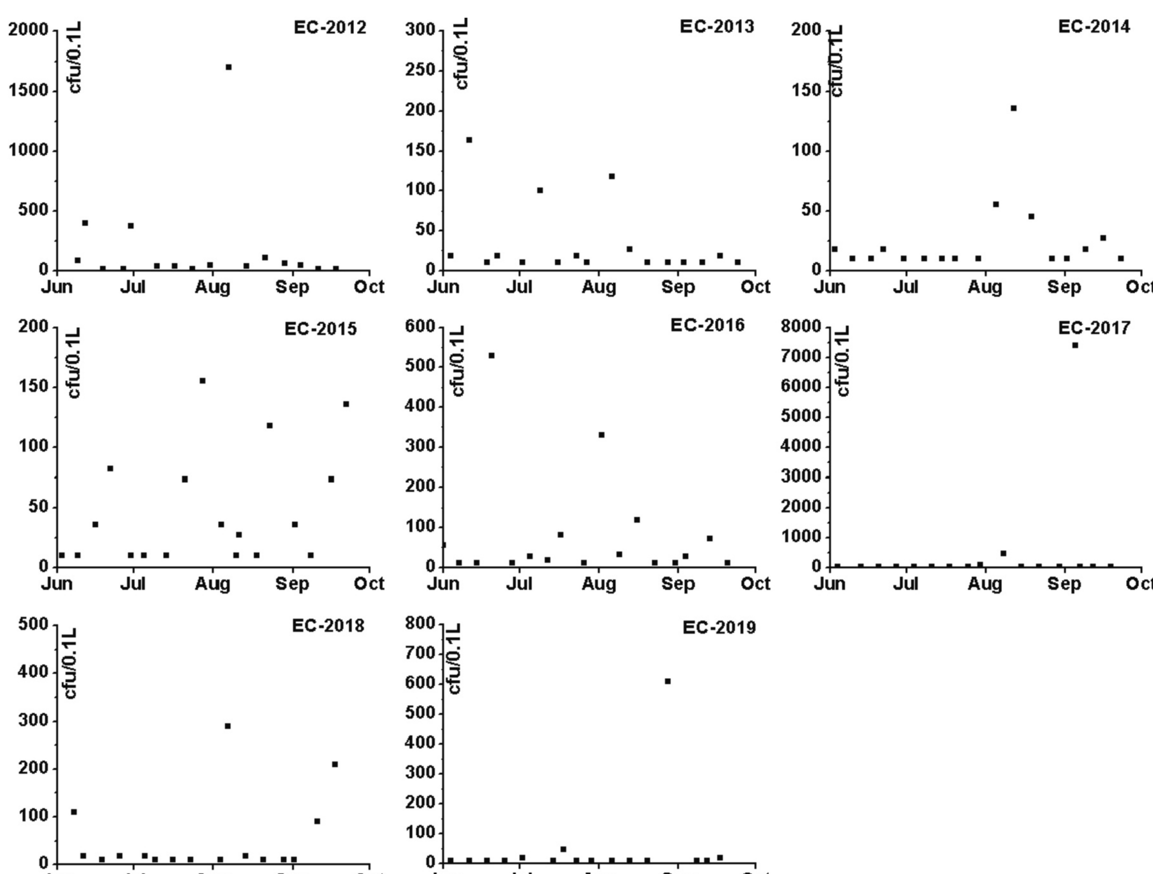

Fig. 2. Time series plots for *Escherichia coli* (EC) at a designated bathing beach (sampling point a) in Cowes (2012–2019).

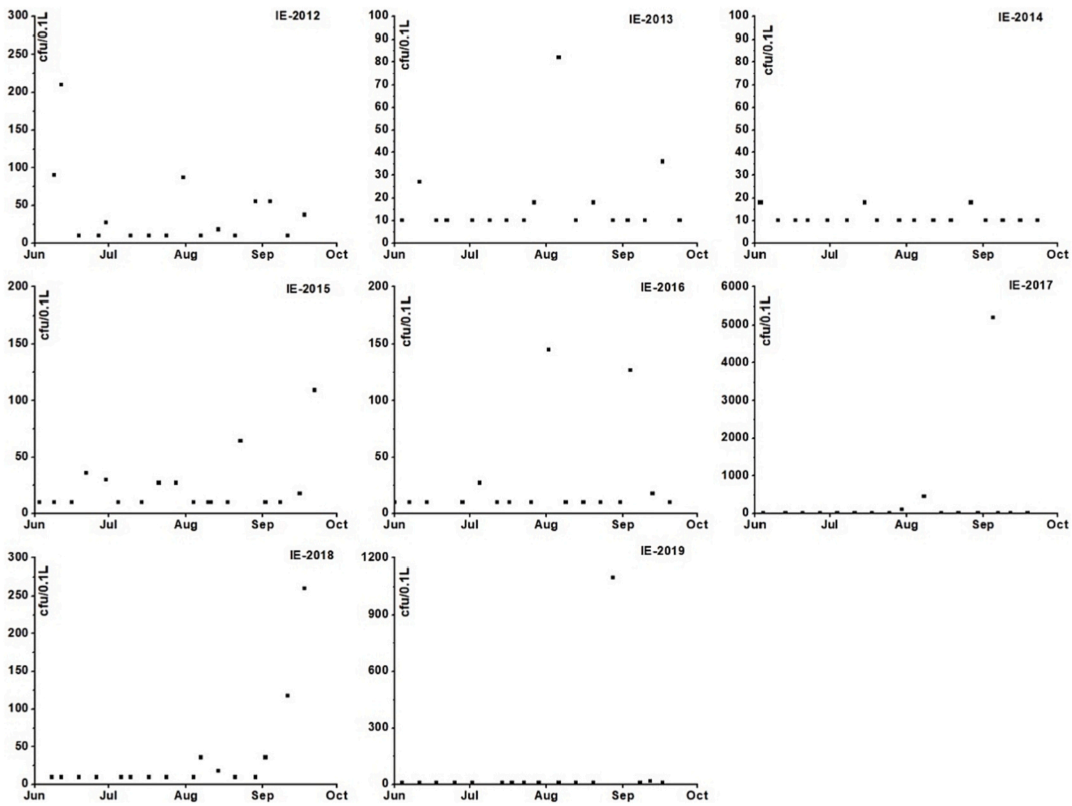

Fig. 3. Time series plot for *intestinal enterococci* (IE) at a Designated Bathing Beach (sampling point a) in Cowes (2012–2019).

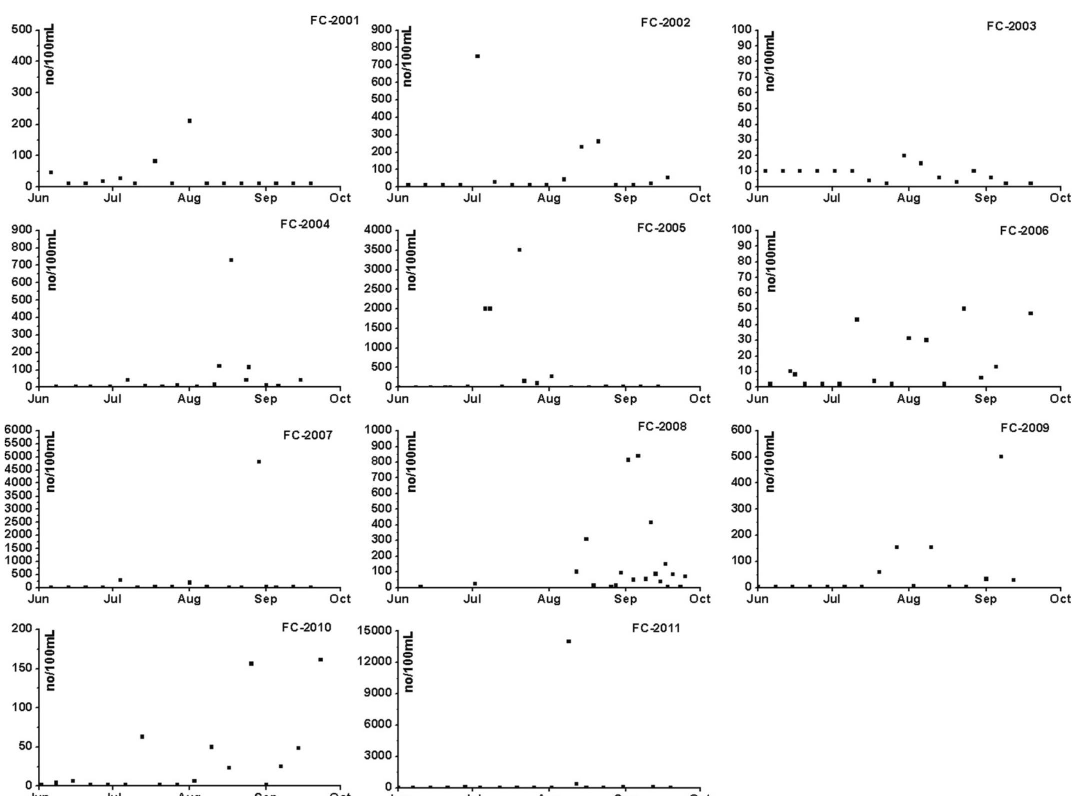

Fig. 4. Time series plot for *faecal coliforms* (FC) at a Designated Bathing Beach (sampling point a) in Cowes (2001–2011).

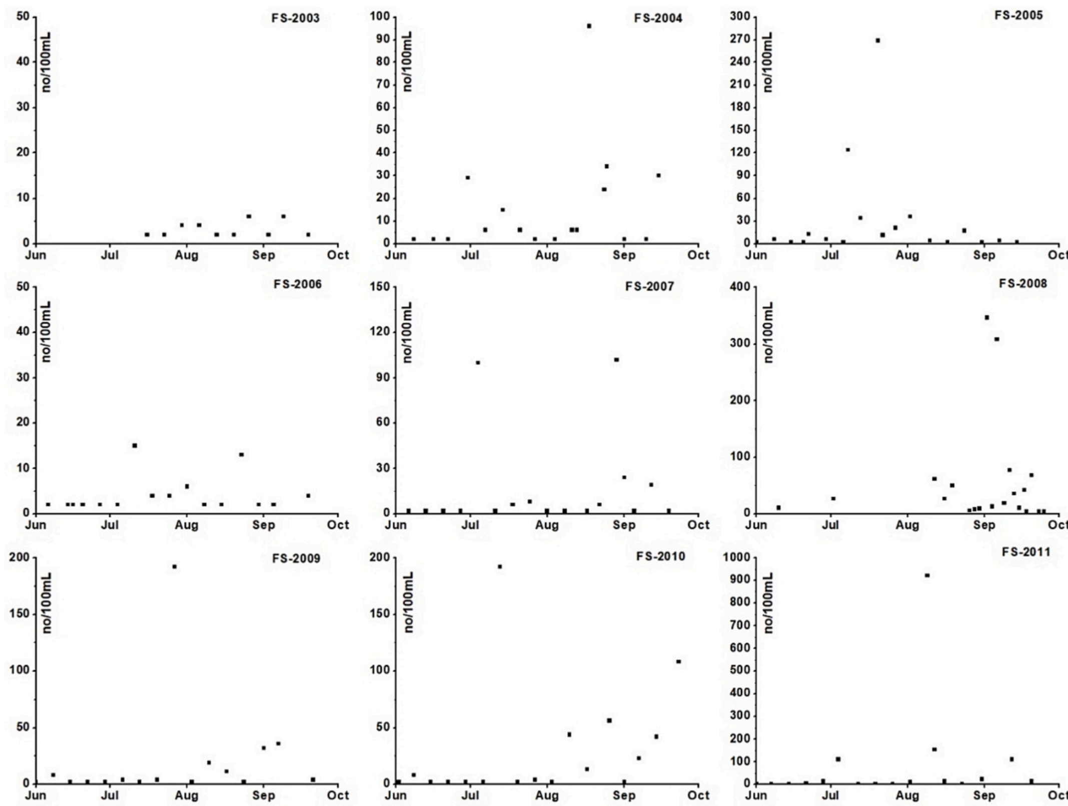

Fig. 5. Time series plot for *faecal streptococci* (FS) at a Designated Bathing Beach (sampling point a) in Cowes (2003–2011).

in Solent. Cruises and sailing races are held in Cowes from March to October every year. In addition to Cowes Week, the Round the Island Race, usually held at the end of June, attracts over 1400 boats and around 15,000 sailors on a single day; as well as other smaller events such as the Cowes Keelboat Solent Series and Cowes Keelboat Championship (Cowes Harbour Commission, 2020).

The start point for the study was dictated by data availability; the earliest relevant record of water quality is from 2001 and the records for Cowes Week from the official website also start at 2001 (Cowes Week Limited, 2020). Monthly water quality data with 7 parameters from 4 sampling points were obtained from the Environment Agency Water Quality Archive (Beta). The three data sampling points shown in Fig. 1 and detailed in Table 1 were chosen because: i) they are geographically close to the venue for Cowes Week and ii) water quality data were recorded continuously at these sites during the study period.

The analysis has been undertaken using United Kingdom Environment Agency (EA) water quality information monitoring system (WIMS) data at designated locations. The water quality indicators chosen are concentrations of nitrite, nitrate, and oxygen saturation, and numbers of *faecal coliforms* (FC), *faecal streptococci* (FS), *Escherichia coli* (EC), and *intestinal enterococci* (IE). These indicators best reflect the impact(s) of recreational boating on water quality, and the records are relatively complete from 2001 to 2019. FC, FS, EC, and IE are the main bacterial indicators of faecal pollution in water quality management and health risk assessment (Meays et al., 2004). In 2012, the UK's Environment Agency stopped testing and recording FC and FS, and replaced them with EC and IE, for they have more advantages as faecal indicators (Odonkor and Ampofo, 2013; Nicholas et al., 2013). For completeness, all four indicators were studied. Although other water quality indicators are provided in the WIMS database, their data scale is limited and discontinuous and generally insufficient/inadequate for detailed time series analysis.

From 2001 to 2011, FC and FS were used to assess bacterial condition; from 2012, EC and IE replaced the former indicators. For EC and IE, colony-forming unit per 0.1 L water (cfu/0.1 L) was used as the unit of measurement; for FC and FS, the number of bacteria per 100 mL water (no/100 mL) was used.

Data are available for designated bathing beaches and designated shellfisheries. Different types of sampling points have different parameters recorded. Details of the four sampling points are shown in Table 1. For designated bathing beaches, the recorded parameters are either related to the condition of beaches, such as the number of beach users and litter on the beach, or have direct impacts on human health, such as the number of *E. coli* and intestinal enterococci in bathing water (European Commission Directive 2006/7/EC). Tiwari et al. (2021) provide a comprehensive over view of bathing water quality monitoring practices in Europe, highlighting the challenges involved in sampling and data interpretation.

Time series box-whisker plots for the studied period were generated to visually summarise and depict the variation of the water quality indicators (McLeod et al., 1991; Helsel and Hirsch, 1992). They are particularly useful since they provide the skewness and symmetry of data, show outliers, and can be applied without statistical assumptions (Massart et al., 2004). The widely used non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was used to detect significant trends in the time series data.

3. Results

3.1. Bacterial indicators

The bacterial indicators all show an almost consistent temporal pattern, with peak values often corresponding to Cowes week (Figs. 2–5, Tables A1–A3). The EC concentrations at a Designated Bathing Beach in Cowes from 2012 to 2019 each year from June to September are shown in Fig. 2. Over the eight years, the maximum number recorded was 7400 cfu/0.1 L in September of 2017. The minimum number was 10 cfu/0.1 L, approximately the detection limit of the assay used, and well below the

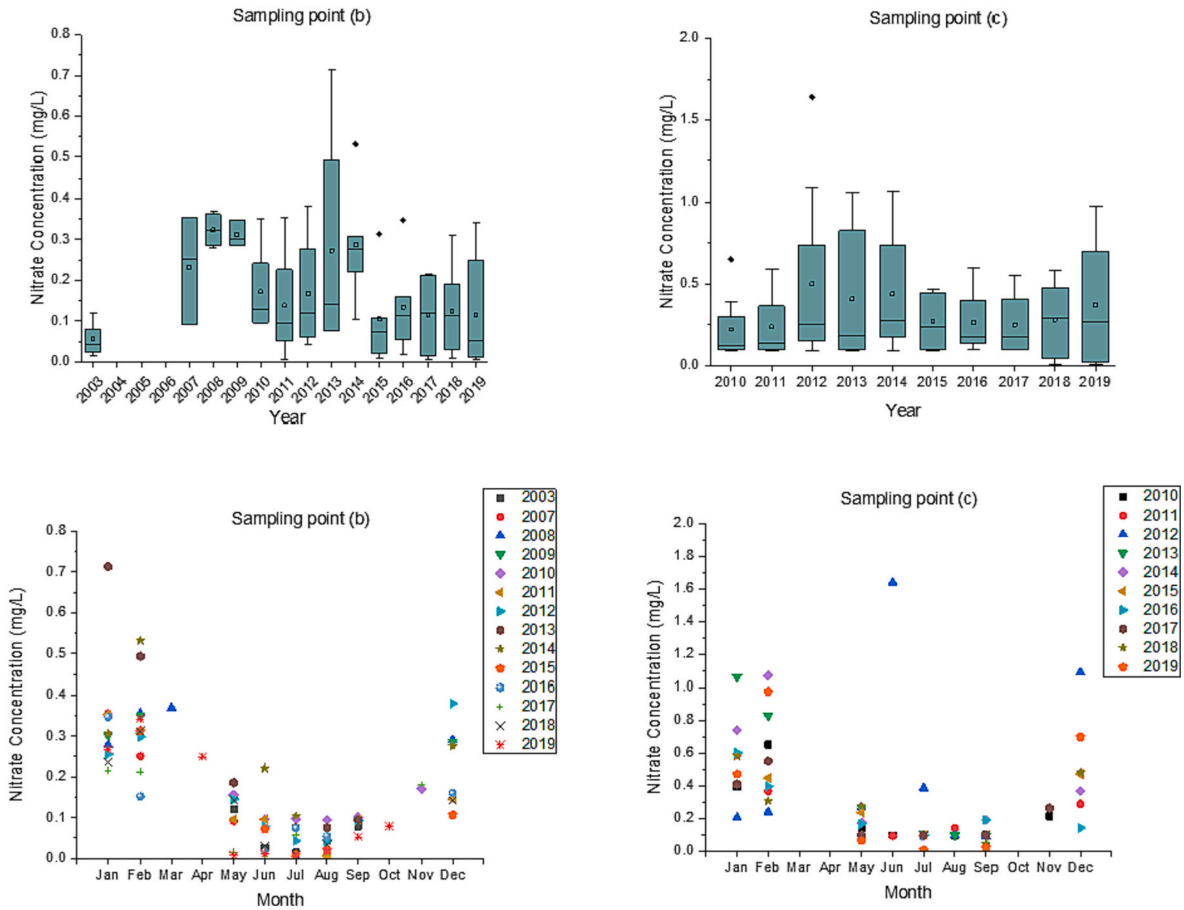

Fig. 6. Nitrate concentration at sampling points (b) and (c) in water in the Solent (2003–2018).

value of ≤500 cfu/0.1 L set out in the European Commission's Bathing Water Directive (Directive 2006/7/EC) that was in force at the time for marine recreational water. Among the 139 results, 53.2 % were recorded as 10 cfu/0.1 L. In 2013 and 2018, the peak occurred during Cowes Week. However, in 2013, two other relatively high values were observed in June and July; in 2018, there was another increasing trend in September, but the maximum was lower than the one in August. Note there was some heavy rain around Cowes during August–September 2018, which could have contributed to faecal runoff. For 2012, 2014, 2016, and 2017, the peak value for EC did not appear during Cowes Week but in the week immediately before or after the event. For example, in 2012, the maximum of 1700 cfu/0.1 L occurred on August 7th, four days before the start of Cowes Week. In 2014, the value increased from August 5th (the third day of Cowes Week) to a maximum value on August 12th (three days after Cowes Week) and then down on August 19th. With the exception of 2015, the overall trend typically shows EC values increasing to a maximum in the lead up to (when boats start to arrive), or just after, Cowes Week, and then dropping after the event (when boats leave).

The values for IE from 2012 to 2019 each year from June to September are shown in Fig. 3. It is difficult to directly compare these values to legal limits since the latter are related to minimum sampling frequencies per bathing season. The maximum was 5200 cfu/0.1 L in September of 2017, the same date as the maximum of EC occurred; the minimum was 10 cfu/0.1 L. Among the 139 results, 98 (70.5 %) of them were recorded as 10 cfu/0.1 L. In six of the eight years (2013, 2015, 2016, 2017, 2018, and 2019), IE values increased significantly about two weeks after Cowes Week. A rise in IE was observed during Cowes Week in 2013, 2016, and 2018. In 2013, the maximum of the four months occurred on Aug 6th, the third day of Cowes Week; in 2016, a peak value appeared on Aug 2nd, the fourth day of Cowes Week. Data for 2017–2019 show the same trend. During 2012, 2014 and 2015, IE showed no marked change during Cowes week, maintaining at 10 cfu/0.1 L. In 2012, a peak value occurred on June 12th, two months before Cowes Week. In 2014, no high values were recorded during Cowes Week; the highest value was 18 cfu/0.1 L over the four months. In 2015, higher values occurred a week after Cowes Week. Hence, although the trends are less consistent than for EC, the overall trend tends to show IE increasing to a maximum in the lead up to, or just after, Cowes Week, and then dropping after the event.

The values of FC reported from 2001 to 2011 are shown in Fig. 4. A total of 191 results were recorded during the 11 years. During 2002, 2004, 2005, 2006, and 2011, increasing trends or peak values occurred during Cowes Week. In 2005, the result was ten times higher than the median value when an extreme value of 3497 FC/100 mL occurred ten days before Cowes Week. The maximum value from 2001 to 2011 occurred on August 9th, the third day of Cowes Week in 2011. The FC level subsequently dropped on August 12th and went down to the lowest level on August 16th.

For the other years (2001, 2003, 2007, 2008, 2009, and 2010), the peak value for FC did not appear during Cowes Week but in the week immediately before or after the event. To illustrate, in 2001, an increasing trend started from July 18th and reached a peak of 210 FC/100 mL on August 1st, three days before Cowes Week. In 2003, FC rose to a maximum of 20/100 mL on July 30th, three days before Cowes Week, and then declined. It is worth noting that additional peaks of FC occurred during September for four years (2006, 2008, 2009, 2010), about 2–3 weeks after the end of Cowes Week. The overall trend typically shows FC values increasing to a maximum in the lead up to, or just after, Cowes Week, and then dropping after the event.

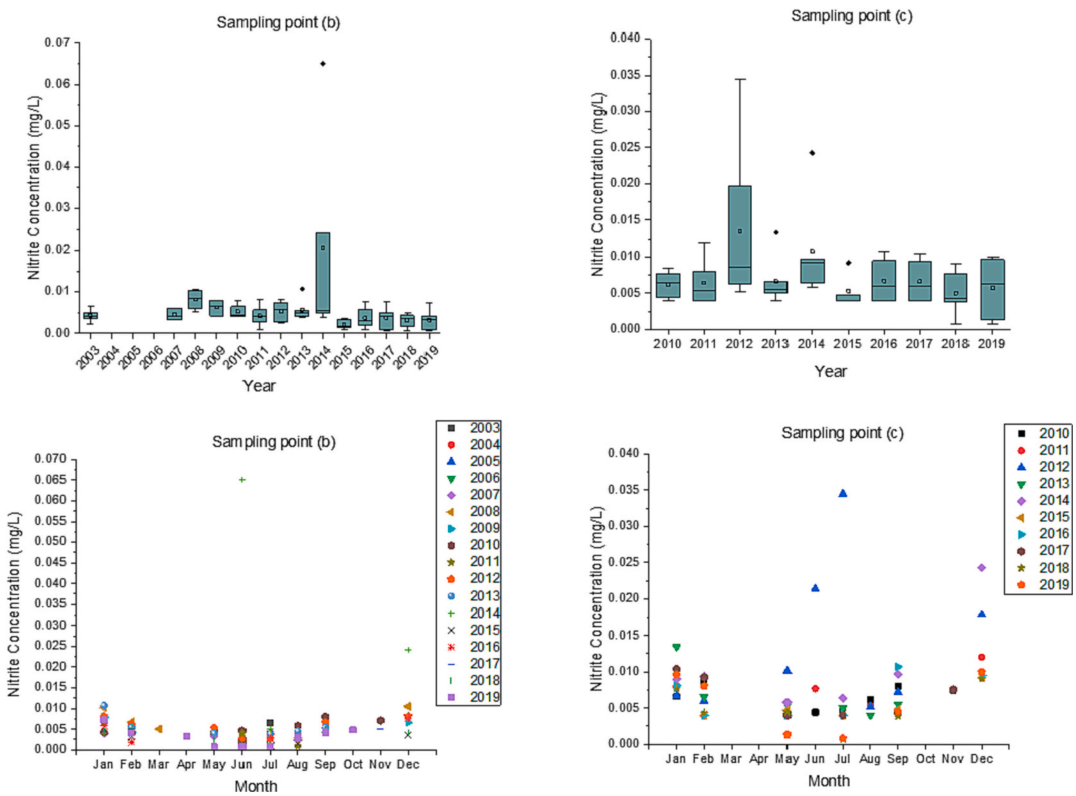

Fig. 7. Nitrite concentrations at sampling points (b) and (c) in water in the Solent (2003–2018).

The values of FS reported from 2003 to 2011 are shown in Fig. 5. A total of 153 results were recorded during these eight years. Only 2011 showed a significant upward trend during Cowes Week with the highest value of 920 FS/100 mL being recorded on Aug 9th, the third day of Cowes Week. Three days after, the value dropped to 154. From 2004 to 2010, FS results did not show a particular trend during Cowes Week.

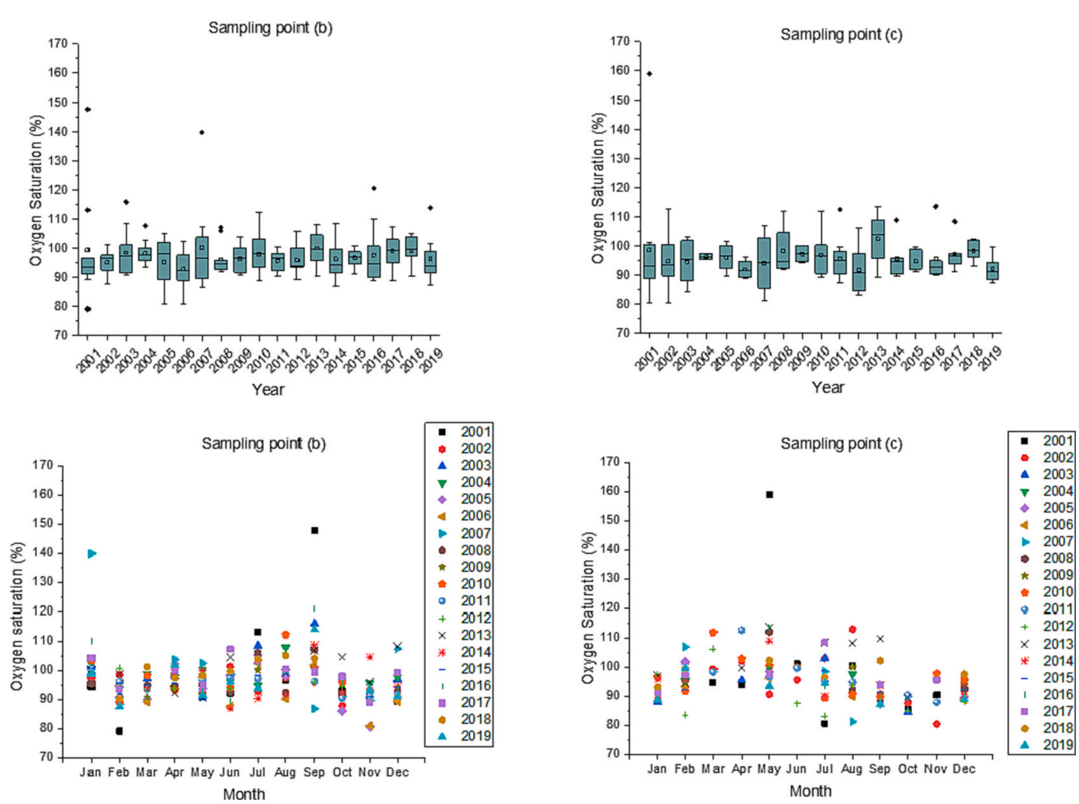

Fig. 8. Oxygen saturation at sampling points (b) and (c) in water in the Solent (2001–2018).

However, trends were observed just before or after Cowes Week. The overall trend for FS is not as clear as for the other bacterial indicators studied, but still typically shows FS increasing to a maximum in the periods leading up to, or just after, Cowes Week, and then dropping after the event.

Descriptive statistics for all indicators are shown in Tables A1–A3 in Appendix A.

3.2. Nitrogen concentrations

Table A2 shows descriptive statistics for nitrate and nitrite concentrations at shellfisheries close to Cowes (sampling points (b) and (c)). The values for nitrate and nitrite at sampling point (c) are higher than those at sampling point (b). The skewness values for all nitrogen indicators are positive, which indicates that the data is asymmetrically distributed and the body of the distribution is centred on the left. Mann-Kendall tests showed no obvious trend for nitrate and nitrite concentration; all P-values were >0.1.

Monthly/yearly changes in nitrate and nitrite concentrations are shown in Figs. 6 and 7, respectively, during the study period. Nitrate and nitrite concentrations at both sampling points show a decreasing trend from May and lowest values each year between June and September. For most of the recorded years, from June to September, nitrate and nitrate concentrations at both sampling points were lower than the mean value.

3.3. Oxygen saturation

Table A3 shows descriptive statistics for oxygen saturation at shellfisheries close to Cowes (sampling points (b) and (c)). The skewness values for both sampling points are positive, indicating that the data is asymmetrically distributed and the body of the distribution is centred on the left. The Mann-Kendall test showed no obvious trend for oxygen saturation as all P-values were >0.1. Annual and monthly changes in oxygen saturation are shown in Fig. 8; these were not significant at both sampling points, although obvious outliers occurred in 2001 and 2007.

4. Discussion

4.1. Bacterial indicators

The concentrations of four bacterial indicators (EC, FS, FC, and IE) in local marine surface waters, for most years of the study period, often changed markedly between the period just before the start of, and after the end of, Cowes Week (see Figs. 2–5). As there were no pollution incidents recorded on the Isle of Wight during these periods (Environment Agency, 2020), and local rainfall during these periods was/is typically relatively low, and shows low seasonal variation (Cefas, 2013), the results suggest that recreational boating during Cowes Week is the main source of these bacteria. As the four bacterial indicators are the main criteria for faecal pollution (Meays et al., 2004), emissions of wastewater from recreational boating during Cowes Week must have led to the observed increase in faecal contamination.

The number of active recreational boats is therefore likely to be a critical factor affecting the concentration of marine faecal pollution. However, activity data for small recreational boats in the Solent and around Cowes is not recorded. According to a study by Smallwood and Beckley (2008), the occupancy rate for these vessels is higher in warm months, ranging from 70 % to over 136 %, whilst in cold months, the highest occupancy rate is no >60 %. In England, the temperature during June to September is higher than in other months (Met Office, 2012). Therefore, although we do not have exact data for recreational boats during Cowes Week, we can safely assume that it is higher than at other times of the year.

Few studies of this type have previously been undertaken. However, our results are consistent with previous studies. Faust (1982) showed that during a holiday weekend, the concentrations of FC and FS increased about tenfold soon after the arrival of the boats in an estuarine area of Rhode River (Maryland, USA) and decreased almost immediately after the end of boating activities. Guillon-Cottard et al. (1998) found that the concentrations of FC and FS exceeded guideline levels for shellfish consumption in France and Europe when boating activity was at its peak at Saint Gervais harbour. Sobsey et al. (2003) found that FC concentrations increased significantly in Southern California as the boating number and berth occupancy rate increased, causing faecal contamination to both open water and unconfined marina.

Although our results suggest that recreational boating is the key contributor to local faecal contamination of marine surface waters during Cowes Week, we cannot fully eliminate other factors. Besides sewage from boating, other sources can also introduce faecal bacteria into the marine environment. The major pathways are animal faecal; resuspension from sediments; runoff from estuaries, land and storm-water overflows (Whitman et al., 2010). Storm water overflows may be an intermittent source and some monitoring takes place, although recently it has come to light that the reporting of such events has been substantially flawed- the regional operator Southern Water having been sentenced to pay a record £90 million in fines for widespread pollution after pleading guilty to 6971 unpermitted sewage discharges (Environment Agency, 2021). Microbial levels are also related to climatic and hydraulic parameters, including water flow, rainfall, relative humidity, vapour pressure, sea level pressure, sunshine hours, and cloud cover (Henry et al., 2016). A detailed description of the complex tidal and water circulation patterns that characterize the Solent Strait is provided by Cefas (2013); currents in these coastal waters are principally guided by a blend of tide, wind and freshwater inputs, and tidal streams are expected to dominate patterns of water circulation under most conditions.

Faecal bacteria in bathing water are linked to health issues for bathers. Cabelli et al. (1982) suggested that swimmers' gastrointestinal symptoms are positively correlated with the mean density of enterococci in water: when the enterococcus density reaches 10^2 per 100 mL of water, ~40 in every 1000 swimmers may develop gastrointestinal symptoms. In addition to gastrointestinal problems, bacteria in the water can cause other illness. A study by Fleisher et al. (1996) showed that when bathers are exposed to >60/100 mL of FS and 100/100 mL of FC, they are more likely to develop respiratory diseases and eye, ear and skin diseases, and the prevalence increases with increased density of those bacteria. We found that the increase in bacterial indicators around Cowes Week exceeded the above disease-causing levels, which may cause health risks for bathers. For the health of bathers, the bathing water during Cowes Week should be monitored closely and access might need to be restricted if necessary. At present there is no requirement for monitoring beyond the current statutory requirements of four per bathing season for *E. coli* and 5 in 30 days for enterococci (Tiwari et al., 2021).

4.2. Nitrogen concentrations

The concentrations of inorganic nitrogen compounds in coastal sea surface waters are typically characterized by a pronounced seasonality; higher concentrations tend to be observed in winter which decrease to low values in the period of high primary productivity between spring and midsummer (Nausch et al., 2008). The UK's Environment Agency has been aware of eutrophication in selected Solent estuaries for decades and consequently, it has undertaken a series of eutrophication reviews and used regulatory means to reduce nitrogen input. The Solent Forum (2022) highlights Environment Agency data that shows reduced amounts of green macroalgae in several Solent estuaries, particularly over the last decade; it has taken time to see signs of recovery due to biological time lag and the influence of groundwater. Concentrations of nitrate and nitrite did not show unexpected trends during the studied period. However, the results suggest that nitrate and nitrite from recreational boating may have little impact on overall concentrations.

There are many factors that affect the concentration of nitrate and nitrite in the marine environment. It is likely that nitrate and nitrite concentrations in marine surface waters are typically low between June and September (incorporating Cowes Week). First, there are many sources of nitrogenous nutrients in the ocean, including atmospheric precipitation, fertiliser, sewage, and land runoff. In the Northern temperate zone, the three largest sources of dissolved inorganic nitrogen in seawater have been reported as fertilisers (37 %), manure (25 %), and N_2-fixation (24 %) (Capone et al., 2008). The first two sources are mainly from farming. Farming on the Isle of Wight, including areas that runoff into the Medina river and estuary, includes agriculture and stockbreeding. The main crops on the island are wheat and maize (DEFRA, 2019a), whilst the main livestock is cattle, dairy cattle, beef, and sheep (DEFRA, 2019b), with both able to introduce fertiliser and manure into the ocean. According to the rainfall data at a climate station on the Isle of Wight from 1980 to 2010, rainfall averages typically fall from April and remain relatively low until August (Shanklin (Isle of Wight) UK climate averages, 2020). Due to gaps in nitrite and nitrate data in April, trends were only observed between May and September. We suspect that low nitrate and nitrite concentrations from June to September may be associated with lower rainfall and higher productivity in marine plants (note: the Solent is an Important Plant Area containing a large number of areas of seagrass, sea-purslane, common sea-lavender and thrift, together with rare marine plants like small cordgrass and foxtail stonewort). Lower rainfall means that less fertiliser and manure are washed into the ocean, resulting in less discharge. As nutrients for phytoplankton, nitrite and nitrate are consumed as they grow (Capone et al., 2008). Indeed, a study by Holley et al. (2007) reports that nutrient levels tend to decrease in the high-salinity estuary area in Southampton Water and the Solent during summer. The low nutrient level is not due to a "summer bloom", but a limiting factor for the growth of phytoplankton. Thus, the low concentrations of nitrate and nitrite are unlikely to be caused by the growth and reproduction of marine phytoplankton.

4.3. Oxygen saturation

Oxygen saturation is relatively stable in marine surface waters close to Cowes. In general, dissolved oxygen should be lower in summer than other seasons throughout the year because higher temperatures can reduce the dissolution of oxygen (Truesdale et al., 1955). Steady and ongoing ocean warming has been reported in UK coastal waters (Zapata-Restrepo et al., 2019). This affects the life history and fitness of marine organisms by, for example, increasing animal metabolism and reducing oxygen availability (Giomi et al., 2019). In coastal environments, animals live adjacent to photosynthetic organisms whose oxygen supply sustains metabolic requirements and may compensate for acute warming. These factors all contribute to the results showing no significant decrease in oxygen saturation in summer. In addition to temperature, oxygen saturation can be affected by inputs of organic matter and nutrients, photosynthesis, and surface disturbance. As discussed in Section 4.2, low nutrient levels in the Cowes area in the summer limit planktonic growth and thus lead to reduced oxygen consumption. An increase of vessel activity during Cowes Week will lead to increased disturbance to the water body but this is unlikely to affect the dissolution of oxygen in this location.

5. Conclusions

Using carefully selected indicators of pollution, a long-term historical analysis of the impacts of recreational boating on marine surface water quality during a major regatta in an internationally crucial waterway has been completed. Robust analysis on the best quality, most authoritative available data has been carefully undertaken. The findings have important implications for the regulation of, and future monitoring and management strategies for, discharges from recreational boats during extended regattas:

1. Sewage discharge from small recreational boats immediately before, during and after the Cowes Week regatta is the key contributor to localised faecal contamination of marine surface waters. For most years during the study period, the level of four bacterial indicators markedly increased between the week before the start of Cowes Week and after the end of Cowes Week.
2. Bathing water quality monitoring and pollution warning systems should be strengthened for bathers in the time periods around extended regattas such as Cowes Week. Although the overall quality of bathing water around Cowes has typically been reported as "good" or "excellent" over the past few years, localised high levels of bacteria in this period may cause adverse impacts on the health of bathers. Bathing water quality monitoring and pollution warning systems should be strengthened for bathers in the time periods

around this type of regatta and access to bathing water areas may need to be restricted.

3. Although pump-out facilities for sewage collection are usually available at locations such as Cowes, the high level of bacteria in surface waters suggests improvements may be required, especially for smaller vessels which are currently not regulated. Adequate and affordable local facilities for recovering sewage wastewater from recreational boats should be provided alongside appropriate mechanisms for communication to sailors.

CRediT authorship contribution statement

D. Xiong: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **I.D. Williams:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. **M.D. Hudson:** Methodology, Validation, Visualization, Writing – review & editing. **P.E. Osborne:** Methodology, Validation, Visualization, Writing – review & editing. **L.M. Zapata-Restrepo:** Methodology, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This paper has been produced as part of the European Union project "EMERGE: Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions" (referred to as "EMERGE"). The EMERGE project has received funding from the European Union's Horizon 2020 - Research and Innovation Framework Programme action under grant agreement No 874990. We are grateful to colleagues from the United Kingdom Environment Agency's Water Quality Information Monitoring System for provision of data.

Appendix A

Table A1
Descriptive statistics for bacterial indicators around Cowes (at a Designated Bathing Beach) during the study period (sampling point "a" in Fig. 1).

	EC	IE	FC	FS
Study period	2012–2019	2012–2019	2001–2011	2003–2011
Units	ccfu/0.1 L		Number/100 mL	
Number of data	139	139	191	153
Minimum value	10	10	2	2
Maximum	7400	5200	14,000	920
Mean	115.4	73.86	190.2	30.37
Median	10	10	10	4
Standard deviation	645.2	451.4	1115	89.5
Skewness	10.46455	10.62759	10.50174	7.139957

Table A2
Descriptive statistics for nitrate and nitrite concentrations (mg/l) at shellfisheries close to Cowes during the study period (sampling points "b" and "c" in Fig. 1).

	Nitrate		Nitrite	
Sampling point	b	c	b	c
Study period	2003, 2007–2019	2010–2019	2003, 2007–2019	2010–2019
Number of samples	98	73	98	73
Minimum	0.001	0.0062	0.0007	0.0007
Maximum	0.713	1.64	0.065	0.0345
Mean	0.155	0.3469	0.0052	0.0076
Median	0.096	0.234	0.0040	0.0065
Standard deviation	0.139	0.334	0.007	0.005
Skewness	1.169904	1.544245	6.664742	0.3341222

Table A3
Descriptive statistics for oxygen saturation (%) at shellfisheries close to Cowes during the study period (sampling points "b" and "c" in Fig. 1).

	Sampling point b	Sampling point c
Study period	2001–2019	2001–2019
Number of samples	253	146
Minimum	79.1	80.4

(*continued on next page*)

Table A3 (*continued*)

	Sampling point b	Sampling point c
Study period	2001–2019	2001–2019
Maximum	147.8	158.9
Mean	97.3	95.9
Median	96.6	94.8
Standard deviation	7.7	2.7
Skewness	2.03749	2.7089

References

Bianchi, A.P., Varney, M.S., 1998. Volatile organic compounds in the surface waters of a British estuary. Part 1 Occurrence distribution and variation. Water Res. 32, 352–370.

Blue Marine Foundation, 2019. Solent oyster recreation project. Available from: https://www.bluemarinefoundation.com/wp-content/uploads/2019/09/20211026_Solent-Oyster-Restoration-Project-1.pdf. Accessed 30 June 2022.

Bray, S., McVean, E., Nelson, A., Herbert, R., Hawkins, S., Hudson, M., 2011. The regional recovery of Nucella lapillus populations from marine pollution, facilitated by man-made structures. J. Mar. Biol. Assoc. U. K. 92 (7), 1585–1594.

Burgin, S., Hardiman, N., 2011. The direct physical, chemical and biotic impacts on australian coastal waters due to recreational boating. Biodivers. Conserv. 20 (4), 683–701.

Cabelli, V., Dufour, A., McCabe, L., Levin, M., 1982. Swimming associated gastroenteritis and water quality. Am. J. Epidemiol. 115 (4), 606–616.

Capone, D., Bronk, D., Mulholland, M., Carpenter, E., 2008. Nitrogen in the Marine Environment, 2nd ed. Academic Press. https://doi.org/10.1016/B978-0-12-372522-6.00001-3. ISBN 9780123725226.

Carcinus Ltd., 2021. Review of The Solent 2013 Sanitary Survey. Carcinus 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 retained EU Law Regulation (EU) 2019/627. Available at: https://www.carcinus.co.uk/wp-content/uploads/2021/10/J0591_21_08_16_Solent_Sanitary_Survey_Review_v3.0_Final.pdf [Accessed 20 September 2022].

Centre for Environment, Fisheries amp, Aquaculture Science (Cefas), 2013. Classification of bivalve mollusc production areas in England and Wales. Sanitary Survey Report: The Solent. Available at: https://www.cefas.co.uk/media/1uufnblg/final-sanitary-survey-report-solent-2013-dj-table-issues.pdf [Accessed 20 September 2022].

Cowes Harbour Commission, 2020. Local yacht clubs and racing. Available from: https://www.cowesharbourcommission.co.uk/local_yacht_clubs_and_racing [Accessed 8 July 2020].

Cowes Week Limited, 2020. Cowes Week - The History of Cowes Week. Available from: http://www.cowesweek.co.uk/web/code/php/main_c.php?map=cw21&ui=cw4&style=std&override=&section=regatta&page=history [Accessed 15 June 2020].

Department of Environment Fisheries and Food (DEFRA), 2019. Maps of crop areas in 2000 and 2010 across England. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/183108/defra-stats-foodfarm-landuselivestock-june-detailedresults-cropmaps111125.pdf [Accessed 9 August 2020].

DEFRA, 2019. Maps of livestock populations in 2000 and 2010 across England. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/183109/defra-stats-foodfarm-landuselivestock-june-detailedresults-livestockmaps111125.pdf [Accessed 9 August 2020].

EC, 2006. European Commission 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. Off. J. Eur. Union 64, 37–51.

EMERGE (Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions, 2021. https://emerge-h2020.eu/ [Accessed 22 July 2021].

Environment Agency, 2020. Pollution incidents history: district of Isle of Wight. Available from: https://environment.data.gov.uk/bwq/profiles/data-pollution-incident.html?district=Isle%20of%20Wight [Accessed 04 August 2020].

Environment Agency, 2021. Record £90m fine for Southern Water following EA prosecution. Available at. https://www.gov.uk/government/news/record-90m-fine-for-southern-water-following-ea-prosecution. Accessed 30 June2022.

Faust, M., 1982. Contribution of pleasure boats to fecal bacteria concentrations in the Rhode River estuary, Maryland, U.S.A. Sci. Total Environ. 25 (3), 255–262.

Fleisher, J., Kay, D., Salmon, R., Jones, F., Wyer, M., Godfree, A., 1996. Marine waters contaminated with domestic sewage: nonenteric illnesses associated with bather exposure in the United Kingdom. Am. J. Public Health 86 (9), 1228–1234.

Fletcher, S., Johnson, D., Hewett, T., 2007. Coastal management in the solent: an introduction. Mar. Policy 31 (5), 585–590.

Giomi, F., Barausse, A., Duarte, C.M., Booth, J., Agusti, S., Saderne, V., Anton, A., Daffonchio, D., Fusi, M., 2019. Oxygen supersaturation protects coastal marine fauna from ocean warming. Science Advances 5 (9), eaax1814. https://doi.org/10.1126/sciadv.aax1814.

Gough, M.A., Fothergill, J., Hendrie, J.D., 1994. A survey of southern England coastal waters for the s-triazine antifouling compound irgarol 1051. Mar. Pollut. Bull. 28, 613–620.

Guillon-Cottard, I., Augier, H., Console, J., Esmieu, O., 1998. Study of microbiological pollution of a pleasure boat harbour using mussels as bioindicators. Mar. Environ. Res. 45 (3), 239–247.

Helsel, D.R., Hirsch, R.M., 1992. Statistical Methods in Water Resources, Vol. 49. Elsevier Science Ltd, Amsterdam, pp. iii–xvi.

Henry, R., Schang, C., Kolotelo, P., Coleman, R., Rooney, G., Schmidt, J., Deletic, A., McCarthy, D., 2016. Effect of environmental parameters on pathogen and faecal indicator organism concentrations within an urban estuary. Estuar. Coast. Shelf Sci. 174, 18–26.

Holley, S.E., Purdie, D.A., Hydes, D.J., Hartman, M.C., 2007. 5 years of plankton monitoring in Southampton Water and the Solent including FerryBox, Dock Monitor and discrete sample data. National Oceanography Centre. Available from: https://eprints.soton.ac.uk/49735/1/NOCS_RC31.pdf [Accessed 8 August 2020].

Houston, M., Lowthion, D., Soulsby, P.G., 1983. The identification and evaluation of benthic macroinvertebrate assemblages in an industrialised estuary-Southampton water, UK, using a longterm, low-level sampling strategy. Mar. Environ. Res. 10, 189–207.

Kendall, M.G., 1975. Rank Correlation Methods, 4th Edition. Charles Grifin, London.

Kersh, J., James, C., Gough, H., 2020. Impacts of high-strength boat waste on activated sludge processes. J. Environ. Eng. 146 (5), 04020023.

Knap, A.H., Peter, P.J., Lysiak, E., 1982. Petroleum hydrocarbons in sediments of Southampton water estuary. Mar. Environ. Res. 7, 235–249.

Leon, L., Warnken, J., 2008. Copper and sewage inputs from recreational vessels at popular anchor sites in a semi-enclosed bay (Qld, Australia): estimates of potential annual loads. Mar. Pollut. Bull. 57 (6–12), 838–845.

Lindgren, J.F., Wilewska-Bien, M., Granhag, L., Andersson, K., Eriksson, K.M., 2016. Discharges to the Sea. In: Andersson, K., Brynolf, S., Lindgren, J.F., Wilewska-Bien, M. (Eds.), Shipping and the Environment: Improving Environmental Performance in Marine Transportation. Heidelberg, Springer, Berlin Heidelberg, Berlin, pp. 125–168.

Lloret, J., Zaragoza, N., Caballero, D., Riera, V., 2008. Impacts of recreational boating on the marine environment of cap de creus (Mediterranean Sea). Ocean & Coastal Management 51 (11), 749–754.

Mann, H.B., 1945. Non-parametric test against trend. Econometrica 13, 245–259.

Massart, D.L., Smeyers-Verbeke, J., Capron, X., Schlesier, K., 2004. Visual presentation of data by means of box plots. LCGC Eur. 18, 2–5.

McLeod, A., Hipel, K., Bodo, B., 1991. Trend analysis methodology for water quality time series. Environmetrics 2 (2), 169–200.

Meays, C., Broersma, K., Nordin, R., Mazumder, A., 2004. Source tracking fecal bacteria in water: a critical review of current methods. J. Environ. Manag. 73 (1), 71–79.

Met Office, 2020. Shanklin (Isle of Wight) UK Climate Averages. Available from: https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gcp0j39m4 [Accessed 10 August 2020].

Met Office, 2012. Climate Averages 1981–2010. Available from. https://web.archive.org/web/20130410093339/http://www.metoffice.gov.uk/climate/uk/averages/19812010/areal/england.html [Accessed 6 August 2020].

Milliken, A.S., Lee, V., 1990. Pollution impacts from recreational boating: a bibliography and summary review, National Oceanic and Atmospheric Administration. Available from: https://repository.library.noaa.gov/view/noaa/11840. Accessed 20 June 2020.

Nausch, G., Nehring, D., Nagel, K., 2008. Nutrient concentrations, trends and their relation to eutrophication. In: Feistel, R., Nausch, G., Wasmund, N. (Eds.), State and Evolution of the Baltic Sea, 1952-2005. John Wiley & Sons, Inc, Hoboken, NJ, pp. 337–366.

Nicholas, J.A., Willie, O.K.G., Mario, S., 2013. Indicators of microbial water quality IN. In: Fewtrell, L., Bartram, J. (Eds.), Water Quality: Guidelines, Standards and Health. IWA Publishing, London, pp. 295–296.

Odonkor, S., Ampofo, J., 2013. Escherichia coli as an indicator of bacteriological quality of water: an overview. Microbiol. Res. 4 (1), 2.

Royal Yachting Association, 2014. Economic contribution of the recreational boater. Available from: https://www.rya.org.uk/SiteCollectionDocuments/legal/Web%20Documents/Environment/Economic_Contribution_From_Recreational_Boating.pdf. Accessed 8 July 2020.

Sharp, J.H., 1983. The distributions of inorganic nitrogen and dissolved and particulate organic nitrogen in the sea. In: Edward, J.C., Douglas, G.C. (Eds.), Nitrogen in the Marine Environment. Academic Press, pp. 1–35. https://doi.org/10.1016/B978-0-12-160280-2.50009-2. ISBN 9780121602802.

Sinclair, R.G., Jones, E.L., Gerba, C.P., 2009. Viruses in recreational water-borne disease outbreaks: a review. J. Appl. Microbiol. 107 (6), 1769–1780.

Smallwood, C., Beckley, L., 2008. Benchmarking Recreational Boating Pressure in the Rottnest Island Reserve, Western Australia. Tour. Mar. Environ. 5 (4), 301–317.

Sobsey, M.D., Perdue, R., Overton, M., Fisher, J., 2003. Factors influencing faecal contamination in coastal marinas. Water Sci. Technol. 47 (3), 199–204.

Solent Forum, 2022. Nutrients. Available from. http://www.solentforum.org/services/Member_Services/css/Nutrients/ [Accessed 21 June 2022].

Solent Forum, 2020. Commercial fishing. Available from: http://www.solentforum.org/solent/our_economy_and_industries/fisheries/ [Accessed 8 July 2020].

Solent Marine Sites, 2022. Available at. http://www.solentems.org.uk/sems/SEMS_sites/ [Accessed 30 June 2022].

Tilley, E., 2014. In: Compendium of Sanitation Systems and Technologies. Eawag, pp. 12–13.

Tiwari, A., Oliver, D.M., Bivins, A., Sherchan, S.P., Pitkänen, T., 2021. Bathing water quality monitoring practices in Europe and the United States. Int. J. Environ. Res. Public Health 18 (11), 5513.

Truesdale, G., Downing, A., Lowden, G., 1955. The solubility of oxygen in pure water and sea-water. J. Appl. Chem. 5 (2), 53–62.

Whitman, R.L., Nevers, M.B., Przybyla-Kelly, K., Byappanahalli, M.N., 2010. Physical and biological factors influencing environmental sources of fecal indicator bacteria in surface water. In: The Fecal Bacteria, pp. 111–134.

Zapata-Restrepo, L.M., Hauton, C., Williams, I.D., Jensen, A., Hudson, M.D., 2019. Effects of the interaction between temperature and steroid hormones on gametogenesis and sex ratio in the European flat oyster (Ostrea edulis). Comp. Biochem. Physiol. A Mol. Integr. Physiol. 236, 110523 https://doi.org/10.1016/j.cbpa.2019.06.023.