Quantifying riverine nitrate loads in the Frome and Piddle catchments

1. Introduction

Reducing nitrate loads into Poole Harbour is key to improve water quality and aquatic habitat. The majority (73%) of nitrate delivery into Poole Harbour has been attributed to riverine inputs, particularly from the Frome and Piddle rivers (Environment Agency and Natural England, 2013). Source-apportionment data have indicated that the main contributors to inorganic nitrogen load are fertiliser from tillage land, manure from livestock, water recycling centres (Environment Agency and Natural England, 2013; Environment Agency and Natural England, 2021), and private sewerage systems (Kite & Natural England, 2023). Historic nitrate data show concentrations steadily increasing until 2003 and 2007 on the River Frome and River Piddle, respectively, but this routine monitoring ceased in 2016. Wessex Water Services Ltd has since installed three nitrate sensors on the Frome and Piddle rivers to re-establish empirical monitoring.

With these data, the aims are:

- to quantify and source-apportion nitrate loads;
- to understand the seasonal and inter-annual dynamics of nitrate export;
- to explore the environmental and anthropogenic controls upon nitrate export in the Frome and Piddle rivers.

2. Methods

Three nitrate sensors (Nitratax, Hach Lange) were installed at key locations on the Rivers Frome and Piddle to coincide with Environment Agency flow gauging stations (Figure 2-1) and geological sub-catchments (Table 2-1). Sensors were deployed at Louds Mill on 18/03/2016, East Stoke on 01/03/2016, and Baggs Mill on 16/12/2017, recording nitrate concentration at a 30-minute resolution until July 2020 and then subsequently at a 10-min resolution. Each sensor was calibrated on an annual basis for nitrate as N (NO_3-N) using 0 mg/L and 11.3 mg/L (50 mg/L NO_3) standard solutions, in addition to frequent inspection and maintenance. Daily mean river discharge data (m^3/s) were obtained from the Environment Agency for each site (Louds Mill station ID: 44205, East Stoke station ID: 44207, Baggs Mill station ID: 44002).

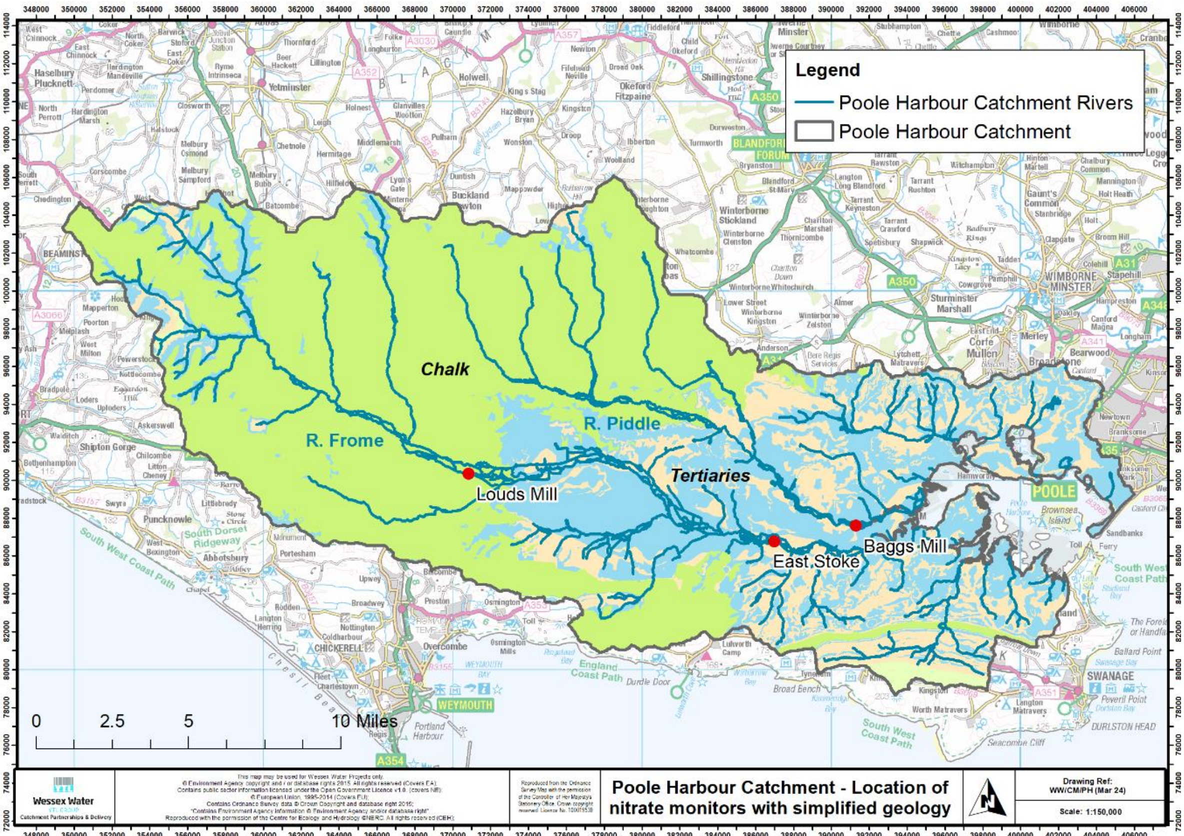

Figure 2-1. Poole Harbour geology and location of nitrate monitoring sides on the River Frome and River Piddle

River water samples were collected and analysed in a quality-assured laboratory for nitrate (NO_3-N mg/L) and nitrite (NO_2-N mg/L) to quality control sensor-based nitrate concentrations. These results showed nitrite concentrations contributed negligibly (< 0.6%) to total organic nitrogen (TON) and, therefore, NO_3-N was assumed equivalent to TON (mg/L).

Up until 30 September 2024, nitrate data completeness was 84% at Louds Mill, 86% at East Stoke, and 79% at Baggs Mill. Missing data were attributed to power loss and data transfer issues. Data gaps of less than eight hours were populated by linear interpolation. Longer periods of data loss were gap-filled using site specific discharge-nitrate concentration relationships. To calculate nitrate loads, high-frequency nitrate concentration data were averaged to daily mean concentrations and then multiplied by daily mean river discharge. Data have been separated and reported on for each hydrological year (1 October – 30 September).

Historical nitrate concentration data were available at East Stoke on the River Frome from regular (approximately weekly) spot sampling (NERC/FBA; Bowes, et al., 2011). To calculate monthly loads, corresponding nitrate concentrations and average daily river flow (m^3/s) were first averaged at a monthly timestep.

The nitrate load contribution from Wessex Water Services Ltd's water recycling centre (WRC) discharges were calculated via a regression between treated effluent nitrate concentration (sampled frequently) and daily total effluent discharge (m^3/d) on sampled days to establish a discharge-concentration relationship. This relationship was applied to measured daily total flow to calculate individual WRC nitrate loads within each monitored sub-catchment. Aggregated point-source nitrate load was subtracted from the total riverine nitrate load measured at the respective monitoring locations to define the ‘diffuse’ catchment load. This assumption acknowledges that the calculated ‘diffuse’ load will include intermittent, smaller volume, discharges such as septic tanks and combined sewer overflows (CSOs).

Table 2-1. Characteristics of monitored catchments on the River Frome and River Piddle.

	Louds Mill (Frome)	**East Stoke (Frome)**	**Baggs Mill (Piddle)**
Size (km^2)	206	414	183
Geology	Chalk: 83% Paleogene: 0% Other: 17%	Chalk: 67% Paleogene: 24% Other: 9%	Chalk: 80% Paleogene: 18% Other: 3%
Soils	Well drained: 60% Slowly permeable: 35% Permeable: 3% Groundwater affected: 3% Other: <1%	Well drained: 88% Slowly permeable: 8% Groundwater affected: 4% Other: <1%	Well drained: 67% Slowly permeable: 24% Permeable: 4% Groundwater affected: 5% Other: <1%
Land Use	Agriculture 77% (*grassland 47%, arable 31%)* Woodland 14% Built-up land 9%	Agriculture 73% (*grassland 43%, arable 30%)* Woodland 17% Built-up land 10%	Agriculture 76% (*grassland 33%, arable 43%)* Woodland 15% Built-up land 8%

3. Results and discussion

3.1 Nitrate concentrations and loads

Annual mean nitrate concentrations (Table 3-1) show lowest values on the River Frome at Louds Mill, 5.02 mg/L) which increase at the downstream East Stoke monitoring site (6.10 mg/L). Highest mean nitrate concentrations were recorded at Baggs Mill on the River Piddle (7.23 mg/L). In addition to recording the highest mean daily nitrate concentration, Baggs Mill also had the highest maximum daily nitrate concentration.

Table 3-1. Nitrate and river discharge characteristics at the three monitoring locations.

	Louds Mill	East Stoke	Baggs Mill
Nitrate concentrations			
Mean daily nitrate concentration (mg/L)	4.99	6.10	7.23
Maximum daily nitrate concentration (mg/L)	8.67	7.63	11.50
Nitrate loads (tonnes)			
2016-2017	273	1011	
2017-2018	396	1410	*490
2018-2019	344	1222	500
2019-2020	521	1640	1087
2020-2021	428	1616	771
2021-2022	277	995	470
2022-2023	406	1464	790
2023-2024	597	2127	999
Annual mean	405	1434	770
Nitrate yields (kg/ha/yr)			
2016-2017	13.3	24.4	
2017-2018	19.2	34.0	*29.8
2018-2019	16.7	29.5	24.1
2019-2020	25.3	39.6	59.2
2020-2021	20.8	39.0	42.1
2021-2022	13.4	24.0	25.7
2022-2023	19.7	35.3	43.1
2023-2024	29.0	51.3	54.6
Annual mean	19.7	34.6	41.5
River discharge (mm)			
2016-2017	263	380	
2017-2018	385	525	365
2018-2019	336	455	361
2019-2020	523	722	755
2020-2021	424	611	567
2021-2022	266	385	332
2022-2023	414	671	515
2023-2024	607	980	825
Mean runoff ratio (%)	38.8	58.0	52.7

*Monitoring began on 16 Dec 2017.

Linear regression of historical annual mean nitrate data at East Stoke (1965 – 2003) showed concentration increased by 0.083 mg/L per year (Environment Agency/Natural England, 2013). Using this trend, the estimated annual mean nitrate concentration in 2024 would equal 7.487 mg/L. The mean nitrate concentration for the 2023-2024 hydrological year is 5.46 mg/L, indicating a significant decline in the rate of increase from 2003 to 2024. Sensor-based mean daily nitrate concentrations are combined with the historical measurements in

Figure 3-1 (NERC-CEH/FBA dataset under license terms). These data also show the recent flattening of the nitrate trend and suggest that annual mean concentrations are starting to decline. Reduced variability in sensor-based nitrate concentrations is expected, reflecting that daily means are derived from more than 48 measurements, as opposed to prior spot measurements which are more greatly influenced by sampling time and short-term dynamics. As such, these data cannot be interpreted as reductions in nitrate concentration variability.

Similarly, at Baggs Mill, the extrapolated trend from monitored data (late 1970s-2007) estimates nitrate concentration at 8.853 mg/L in 2024. The recent measured data show concentrations > 1 mg/L lower, suggesting the rate of increase has similarly declined here. No such comparison is possible at Louds Mill.

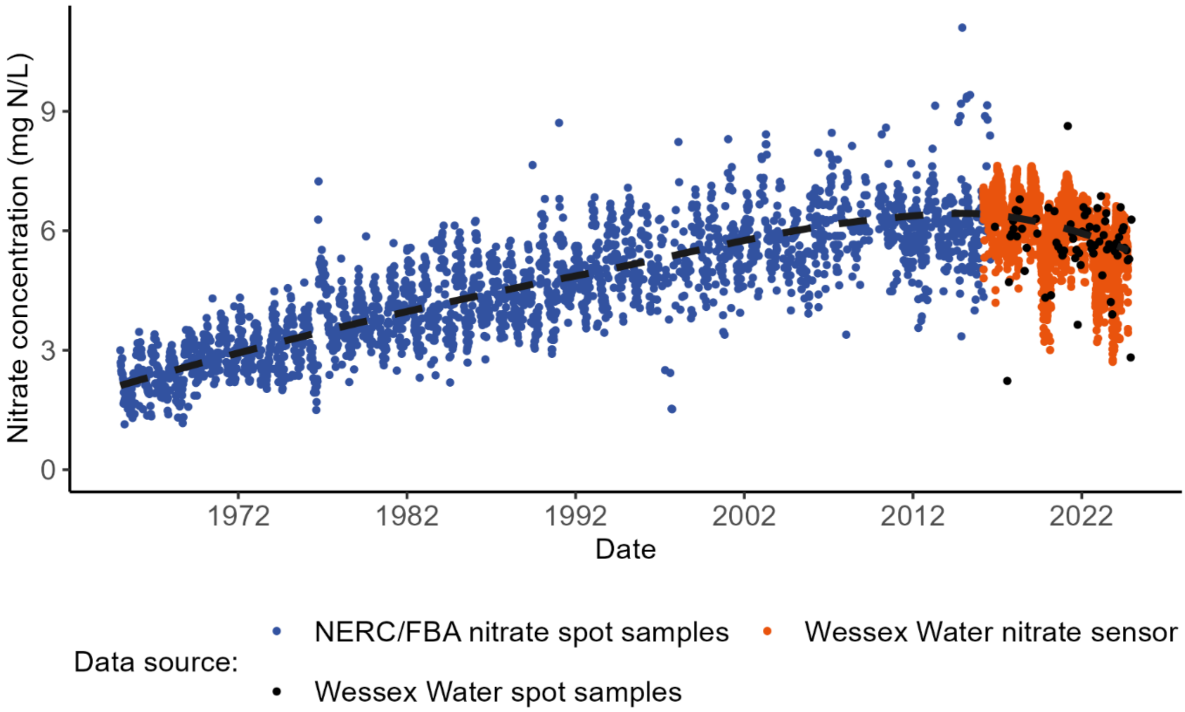

Figure 3-1. Nitrate concentration at East Stoke (River Frome) from 1965 to 2023. Data from 1965 to 2016 is jointly owned by the Centre for Ecology & Hydrology and Freshwater Biological Association (FBA) (Bowes, et al., 2011). Black dashed line represents LOESS (locally weighted polynomial) curve.

Nitrate loads are highest at East Stoke which drains the largest catchment area and yields the greatest amount of runoff. The higher runoff ratio here, relative to the other two sites, indicates that a greater proportion of runoff is delivered via quick-flow hydrological pathways, consistent with the greater influence of impermeable Palaeogene lithologies. Slower hydrological pathways, i.e. through groundwater, are more dominant at Louds Mill and Baggs Mill, consistent with the greater proportions of permeable chalk in their sub-catchments. Although Louds Mill and Baggs Mill have similar annual river discharge, nitrate loads are approximately a third greater at the latter due to higher baseflow concentrations in the Piddle catchment.

Combined, the River Frome and River Piddle, have averagely exported 2,080 tonnes of nitrate per year into Poole Harbour since 2018 (using complete sensor-based data at East Stoke and Baggs Mill only). However, nitrate load, yield and runoff data significantly vary between individual years. This year (2023-2024), combined exported load was 37% above the mean at 3,126 tonnes, driven by a very wet year rather than higher nitrate concentrations (total rainfall was 57% higher than the preceding seven years and total runoff at East Stoke and Baggs Mills were the highest recorded since sensor installation). Similarly, combined load was high in 2019–2020 due to particularly high rainfall over the winter period. This indicates that export of nitrate is transport-limited, dominated by the legacy store of nitrate in the Chalk aquifer. The lowest combined exported load was in 2021-2022, which was a particularly dry year with the lowest recorded annual rainfall since high-frequency monitoring began.

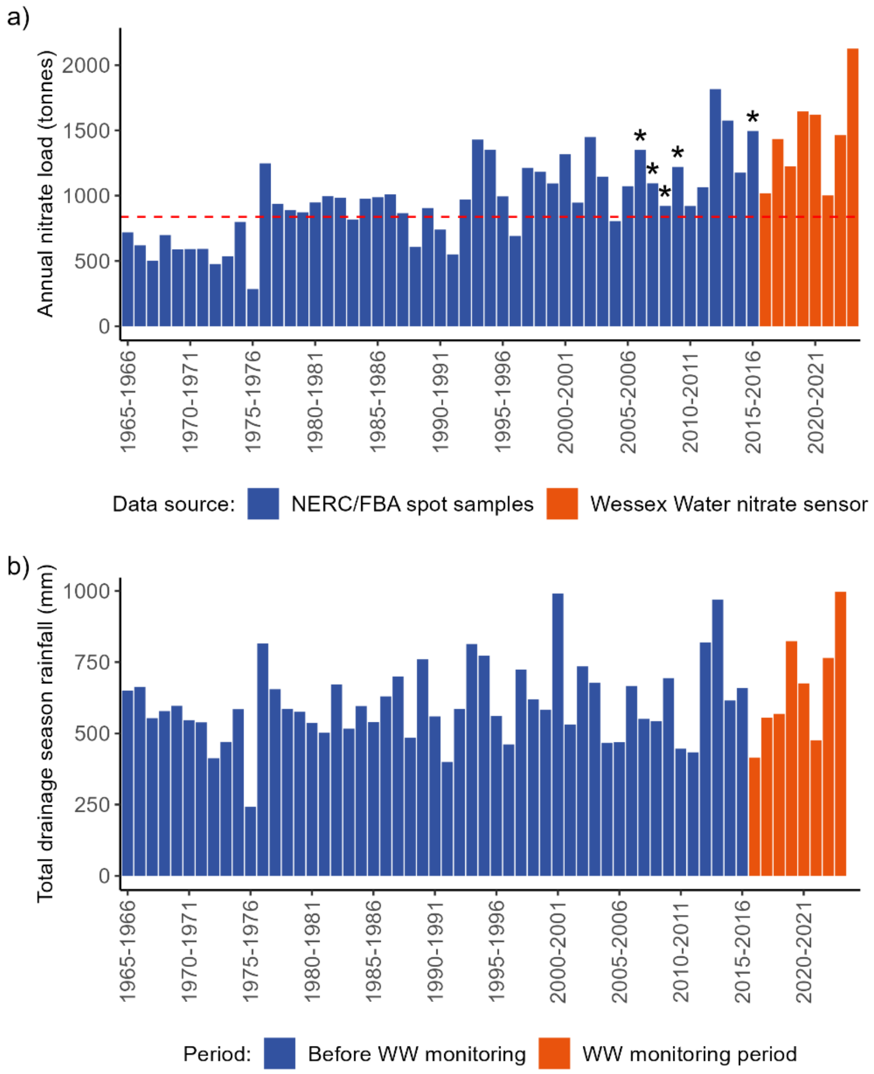

Figure 3-2. a) Annual nitrate load by hydrological year from CEH/FBA (blue) and Wessex Water (orange) monitoring. Note: CEH/FBA loads calculated from monthly grab samples. * indicates some data missing from year. Red dashed line is recommended maximum load limit from River Frome to avoid gross macroalgal growth in Poole Harbour (Environment Agency/Natural England, 2013). b) Poole Harbour total drainage season (October to April) catchment rainfall (mm) by hydrological year.

Figure 3-2 shows historical nitrate loads at East Stoke along with historical catchment rainfall during the drainage season (October – April). Loads have also shown an increasing trend during the approximate period from 1965 to 2016, in agreement with the increasing concentration trend. The red dashed line indicates the estimated maximum nitrate load limit (tonnes/yr) for the River Frome to achieve acceptable macroalgal cover in Poole Harbour, which was first breached in the early 1980s (Environment Agency/Natural England, 2013). Riverine load shows much greater inter-annual variability compared to concentration because nitrate is transport-limited and annual loads are therefore correlated with rainfall. This relationship is clearer in Figure 3-3, which shows the linear correlation between annual loads and total drainage season rainfall (the period where more nitrate is leached and mobilised). Therefore, despite the recent decline in riverine concentrations, loads have remained high and spiked last year, driven primarily by more intense winter rainfall, which may become increasingly extreme due to climate change.

Previous assessments of the total nitrate input into Poole Harbour for the period 2006 to 2010 (approximately 2,100 tonnes), suggested that the Frome catchment and Piddle catchment contributed 941 tonnes (44.8%) and 441 tonnes (21.0%), respectively (Environment Agency/Natural England, 2013). This was revised to a total of 2,300 tonnes for the period 2013-2017, with 1,253 tonnes (54.5%) and 655 tonnes (28.5%) coming from the Frome and Piddle catchments, respectively (Kite & Nicholson, 2018). Based on the mean annual data presented in this report, contributions from both rivers (Frome: 1,434 tonnes, Piddle: 770 tonnes) are higher than the 2006-2010 and 2013-2017 estimations. However, direct comparisons should be treated with caution due to short time series considered and the influence of extreme hydrological years e.g. 2019-2020 and 2023-2024.

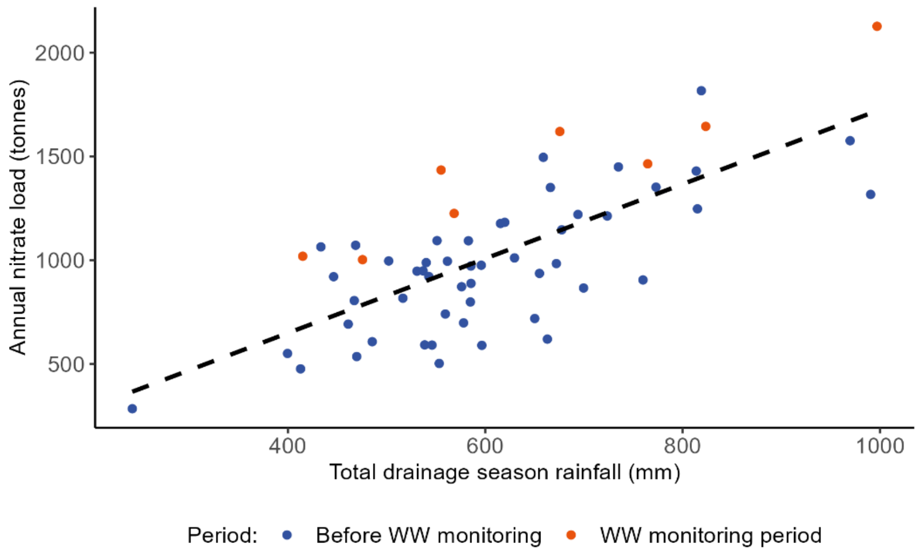

Figure 3-3. Relationship between annual nitrate load (tonnes) and total drainage season (October to April) rainfall (mm). Dashed line shows linear regression model.

3.2 Nitrate sources

Multiple diffuse- and point-sources of nitrate are present in the monitored catchments. Mean annual nitrate loads from WRC discharges (sewage treatment work discharges) totalled 8.00, 134, and 11.3 tonnes in the Louds Mill, East Stoke, and Baggs Mill catchments, respectively (Figure 3-4). This equates to a 2.1%, 9.8%, and 1.7% contribution to total riverine load, respectively, which is lower than a previous estimate of 15% calculated across the whole Poole Harbour catchment (Environment Agency/Natural England, 2013). The remaining nitrate load contributions are classified as diffuse source, dominated by agricultural losses. Although this technically includes combined sewer overflow (CSO) and private sewage discharges, these contributions are considered negligible. Within the East Stoke catchment, Wessex Water offsets a proportion of sewage nitrate load by funding measures to proactively reduce nitrate losses from agriculture with a target of 40 tonnes of N per year. This target has been incorporated into Figure 3-4 and Figure 3-5 to demonstrate its relative saving.

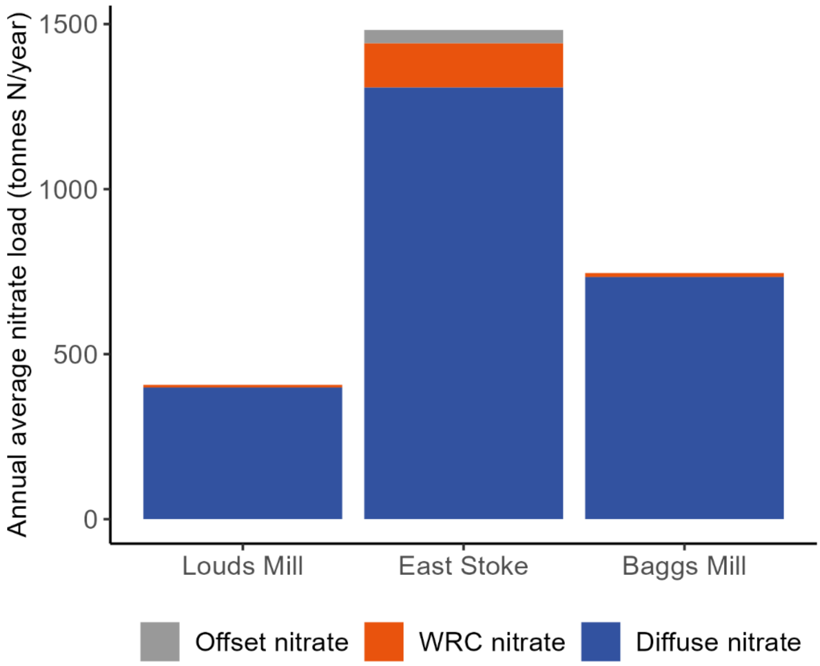

Figure 3-4. Source-contribution of mean annual riverine nitrate loads, including WRC-offset target.

Figure 3-5 shows that the inter-annual source-contribution from point and diffuse loads are consistent across the monitoring period due to the dominance and stability of baseflow inputs within these catchments. Minor variation reflects variability in hydrology, with the wettest year (2023–2024) yielding the highest diffuse contribution and the driest year (2021–2022) yielding the lowest diffuse-source contribution. The remaining analysis will focus on diffuse sources only to interpret possible temporal trends.

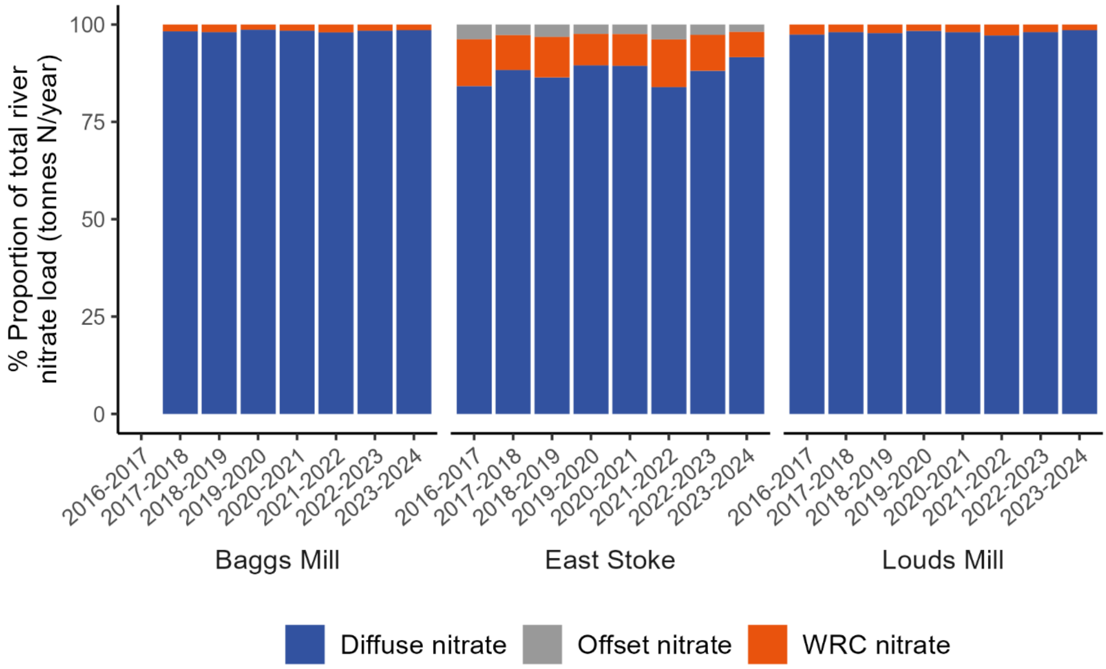

Figure 3-5. Nitrate load from breakdown from contributing sources per catchment, a) annual average breakdown of diffuse, WRC and offset-WRC nitrate, and b) annual breakdown of contributing catchment source proportions over the monitoring period.

Mean monthly diffuse nitrate loads are elevated between November and April, peaking in January (Figure 3-6). The peaks coincide with maximum groundwater levels and reflect periods of greatest baseflow contribution. Baggs Mill has similar monthly loads to Louds Mill between June and October, when river flows are comparable, but exports significantly more nitrate from November to May when flows are typically greater. Baggs Mill also has higher baseflow nitrate concentrations, likely due to a higher proportion of arable land within this catchment.

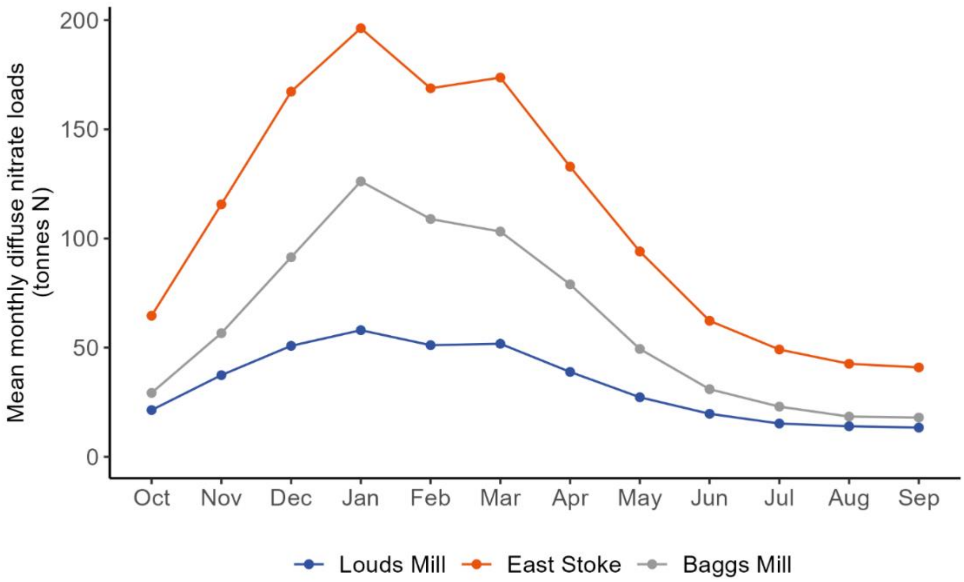

Figure 3-6. Average monthly diffuse nitrate loads at monitoring stations on the River Frome (Louds Mill and East Stoke) and River Piddle (Baggs Mill).

Monthly diffuse nitrate loads across the complete time series show the consistent pattern of peaks during the winter months and lower values during summer months (Figure 3-7). The trend is reflective of groundwater levels and river discharge and thus driven by rainfall patterns. For example, nitrate loads remain high between November and April 2023–2024 due to consistent and extreme rainfall over this winter period. Considering the lower total rainfall amount received in 2017–2018, relative to the previous and following years, nitrate loads were much greater indicating the significance of rainfall timing. A detailed analysis on the intricate sources and transport pathways of nitrate within the catchment is challenging with these available data and outside the scope of this report.

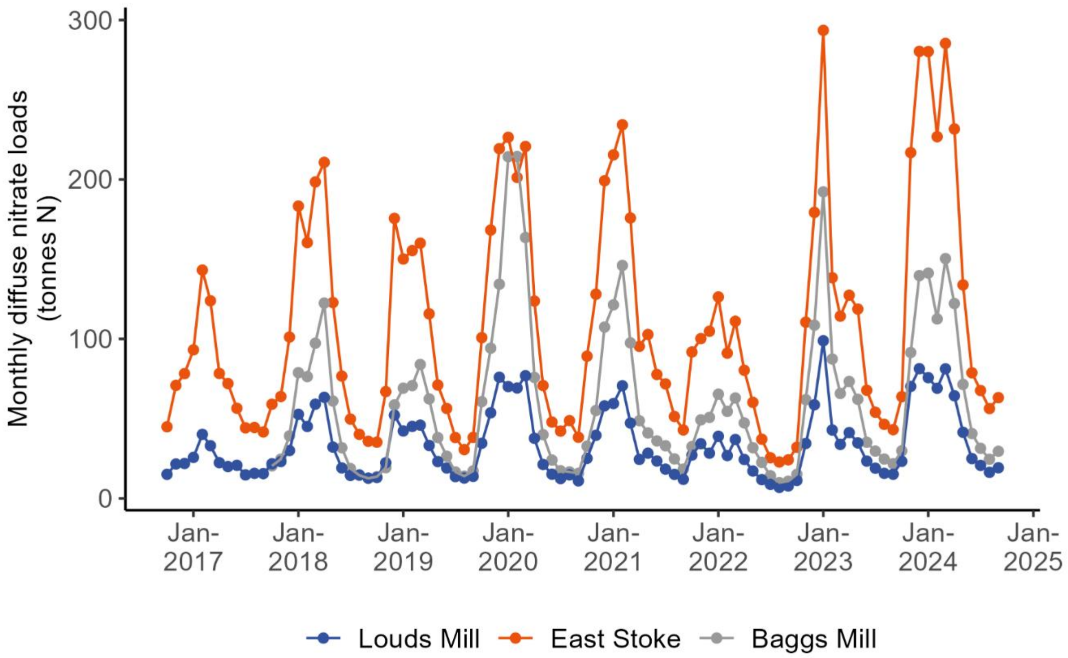

Figure 3-7. Monthly diffuse nitrate loads at monitoring stations on the River Frome (Louds Mill and East Stoke) and River Piddle (Baggs Mill).

Monthly flow-weighted diffuse nitrate concentration is an additional metric to indicate source availability and/or establishment of transport pathways to deliver nitrate. Higher concentrations correspond to more nitrate delivered per unit of flow and thus more source-availability relative to other months. The period of elevated flow-weighted concentrations slightly lags nitrate loads and river discharge, starting in December/January and extending until June (Figure 3-8). This lag could reflect the slower advective velocity of nitrate through the aquifer relative to the celerity of winter recharge, following preceding autumn storms and nitrate leaching (Worthington, 2024). The data indicate that this source of nitrate remains important until June when groundwater levels have receded and thus no longer intercept horizons of potentially higher nitrate concentrations, but more years of monitoring are required before robust conclusions can be drawn from the data.

Overall seasonal variability is lower and less pronounced than the seasonal load distribution due to the dominant stable inputs from baseflow, further supporting the inference that nitrate is transport-limited, rather than source-limited, in these catchments. Baggs Mill mean flow-weighted diffuse nitrate concentrations are considerably higher and show more seasonality, likely reflecting the more arable landscape and associated arable land-management practices. Land-based activities potentially influencing nitrogen losses include the Nitrate Vulnerable Zone window for nitrate applications (closed period: September to January), leaching of residual soil nitrogen from winter sown crops, and mineralisation and loss of soil nitrogen under spring sown crops. Similar nitrate responses have been observed in weekly flow-weighted nitrate data from smaller, well-drained, agriculturally intensive catchments elsewhere (Shore, et al., 2016).

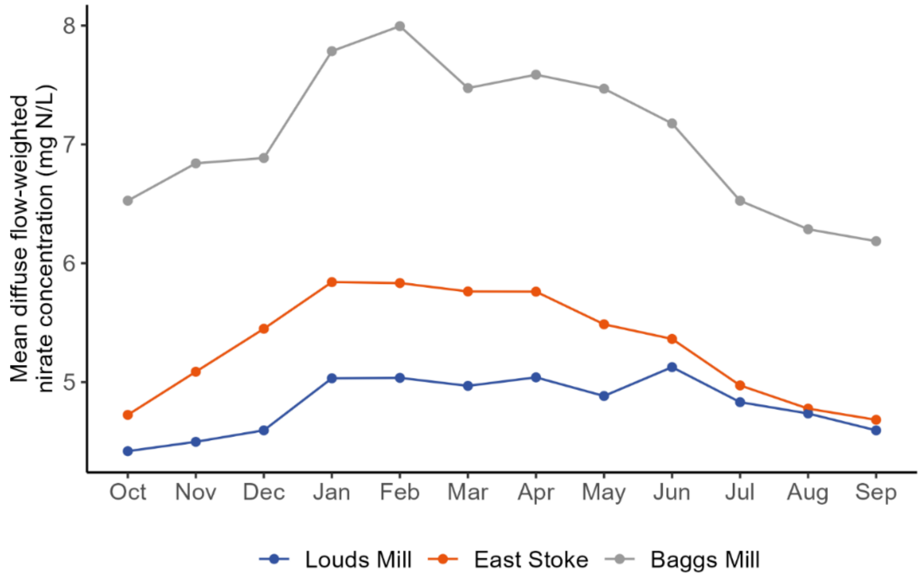

Figure 3-8. Mean monthly flow-weighted mean diffuse nitrate concentration at monitoring stations on the River Frome (Louds Mill and East Stoke) and River Piddle (Baggs Mill).

Figure 3-9 shows the time series of monthly flow-weighted diffuse nitrate concentrations. The linear trends show a decline at all three monitoring locations, but a steepest rate of decline at East Stoke, followed by Baggs Mill, and then Louds Mill. The declines reflect decreasing catchment nitrate loadings, but likely show greater rates of decline at East Stoke due to quicker sub-surface transport times through Palaeogene lithologies, whereas nitrate reductions in sub-catchments predominantly underlain with Chalk (Louds Mill) are buffered by slow transit times and large nitrate storage reservoirs.

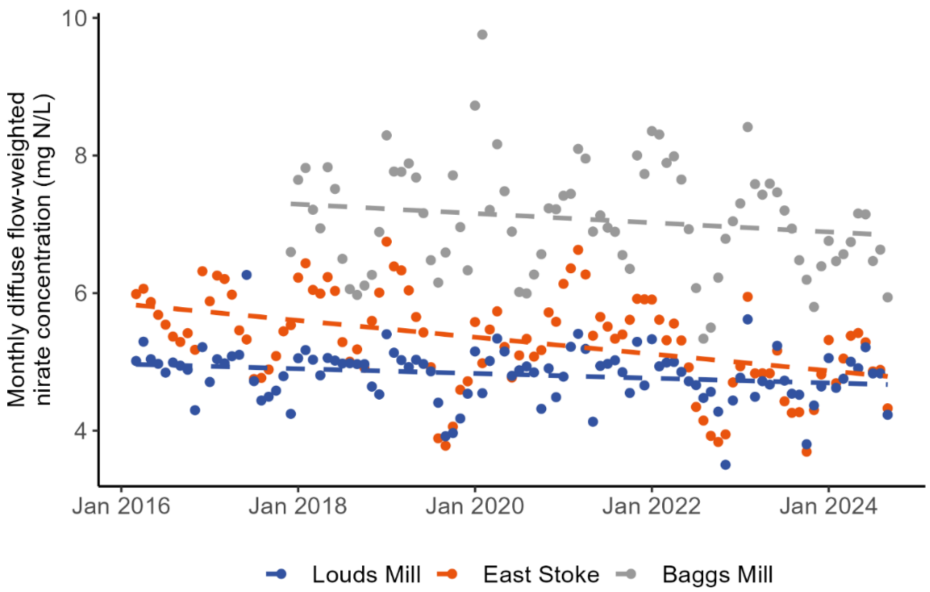

Figure 3-9. Monthly flow-weighted diffuse nitrate concentration at monitoring stations on the River Frome (Louds Mill and East Stoke) and River Piddle (Baggs Mill).

4. Summary

- Nitrate loading and concentration dynamics have been quantified for the two largest rivers which drain into Poole Harbour.
- Mean and flow-weighted concentrations continue to show a declining trend relative to historical data and since high-frequency monitoring began.
- These declines appear to be faster in sub-catchments underlain with more Palaeogene lithologies (East Stoke and Baggs Mill) likely due to quicker sub-surface transport times, compared to sub-catchments predominantly underlain with chalk which are buffered by long sub-surface transit times and large legacy stores of nitrate.
- Despite declines in concentration, the greatest export of nitrate to Poole Harbour occurred this hydrological year (2023–2024), with loads 37% above the mean.
- This was primarily driven by the highest recorded total rainfall (57% above mean) since high-frequency monitoring began and highest mean river discharges.
- Due to continual nitrate loadings to land and large legacy stores in the chalk aquifer, nitrate exports are transported-limited and thus load variability reflects hydrological variability. Although surface nitrate applications show signs of decreasing, we may continue to see a rise in exported nitrate loads to Poole Harbour, in the short-term, due to the potential for more extreme winter rainfall driven by climate change.
- Despite similar catchment areas, Baggs Mill (River Piddle) shows approximately a third greater nitrate load than Louds Mill (River Frome), as well as the highest nitrate yield and much higher flow-weighted concentrations compared to all catchments. This is most likely related to more arable land use in this catchment.
- Further disentanglement of potential sources and flow-mechanisms of nitrate delivery will require a longer dataset and more detailed analysis of the high-frequency data.

Document revisions

No	Details	Lead contact	Date
1	Draft issued internally	Sophie Sherriff	01/04/2020
2	Updated with data to May 2020	Sophie Sherriff	19/06/2020
3	Updated with data to May 2021	Sophie Sherriff	04/06/2021
4	Updated with data to October 2023	Rebecca Huggett	12/02/2024
5	Updated with data to Oct 2024 and relatively minor revisions to text	Tomo Homan	09/01/2024

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