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A 50-YEAR RECORD OF NITRATE CONCENTRATIONS IN THE SLAPTON LEY CATCHMENT, DEVON, UNITED KINGDOM

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Abstract

Slapton Ley, a coastal lake, is the largest natural body of fresh water in south-west England. There was concern in the 1960s that the lake was becoming increasingly eutrophic. To quantify inputs of water, sediment and nutrients into the lake, Slapton Ley Field Centre initiated a programme of weekly water quality sampling in September 1970. Of all the chemical properties which have been measured over the decades, the nitrate record has been the subject of more research than any other. The weekly monitoring has been supplemented by research projects aimed at understanding aspects of processes and patterns of nitrate delivery to the stream network. Three aspects of the nitrate record are reviewed: short-term process

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dynamics; the annual cycle of influent streams and the lake itself; and long-term trends. In the first two decades of monitoring, there was increasing concern about a trend of rising nitrate concentrations, an issue in most lowland rivers in the UK at the time. In the 1990s, nitrate concentrations levelled off and then have fallen steadily in recent years. In relation to eutrophication, there are clear signs of improvement in the influent streams, but concerns remain about water quality in the lake itself.

Introduction

Long-term trends in water quality have been of interest to hydrologists for some decades. However, it can be difficult to detect significant trends because there are insufficient data available (Burt et al., 2013), or because the available datasets might not have been maintained at a sufficient time-resolution to enable a statistical analysis (Burt et al, 2010; 2011a,b). It is, of course, a much greater challenge to assess long-term water quality changes because, unlike for water quantity, there are no inexpensive and easy methods to automatically (and continuously) measure all water quality determinands of interest: both the cost and the logistics may be prohibitive. It is therefore necessary to rely on a small number of benchmark sites from which to draw a broad view of generic trends (e.g. Burt et al. (2011a).

In addition to the challenges of acquiring water quality records, the hydrochemical sources that contribute to observed fluvial responses need to be considered. This necessity adds a further layer of complexity and necessitates a large body of historical knowledge to be accrued as to land use and land use changes, hydrological residence times, and anthropogenic inputs to catchment areas over potentially long time periods. For these reasons there tend to be few monitored basins where such data are available. In the UK there are a few catchments where long-term water quality sampling has been maintained: for example, the Frome and Piddle Rivers in Dorset (Casey and Clarke, 1979; Howden and Burt, 2008; Burt and Howden, 2009), the Essex Stour (Burt et al., 2008), and the River Thames (Howden et al., 2010; Haygarth et al., 2014; Powers et al., 2016). The Slapton Ley catchment, the subject of this article, is a further example of such an area, but it is unique in that, not only is the catchment a relatively small area, but the catchment outfall is a coastal lake: a nature reserve of international importance where water quality is a key concern for local ecology and landscape quality within a popular tourist destination area. Burt and McDonnell (2015) note that field hydrology is on the decline, yet the need for new, field-derived insight into the age, origin and pathway of water in the headwaters, where most runoff is generated, is more needed than ever. Research in the Slapton Ley catchment has helped in this regard.

The first World Health Organisation (WHO) document dealing specifically with public drinking-water quality (WHO, 1958) stated that the ingestion of water with a nitrate concentration in excess of 50–100 mg/l NO_3 might give rise to *methaemoglobinaemia* in infants under 1 year of age, with standards for nitrate in drinking water in Europe being recommended by the WHO in 1961. From this time, there was increasing interest in nitrate concentrations in rivers and groundwater. Initially, the problem was linked to the intensification of agriculture, the use of nitrogenous fertilisers in particular, helping to secure food supplies, but causing pollution. Gradually, the impact of wastewater treatment, especially from areas of high population density, was acknowledged. Atmospheric deposition of nitrogen oxides from urban areas and ammonia emissions from agriculture are also a concern. In the UK, concerns expressed in the Seventh Report of the Royal Commission on

Environmental Pollution (1979) prompted the Royal Society to organise a study group to collate, assess and present the scattered but substantial information concerning nitrate in UK waters (Royal Society, 1983). Prominent evidence in the report was trends in annual nitrate concentration for large rivers for which long-term data were available, including the Thames from 1928 (Howden et al., 2010). For long records like the Thames, the upward trend observed since the 1940s started with the effects of large-scale ploughing of grassland at the start of World War II, resulting in organic nitrogen mineralisation. The steep rise in nitrate concentrations in the 1960s and 1970s related both to the mechanisation of agriculture and the much-increased use of inorganic fertilisers (Howden et al., 2013). Because of the delay caused by water flow through the Chalk aquifer: nitrate leached in the early 1940s would take several decades to travel down through the unsaturated Chalk limestone before being transmitted quite quickly through the saturated zone to the river (Howden et al., 2010; 2011a,b). This growing awareness of nitrate pollution was the national context within which the nitrate monitoring started at Slapton, but local concerns about water quality in the Ley and its detrimental impact on flora and fauna were of paramount concern there. These worries were prescient since more recently the impact of nitrate pollution on the eutrophication of fresh and marine waters has been regarded as of equal importance to drinking water, for example in the Nitrates Directive of the European Commission (EC 91/676).

The aim of this paper is to review fifty years of monitoring of nitrate concentrations in a small catchment in south-west England, an exceptionally long record for such a small agricultural basin. Building upon previous work, nitrate losses are placed in the context of hydrological processes operating in the basin, which are dominated by shallow subsurface stormflow. After discussion of the annual cycle, long-term trends in nitrate concentration provide the main focus, contrasting rising concentrations in the first two decades with a welcome reduction in recent years.

The catchment of Slapton Ley

Slapton Ley is a freshwater coastal lake; 'ley' is the local dialect word for a small lake (latitude 50° 16′ N, longitude 3° 39′ W; UK grid reference SX 825479: Figure 1). The Ley is part of a wetland, 116 ha in area, which is divided into two basins: the Higher Ley (39 ha) is mainly reed swamp; and the Lower Ley (77 ha) is open water fringed with reed. The Ley, together with surrounding woodland, ancient cliff-line and shingle (small, rounded pebbles) ridge (which separates the freshwater lake from the sea), is a grade-1 Site of Special Scientific Interest (SSSI) and in 1993 was designated a UK National Nature Reserve.

Unlike some similar coastal locations along the south coast of England, notably the Fleet behind Chesil Bank, which are connected to the sea and therefore have brackish water, Slapton Ley is entirely fresh water. The lake occupies a former marine embayment, the limits of which are defined by a degraded cliff line along its landward margin; this shoreline relates to a former interglacial being 7 m above current sea level. It seems likely that the shingle barrier was driven west towards the modern coast as sea level rose to its present level during the Flandrian transgression and had reached its present location by about 2000 years ago (Job, 1993). It is thought that the Ley may have originally drained to the sea at its northern end, but drainage of the Lower Ley was changed completely when a road was built along the ridge in 1856, when an outflow was constructed at the southern end at Torcross. This outflow consists of a horizontal weir, culvert and sluice gate system which remains inoperative for most of year, due to blockage by shingle at the beach end, and is only opened as a consequence of unacceptable flooding (van Vlymen, 1979). The level of the overflow into the culvert was raised in the 1920s. At low flow, the lake simply drains through the shingle. Prior to the road being built, there may have been occasional catastrophic failures of the shingle barrier during storms, but these breaches would have soon been blocked by subsequent constructional wave activity. The limited depth of lake sediment obtained by Jenns (1997) suggests that lake sediments may have been evacuated during such episodes with current sediments being perhaps no older than about 200 years. Prior to 1945, the lake was a shallow, eutrophic but clear water environment. With agricultural intensification since the 1950s coupled with discharge from new sewage treatment works, there was an increase in the incidence of algal blooms, linked to increasing inputs of sediment and nutrients into the Ley, raising concerns over the future trophic status of the lake (Johnes and Wilson, 1996).

The catchment area of Slapton Ley occupies 46 km^2 and is characterised by an extensive plateau of low-gradient farmland (below 5°) with all streams having valleys with steep slopes (up to 24°) incised into the plateau. A network of dry valleys links the plateau areas with the permanent streams (Burt and Butcher, 1985). The catchment (Figure 1) comprises four main basins of which the Gara (gauged area, 23.6 km^2) and the Start (gauged area, 10.8 km^2) are the largest. Given its proximity to the Slapton Ley Field Centre, much attention has been paid to the Slapton Wood catchment, despite its small area (gauged area, 0.93 km^2). The fourth of these basins, the Stokeley Barton stream (gauged area, 1.5 km^2) drains the southern end of the catchment. In addition to the gauged area, there is a total of 5.6 km^2 of ungauged area below the four gauging stations, and a further 3.1 km^2 of minor drainage basins which drain directly into the Ley. Thus, the gauged area of 36.8 km^2 comprises 81% of the catchment area (van Vlymen, 1979). Most of the catchment is farmland with arable crops at lower altitudes and more grassland in the upper parts. There are many farms across the area with two villages, Slapton and Blackawton.

Burt (1993) estimates the water balance of the Slapton Wood catchment for the water year 1990 as follows:

Precipitation	1015 mm
Runoff	540 mm
Actual evaporation	475 mm
Potential evaporation	767 mm

Mean annual rainfall at the Field Centre (1981-2010) is 1080 mm. December is the wettest month (134 mm) and June the driest (61 mm). Winter is the wettest season (354 mm) followed by autumn (306 mm) with summer the driest season (197 mm). Burt (1993) noted that rainfall at the Field Centre was 88% of that for the Slapton Wood catchment, whilst Van Vlymen (1979) argued that rainfall for the Slapton Ley catchment as a whole is underestimated by 15-20% by the Centre rain gauge. Van Vlymen (1979) gives average runoff (1973-77) for the four gauged streams as follows:

Gara	781 mm
Start	535 mm
Slapton Wood	463 mm
Stokeley Barton	294 mm

Mean air temperature (MAT, 1961-97) at the Field Centre is 10.7 °C (Burt and Horton, 2001) with a minimum MAT in February of 5.9 °C and a maximum in July and August of 16.3 °C.

Methods

The major rivers and stream draining into Slapton Ley have been gauged from the early 1970s; full details are given in van Vlymen (1979). Although high-frequency records of stream discharge are only available for part of the time, the stage height associated with each weekly water sample is always noted.

Water samples (single sample collected by hand at each gauging station) are first recorded on 7th September 1970. Although the sampling frequency is weekly, the analysis here is for monthly averages, because this averaging gets over any problems of missing data and generally makes patterns easier to identify and interpret. To our knowledge, no water quality data collected by the Field Centre are available for the lake itself before 14th February 1979. Note that some water quality data are available from the UK Environment Agency (EA) for the lake and influent streams from April 1975, with more complete coverage from 1990. Data from the water year 1984 (starting 01/10/1983) are used in Table 1 as this was a period when water samples were taken every two hours (Burt and Arkell, 1987); during the year, failure of automatic pump water samplers resulted in the loss of water samples for a total of seventeen days, no period lasting more than four days. Together with high-frequency analysis of stage records, these data provided the most accurate estimation of stream nitrate loads during the whole monitoring period. For a more comprehensive statistical analysis of the data, readers are referred to Burt et al. (1985) and Burt and Worrall (2009).

Analyses of water chemistry have been provided by various universities over the last fifty years: Exeter University, Seale Hayne College (now University of Plymouth), the University of Plymouth itself and, since 2005, Durham University. Of course, analytical techniques have changed over five decades. Originally, analysis would have been by flame photometer, then by atomic absorption spectrophotometry, by ion-selective probe and then by auto-analyser. Most recently at Durham, analysis of water chemistry (cations and anions) has been done by ion chromatography. No significant inhomogeneities are evident in the nitrate concentration series despite changing analytical methods and the different laboratories involved.

A full suite of meteorological observations has been made daily at the Field Centre in Slapton village since spring 1960 (Burt and Horton, 2001: https://www.slnnr.org.uk/research/weather-data.aspx).

Hydrology and nitrate leaching

The occurrence of subsurface stormflow in the Slapton Wood catchment was first noted by Troake and Walling (1973). They described one large runoff event where a second "delayed" peak in stream discharge was observed several days after the "storm" discharge peak (which coincided closely with the rainfall input). At the time, this type of response in the catchment was regarded as rare, but we now know that as many as ten such double-peaked hydrographs can occur each winter (Burt and Butcher, 1985). The development of such double-peaked hydrographs shows that subsurface stormflow (or throughflow) is the dominant runoff process operating. Delayed subsurface stormflow may dominate the runoff response both volumetrically and in terms of peak discharge where deep permeable soils overlie impermeable bedrock and where steep valley-side slopes border a narrow valley floor (Anderson and Burt, 1990). In the Slapton catchments, the main bulk of the shale bedrock is totally impermeable but the soil and regolith, several metres deep, are very permeable allowing large volumes of subsurface stormflow to be produced quickly after rainfall. Hydraulic conductivities of up to 1 m per hour have been measured at the base of the soil profile (Burt and Butcher, 1985). Examining 44 hydrographs for the period 1969-1982, Burt and Butcher (1985) found that during the winter half of the year, these delayed hydrographs accounted for 46% of the runoff and occupied over half the time; by contrast, quickflow occupied only 2% of the time and contributed less than 4% of the runoff. A study of soil moisture distributions using an automatic tensiometer system showed that the generation of delayed hydrographs is associated with the formation of a 'saturated wedge' which builds up within the soil above the impermeable bedrock. During periods of high subsurface discharge, the saturated wedge extends up the major dry valleys to link with saturated zones on the plateau (Burt and Butcher, 1985).

The delayed hydrograph is an especially important time for nitrate leaching because both flow and concentration are high at the time. Figure 2 shows (a) stream discharge and (b) nitrate concentration in the Slapton Wood stream and for a throughflow trough at the base of the slope in the woodland. The throughflow has a lower concentration than the stream because much of the hillslope is wooded, although there is a field at the top from which some nitrate will leach into the subsurface flow (Burt and Arkell, 1987). The stream better reflects the catchment, which is largely agricultural, but both hydrographs attest to the importance of subsurface flow. Burt and Butcher (1985) mapped areas of soil saturation at the soil-bedrock interface in the Eastergrounds contributing area (see Figure 2), demonstrating a clear link between streamflow and subsurface stormflow draining from the plateau downslope to the stream network. During the quickflow response, the stream nitrate is significantly diluted by low-concentration overland flow from roads and paths; there is only a very little dilution effect for the throughflow. During the delayed response, the concentration of nitrate in the throughflow rises significantly, corresponding to the overall stream response. The delayed subsurface stormflow response, generated by the growth of the saturated wedge, is a time of significant nitrate leaching, with both discharge and concentration increasing. The nitrate leaching is associated with both infiltration through the soil profile and with the vertical growth of the saturated wedge upwards into surface soil horizons which have not been saturated since the last event of comparable size.

Even in a small, low-order drainage basin like the Slapton Wood catchment, land use controls the pattern of nitrate input to the stream. Burt and Arkell (1987) mapped nitrate concentration and load along Slapton Wood stream (Figure 2c). As expected, the largest nitrate loads per unit area (and the highest concentrations) were derived from the mainly arable headwaters. Whilst the Carness and Eastergrounds hollows (see Figure 2a) were important point source of discharge and nitrate, their drainage areas include large areas distant from the stream which contribute little runoff; thus, their unit area nitrate load was less than might have been expected. The wooded part of the catchment provided the smallest input of nitrate, but even here, there were fertilised fields upslope of the wood which contributed nitrate via subsurface flow during the large throughflow events.

The annual cycle in nitrate leaching

Mean monthly nitrate concentration in the Slapton Wood stream, River Gara and the Lower Ley are shown in Figure 3. There is an asymmetric pattern to the annual cycle in the two rivers with a steeper increase in late autumn and early winter to peak in January and February, followed by a steady decline through spring, summer and early autumn (Burt and Worrall, 2009). Of course, long-period averages necessarily produce a smooth seasonal regime, and individual years will differ, but a smooth annual cycle of this type is typical of catchments dominated by subsurface flow. A smooth nitrate cycle is best developed in catchments with deeper soils or aquifers, or both, so that some delay and attenuation occurs between leaching of nitrate from the soil in autumn and the time of peak nitrate concentration (and maximum groundwater flow) in midwinter (Johnes and Burt, 1993). Note that some catchments do not display clear annual nitrate regimes; for example, under-drained clay soils have a nitrate peak in autumn and concentrations decline steadily thereafter throughout the winter (Haigh and White, 1986); peaks in nitrate concentration are much more likely here in runoff events immediately following fertiliser application too. The Slapton Wood stream has higher concentrations than the River Gara, reflecting its lower altitude and more intensive agricultural activity. The Gara is a much larger basin and includes less intensively farmed areas at higher altitudes furthest from the coast.

The Lower Ley has a very different annual cycle compared to the influent streams. Only in midwinter does the nitrate concentration in the Ley match concentrations in the River Gara, the biggest discharge into the lake; this is the time of maximum inflow and minimum hydraulic retention. Van Vlymen (1979) argues that as much as a third of the lake's volume may be displaced in 24 hours at times of peak winter flood. From March onwards through to the late autumn, nitrate concentrations in the Ley are lower than concentrations in the inflow. This lowering of concentrations is likely driven by both microbial denitrification and assimilation of nitrate by primary production (Jarvie et al, 2018). Indeed, summer pH levels average 9 or above, are indicative of high rates of primary production, with algae removing carbon dioxide from the lake water for photosynthesis (Talling, 1976; Burt et al, 2019). At the height of summer, with low inflow and no flushing of the system, nitrate concentrations in the Ley regularly fall to very low concentrations, often below the limits of detection. Recycling of internal 'legacy' phosphorus stored in lake sediments is thought to be the primary driver of eutrophication within the Ley. Indeed the redox conditions which mobilise P from bed sediments (reductive dissolution of iron oxyhydroxides and consequent release of sorbed P) are also conducive to denitrification which, in combination with assimilation, results in nitrogen depletion relative to phosphorus (Orihel et al., 2017; Scott et al., 2019). Growth of nitrogen-fixing cyanobacteria in midsummer may reflect significant depletion in nitrogen within the water column at times when there is a plentiful supply of phosphorus being released from the bed sediments (Burt et al., 2019).

Nitrate losses from the Slapton Wood catchment in a typical water year are shown in Table 1. After a below-average autumn rainfall, heavy rainfall in December and January was reflected in a sharp increase in runoff; mean nitrate concentrations rose too, reflecting a large increase in subsurface stormflow. In this particular example, the three winter months account for 76% of runoff and 78% of nitrate load. Note that nitrate concentrations correlate positively with runoff, underlining the importance of subsurface runoff in the catchment. As noted earlier, delayed hydrographs are important times for nitrate export (Figure 2a). No doubt there is some biological uptake of nitrate from the stream in warmer months and probably denitrification in all seasons as well; these have not been measured but are not thought to be significant compared to leaching losses.

Long-term trends

Burt et al (1988) presented the first 15 years of nitrate data for the Slapton Wood catchment at a time of growing concern that nitrate concentrations in rivers and groundwater were increasing. The results showed a clear upward trend in the 15 years since 1970. The mean monthly nitrate concentration in the first water year studied was 5.3 mg l^{-1} NO_3-N rising to 8.3 mg l^{-1} NO_3-N by 1985. It was not then clear when or if the upward trends would level off, given no apparent increase in fertiliser use over the study period. In fact, with the benefit of hindsight and a much longer record (Figure 4), it can be seen that nitrate concentrations did reach a plateau in the mid-1980s and, after staying at much the same level for about twenty years, concentrations have fallen gradually in the last 15 years. There are several possible reasons for the recent decline in concentrations: improved sewage treatment; reduced inputs of fertiliser; and, some tendency for less intensive farming. Reductions in deposition of atmospheric nitrogen are not thought to have been significant in this relatively remote rural location in south-west England. In relation to the intensity of farming activity, the farm at the top of the Slapton Wood catchment has not grown arable crops for a decade now; this change of land use has had a clear impact on nitrate leaching with mean nitrate concentration falling from 7.4 mg l^{-1} NO_3-N in the 2000s to 4.8 mg l^{-1} NO_3-N in the 2010s. For the River Gara, mean concentrations fell from 5.0 to 4.3 mg l^{-1} NO_3-N across the same two decades. What is perhaps most interesting about the recent decrease in concentration is a clear reduction in the amplitude of the seasonal cycle. This change can be seen clearly on Figure 5 which shows monthly means for the River Gara and the Lower Ley since 2005. Note the strong seasonal cycle within the Ley as discussed in the previous section; concentrations fall to zero every summer except where summers are unusually wet as in 2012. The recent decrease in nitrate concentration in the Slapton streams over the past two decades accords well with what has been seen widely across Europe (EEA, 2019). In the Slapton Wood stream, monthly mean nitrate concentration has not exceeded the maximum allowable since 2005 (Figure 4b).

Conclusions

Improvements in water quality in the Slapton catchments have taken place within the context of the EC Directive on Nitrates (EC 91/676) in 1991, which aimed to protect water quality across Europe by preventing nitrate from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices. The significance of the Directive is that it was proactive and preventative, coupling input management with water protection and restricting intensive agriculture for the sake of water quality. The Nitrates Directive acknowledged that nitrate pollution was not just a matter of public health but related to the health of the aquatic environment too. However, notwithstanding improvements in water quality in the influent streams, water quality in the Lower Ley remains poor, especially in summer, and the annual appearance of toxic algal blooms shows no signs of abating. Summer pH levels average 9 or above, a sure sign that algae and underwater plants are removing carbon dioxide from the lake water for photosynthesis (Talling, 1976). It is likely that phosphorus stored in surface sediments is being released by a mixture of desorption and dissolution. P seems to be the main driver of eutrophication, but very low levels of nitrate in the lake water in summer can encourage nitrogen-fixing cyanobacteria to flourish at this time (Burt et al., 2019). The phosphorus legacy seems likely to be influential for many years to come: the justification for long-term monitoring remains as vital as ever. Further work is needed to explore the role of in-lake biogeochemical processes, including assimilation, denitrification, the potential for P release at the sediment-water interface, and the possibility that N can become the limiting nutrient during summer low-flow conditions .

The importance of long-term observation of the natural environment has long been recognised, but 'monitoring' is often dismissed as low-grade science (Burt, 1994). Field work, by its very nature, involves observation, curiosity about the world around us (Burt and McDonnell, 2015); continued observation of the Slapton Ley catchment continues to raise new questions. Results from the Slapton catchments show how long datasets allow slow, subtle processes can be detected from highly variable, noisy records (Burt and Worrall, 2009). They reveal new patterns to be explained and are more likely to include the influence of rare events such as the 1975-76 drought (Burt et al., 1985). They are essential for testing hypotheses undreamt of at the time the monitoring was set up, such as the influence of legacy P. Most importantly perhaps, they continue to provide an essential way of discovering whether there are significant changes taking place that may ultimately be harmful to the natural environment and to humans themselves. We see a continuing need for long-term monitoring in the Slapton catchments stretching far into the future.

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Table 1. Nitrate losses from the Slapton Wood catchment, water year 1984. Based on Burt et al. (1988) and Johnes and Burt (1993)

	Month	Rainfall (mm)	Runoff (mm)	Mean nitrate concentration (mg l^{-1} NO_3-N)	Nitrate load (kg NO_3-N
1983	October	75	12	6.4	72
	November	69	13	7	82
	December	117	83	7.8	605
1984	January	243	184	7.8	1347
	February	70	104	9.2	895
	March	65	29	8.3	226
	April	8	25	7.1	163
	May	62	16	6.6	101
	June	9	8	6.2	49
	July	34	6	5.9	30
	August	54	5	6	30
	September	89	4	7.2	28
	Annual	895	489	7.1	3627

Table 2. Decadal mean nitrate concentrations (mg l^{-1} NO_3-N) by season and year for the River Gara and Lower Ley, 1971-2020.

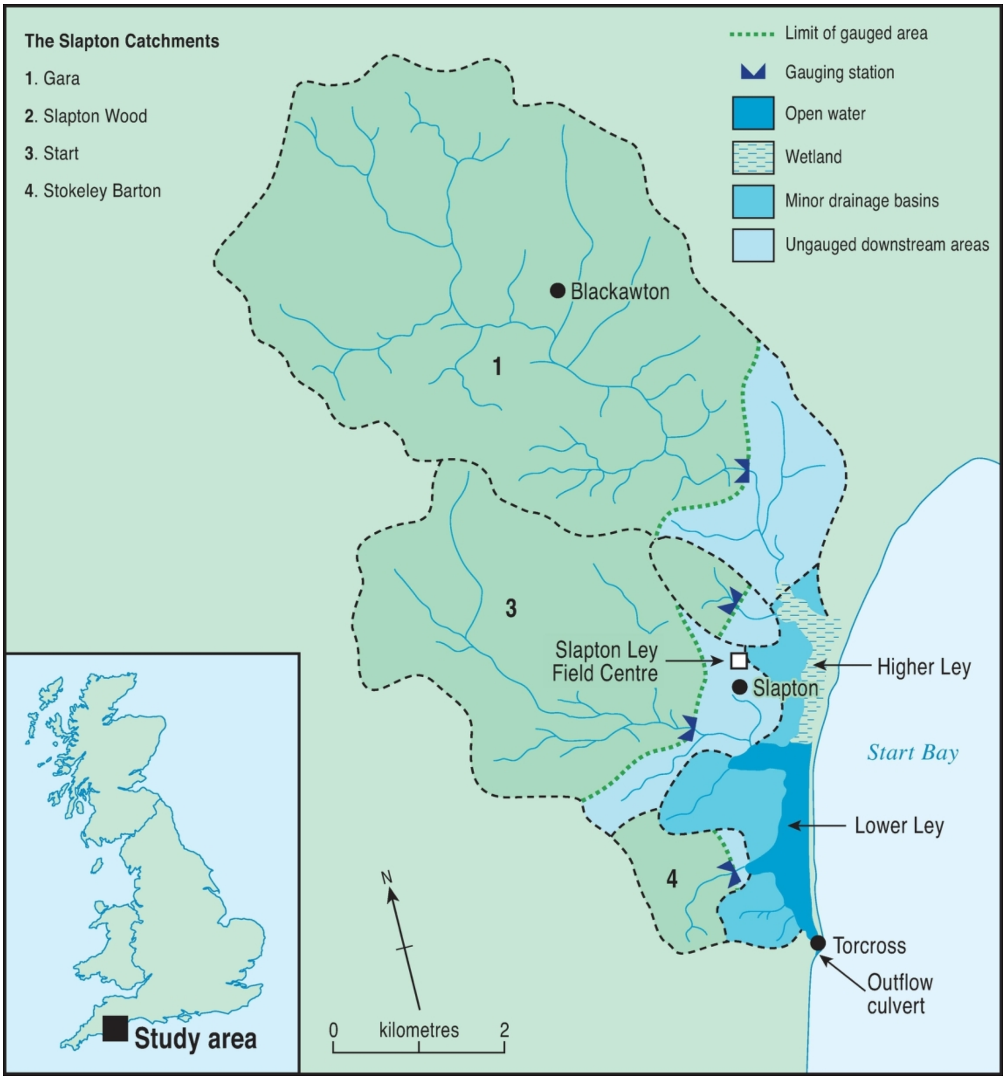
	Decade	Winter	Spring	Summer	Autumn	Annual
(a) River Gara	1971-1980	4.6	4.4	3.7	4.2	4.2
	1981-1990	6.2	5.3	4.6	4.7	5.2
	1991-2000	5.3	5.5	4.8	4.4	5.0
	2001-2010	5.8	5.4	4.4	4.5	5.0
	2011-2020	4.3	4.1	3.7	3.5	3.9
(b) Lower Ley	1971-1980	6.2	4.5	0.7	2.4	3.5
	1981-1990	6.3	3.7	1.5	2.2	3.3
	1991-2000	4.7	3.6	1.2	1.5	2.8
	2001-2010	5.1	4.1	0.8	1.2	2.8
	2011-2020	4.2	3.3	0.5	1.5	2.4

Figure captions

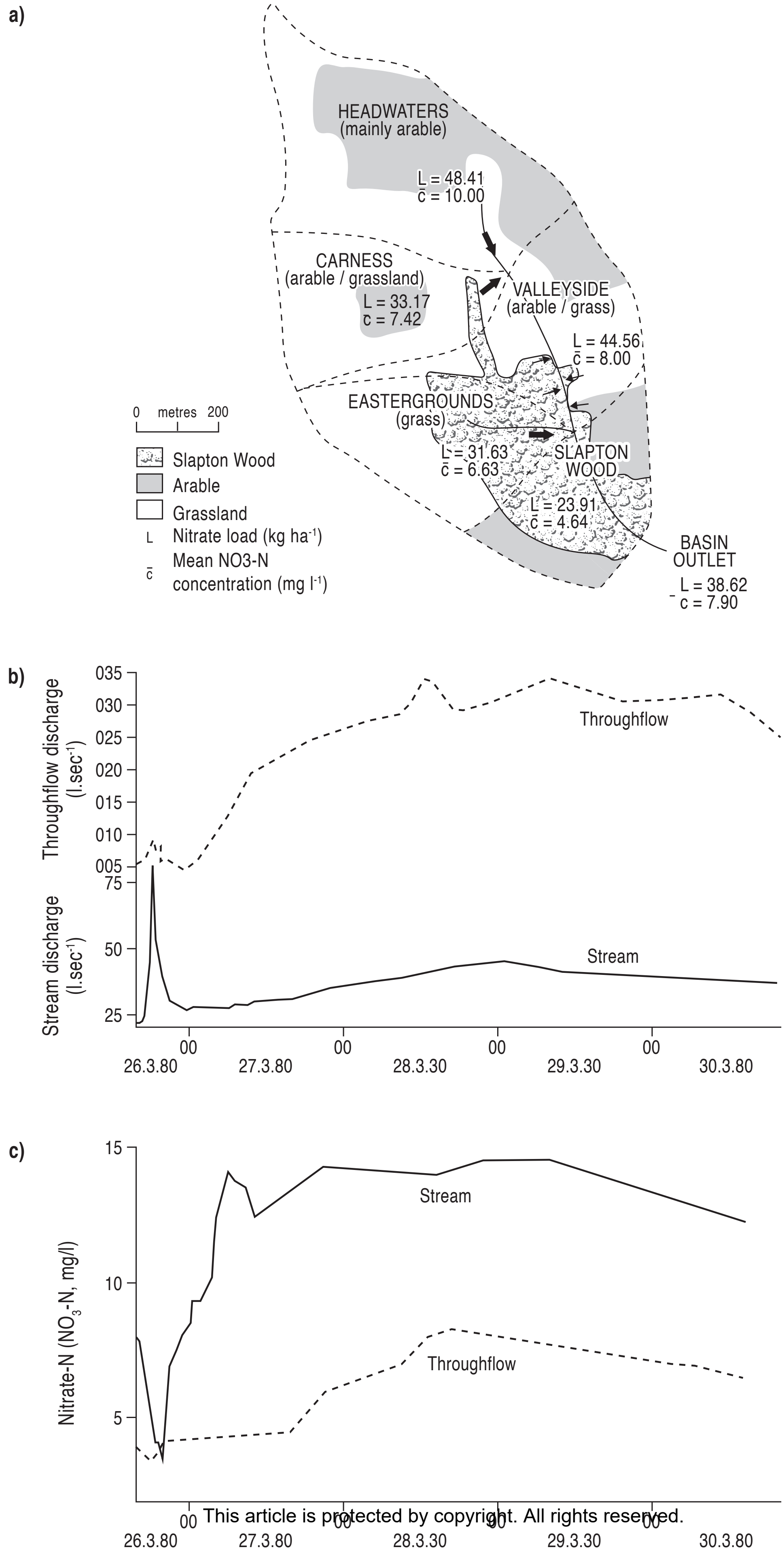
1. Map of the Slapton Ley catchment.
2. (a) Discharge and (b) nitrate concentration in the Slapton Wood stream and for a throughflow trough at the base of the slope in the woodland for a double-peaked storm event; and (c) the spatial pattern of nitrate leaching in the Slapton Wood catchment as indicated by dilution gauging (large arrows indicate point sources of nitrate; small arrows indicate non-point inputs for that section of stream).
3. Mean monthly nitrate concentrations (mg l^{-1} NO_3-N) in the Slapton Wood stream, River Gara and Lower Ley, 1971-2019.
4. Monthly average nitrate concentrations for (a) the River Gara at Higher North Mill (blue line) plus a 12-month running mean (red line) and (b) for the Slapton Wood stream, 1970-2019. Note that the maximum allowable nitrate concentration in drinking water (11.3 mg l^{-1} NO_3-N) is indicated on Figure 4b; this concentration is also the target adopted in the EC Nitrates Directive 91/676.
5. Monthly average nitrate concentrations for the River Gara and Lower Ley, 2005-2019.

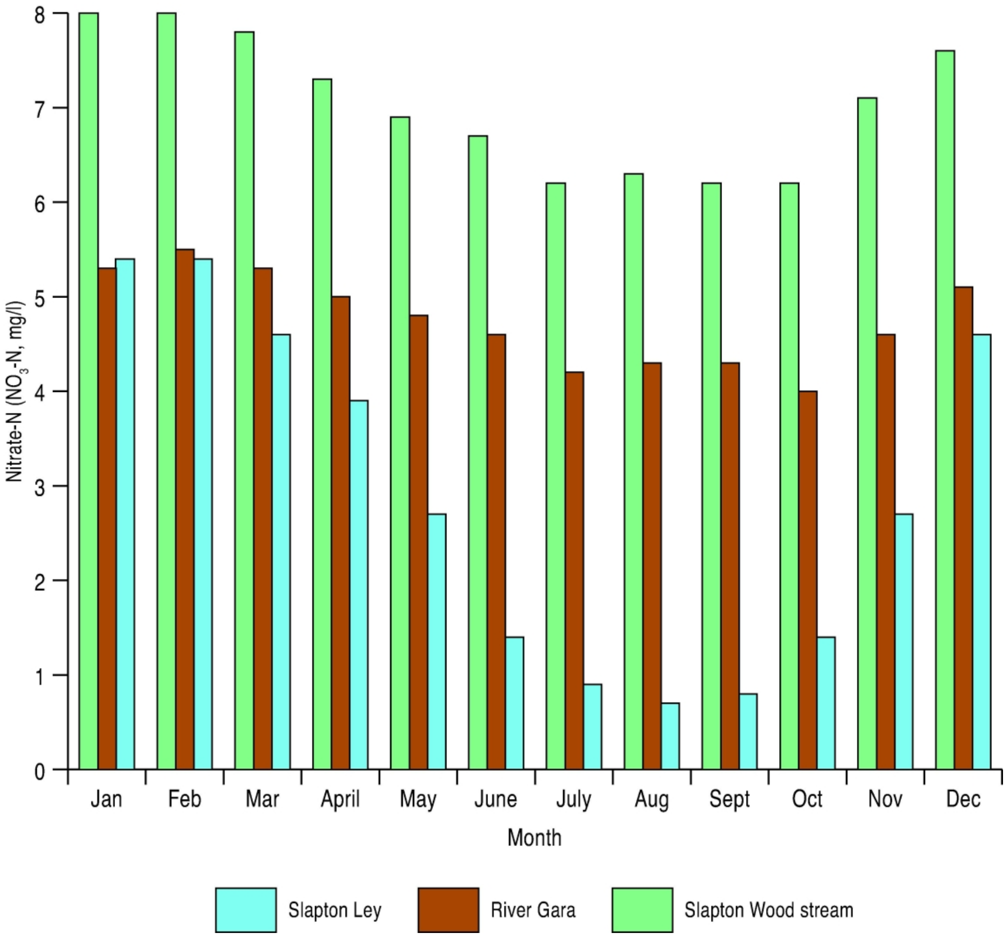
Data availability

Monthly mean nitrate concentration will be made available for sites analysed in the article at https://www.field-studies-council.org/locations/slaptonleynnr/ which is the website for the Slapton Ley National Nature Reserve (NNR).

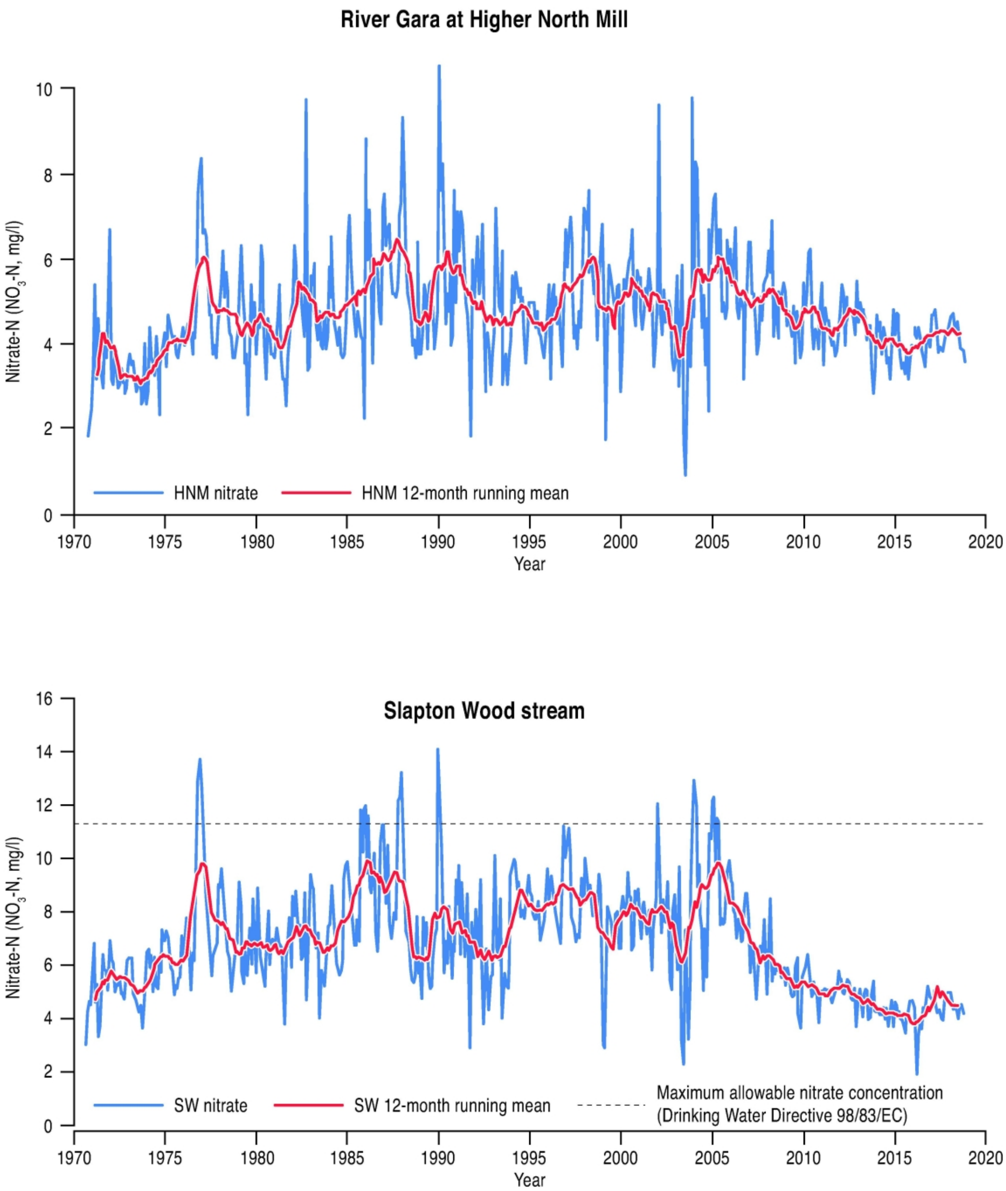


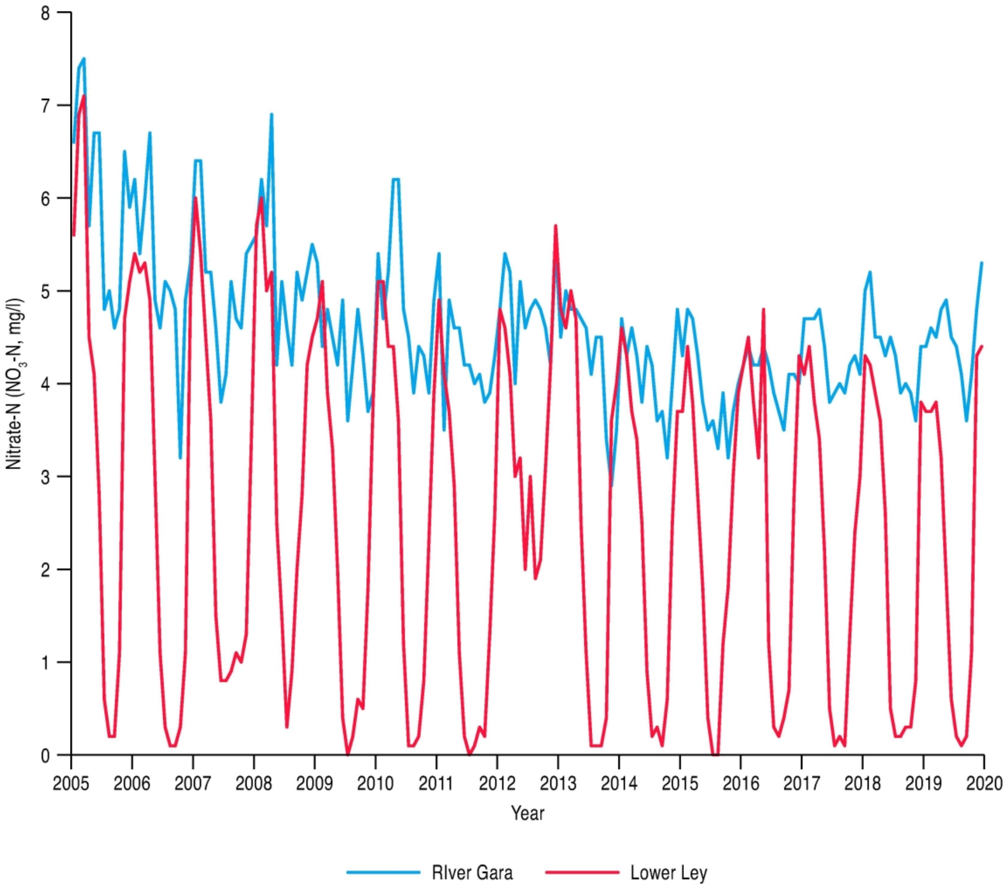
The Slapton Catchments
1. Gara
2. Slapton Wood
3. Start
4. Stokeley Barton
Limit of gauged area
Gauging station
Open water
Wetland
Minor drainage basins
Ungauged downstream areas
Blackawton
1
3
4
Slapton Ley
Field Centre
Slapton
Higher Ley
Start Bay
Lower Ley
Torcross
Outflow
culvert
N
0
kilometres
2
Study area


a)
HEADWATERS
(mainly arable)
L = 48.41
c̄ = 10.00
CARNESS
(arable / grassland)
L = 33.17
c̄ = 7.42
VALLEYSIDE
(arable / grass)
L = 44.56
c̄ = 8.00
EASTERGROUNDS
(grass)
L = 31.63
c̄ = 6.63
SLAPTON
WOOD
L = 23.91
c̄ = 4.64
BASIN
OUTLET
L = 38.62
c̄ = 7.90
0 metres 200
Slapton Wood
Arable
Grassland
L Nitrate load (kg ha-1)
c̄ Mean NO3-N concentration (mg l-1)
b)
Throughflow discharge (l.sec-1)
035
030
025
020
015
010
005
Throughflow
Stream discharge (l.sec-1)
75
50
25
Stream
00
26.3.80
27.3.80
28.3.30
29.3.30
30.3.80
c)
Nitrate-N (NO3-N, mg/l)
15
10
5
Stream
Throughflow
00
26.3.80
27.3.80
28.3.30
29.3.30
30.3.80



8
7
6
5
4
3
2
1
0
Nitrate-N (NO_3-N, mg/l)
Jan
Feb
Mar
April
May
June
July
Aug
Sept
Oct
Nov
Dec
Month
Slapton Ley
River Gara
Slapton Wood stream


River Gara at Higher North Mill
Nitrate-N (NO3-N, mg/l)
0
2
4
6
8
10
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year
HNM nitrate
HNM 12-month running mean
Slapton Wood stream
Nitrate-N (NO3-N, mg/l)
0
2
4
6
8
10
12
14
16
SW nitrate
SW 12-month running mean
Maximum allowable nitrate concentration
(Drinking Water Directive 98/83/EC)
Year



8
7
6
5
4
3
2
1
0
Nitrate-N (NO3-N, mg/l)
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Year
RIver Gara
Lower Ley