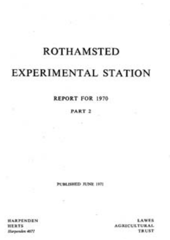
ROTHAMSTED RESEARCH

# Rothamsted Experimental Station Report for 1970 Part 2


ROTHAMSTED
EXPERIMENTAL STATION
REPORT FOR 1970
PART 2

Full Table of Content

# The Chemical Composition of Water from Land Drains at Saxmundham and Woburn, and the Influence of Rainfall Upon Nutrient Losses

## R. J. B. Williams

*The Chemical Composition of Water from Land Drains at Saxmundham and Woburn, and the Influence of Rainfall Upon Nutrient Losses*, R. J. B. Williams (1971) Rothamsted Experimental Station Report For 1970 Part 2, pp 36 - 67 **- DOI: https://doi.org/10.23637/ERADOC-1-34800**

# The chemical composition of water from land drains at Saxmundham and Woburn, and the influence of rainfall upon nutrient losses

R. J. B. WILLIAMS

## Introduction

Most of the work on the composition of drainage done since Lawes, Gilbert and Warington (1882) published their classic account of the drainage from the Broadbalk Wheat Experiment, has been concerned with drainage from soil columns and boxes, or from filled lysimeters, in which conditions are rarely comparable to those in the field. Work with lysimeters constructed around undisturbed soil blocks are more relevant to field drainage, but they may leak or water may flow through fissures made in constructing the lysimeter or between its wall and the soil. Examples in the United Kingdom of work with soil block lysimeters are at Rothamsted (Lawes & Gilbert, 1881; Miller, 1906) and at Craibstone, near Aberdeen (Hendrick, 1930; Hendrick & Welsh, 1938). The composition of drainage from farmland on different soil types has been little studied. In their work at Rothamsted, Lawes, Gilbert and Warington (1882) used the drainage system installed on Broadbalk field in 1849 to measure the losses of plant nutrients from experimental plots under continuous wheat. Work done in other countries has been comprehensively listed by S. F. Atkins (1970) and by the Tennessee Valley Authority (1969). Both publications emphasise losses of nitrate from agricultural land. Comprehensive work on composition of drainage has been done recently in irrigated areas of U.S.A. (Johnston *et al.*, 1965). Wadleigh (1968), who reviewed recent work on losses of nutrients from agricultural sources, concluded that nitrate in well waters came mainly from the natural nitrification in soils and from the nitrification of human and animal sewage; he found no clear evidence that using fertiliser resulted directly in large nitrate concentrations. Losses of nitrogen and phosphorus from agricultural land in Britain were discussed by Cooke and Williams (1970) at a Symposium of the Society for Water Treatment and Examination, where Owen (1970) reported on the composition of land drainage in the Ouse Valley, and Tomlinson (1970) described changes in nitrate in river water in relation to changes in the fertilisers used in the catchment areas concerned.

The measurements now to be described were on two different soils, 100 miles apart, having contrasted drainage systems, but both given current dressings of fertiliser. The influence of soil type on the chemical composition and volume of drainage water is discussed. The results, thought to be unique for modern conditions in England, are relevant to eutrophication of natural waters, and to all work intended to make fertilisers more efficient.

The chemical compositions and flowrates of drainage water at Woburn and Saxmundham Experimental Stations were measured from March 1968 until March 1970. At Woburn, the drainage was sampled twice a month; at Saxmundham, where drainage flows varied more, sampling was more frequent, especially during very wet periods in spring and autumn when losses of nutrients, especially nitrogen, were most. Figure 1 shows the positions and numbers of the drains at the two sites. Methods of sampling and estimating flows, and analytical methods, are briefly described in the Appendix.

## LOSSES OF PLANT NUTRIENTS IN DRAINAGE WATER

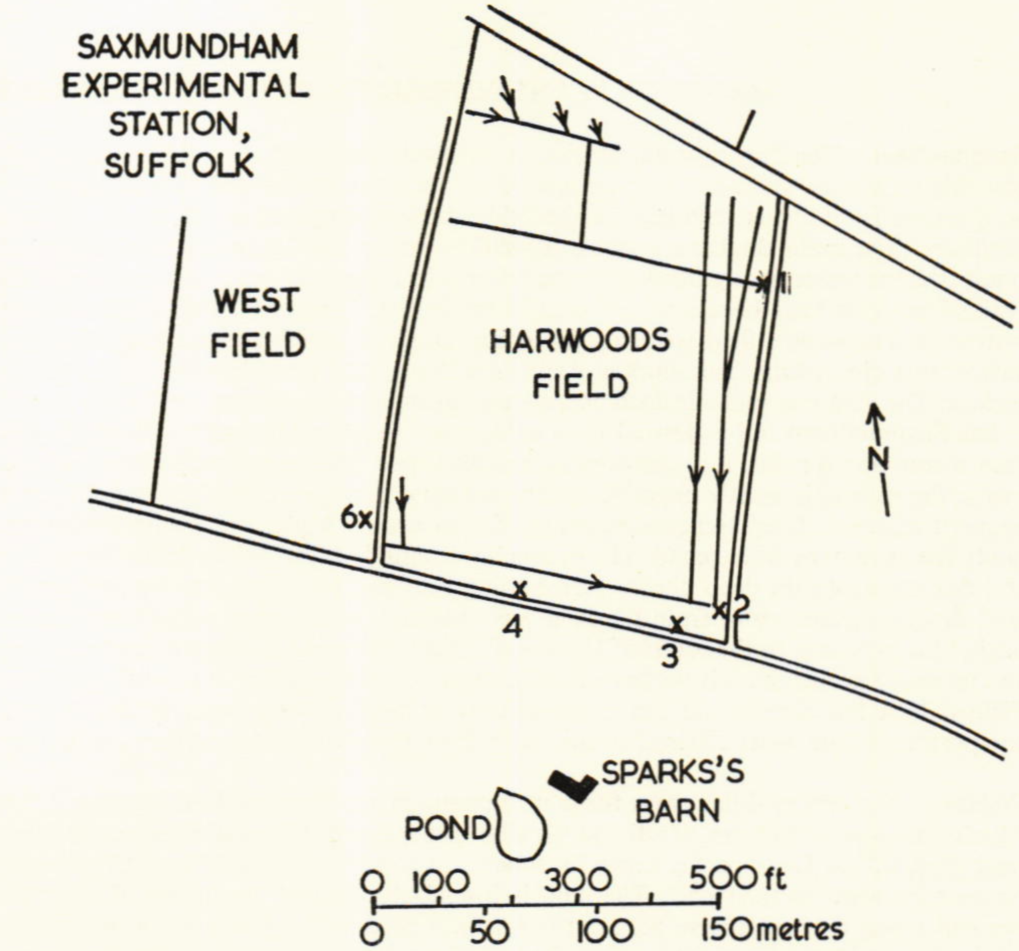
**Saxmundham.** The Experimental Station at Saxmundham, started in 1898, is now only one field (Harwood's about 3 ha) surrounded by deep ditches. Animals are not kept and no drainage from higher land reaches the field; nutrients come solely from rain, soil and fertilisers. The main ditch runs down a shallow valley and intermittently becomes a small stream; water finally flows into the River Alde. The positions and outfalls of the drains known to have been installed in 1948 are in Fig. 1; records of an older drainage system on Harwood's field were lost in a fire. Drain 4, which flows intermittently, is part of this old system. The modern drains are thought to be at least 65 cm below the surface. The field was mole-drained 56 cm deep during the dry autumn of 1964.

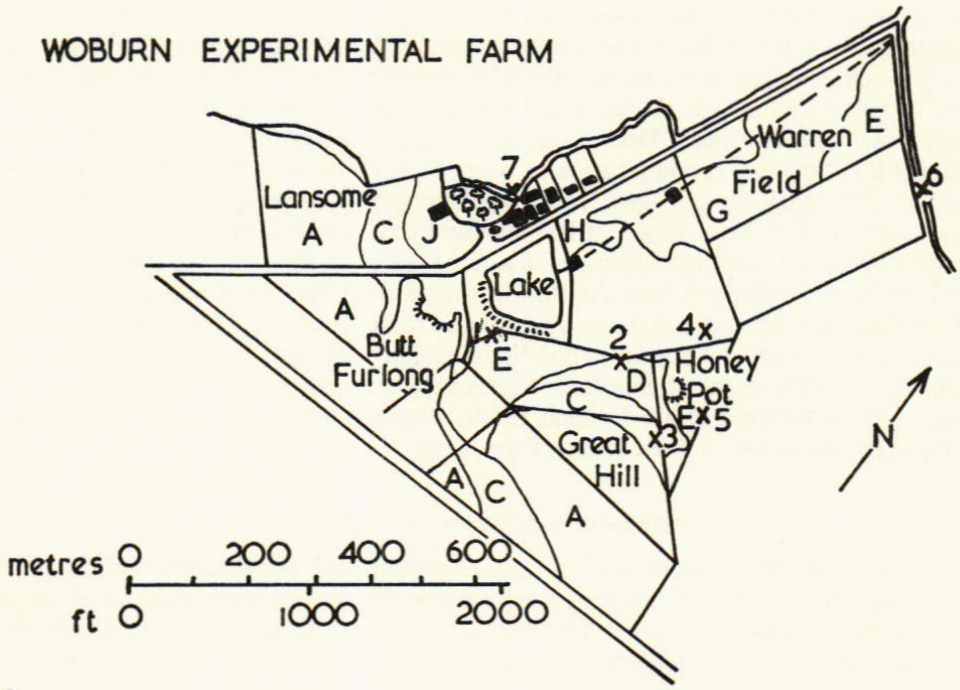
The Saxmundham soil is derived from calcareous boulder clay with rather more sand than is common for this. It is classified as Beccles Series. The surface soil slakes and caps easily; the subsoil is mostly impervious compact clay, interspersed with lenses of lighter-textured material. Deep trenches excavated 500 m away for gas mains suggest that the sandy lenses may be widespread. The drains have outfalls 1·2 to 1·5 m below the surface and discharge into the deep ditches surrounding the field. In addition to water from the land drains, surface water from the field was analysed, as also was water from a pond behind Spark's barn to the south of Harwood's Field; the pond is filled by land drainage and in most seasons there is no flow from it. Drain 6 discharged from the adjacent West Field (which has similar soil but is imperfectly drained); it was sampled because the composition of the water differed considerably from that drained from Harwood's Field.

**Woburn.** The drains differ from those at Saxmundham. Crawley Mill Farm is 1·5 to 3 km north-east of Woburn, mostly on the edge of the Lower Greensand ridge and down-wash from it. The lower part is heavy Drift deposits overlying Oxford Clay. All the water drains northward to the Ouzel. The land is irregularly drained, by drains of uncertain age and extent that must have been put in for local need and not to any general pattern. Drains 1, 2 and 3 run from deep soil profiles of lighter drift overlying relatively impervious resorted Oxford Clay; they flow continuously through the year. Drain 4 collects water from an area of resorted Oxford Clay under permanent grass that is periodically grazed. Its flow is much less than those of the other drains and there is little or none during dry weather. Drains 5 and 6 both originate in a spring at the rear of Honeypot Field; No. 5 discharges into a nearby ditch, Drain 6 traverses shallowly a cattle watering point in an adjacent field. Differences in composition of water from these two drains reflects pollution in Drain 6. The small stream (No. 7) comes from an underground source, provided with soil traps, in Mill Dam Close. It flows behind the farm buildings, joins the stream to the north of Long Mead and ultimately discharges into the River Ouzel. It was sampled north of the farm buildings where the flow was measured at a small weir. This stream flowed continuously throughout the two years, and diminished only in very dry weather. The artificial lake south of the farm buildings, which was sampled as a static source, discharges by a drain to the stream and its composition was an interesting comparison with that of the water from Drain 1 which fed it. Figure 1 shows the extent and nature of the types of soil in the drained areas of the farm.

### Effects of weather on drainage

Tables 2 and 3 show the amount and intensity of rainfall, soil temperature and drainage, and the mean combined flow of the drains at each site. Table 1 gives the means and ranges of the flowrates of individual drains. For Saxmundham, the total monthly drainage flow is also expressed as a percentage of the monthly rain, as the drains serve a finite area.


SAXMUNDHAM EXPERIMENTAL STATION, SUFFOLK
WEST FIELD
HARWOODS FIELD
N
1
6x
x 2
x 4
x 3
SPARKS'S BARN
POND
0 100 300 500 ft
0 50 100 150 metres


WOBURN EXPERIMENTAL FARM
Lansome
A C J
7
H
Warren Field
E
G
6
Lake
A
Butt Furlong
E
2
4x
Honey Pot
D
C
E x5
Great Hill
x3
A C
A
N
metres 0 200 400 600
ft 0 1000 2000

38

At Woburn the catchment areas are not known and a similar calculation cannot be made.

Mean flowrates were greater at Woburn than at Saxmundham but varied less. At Saxmundham very large flowrates were recorded for short periods, but often the drains ran very little or not at all. The flow from Drain 6 (West Field) was most erratic, especially during the second year; although the drainage system in West Field is recent, it works badly, and the field is often waterlogged with much surface run-off during heavy rain.

**Saxmundham.** The mean flow from Drains 1–4 at Saxmundham was much greater during the second (16 l/min) than the first year (9·4 l/min). The mean monthly flow-rates also differed during these two years, with flows much larger in the first three months and the last five months of the second year, when September and October were dry. The drainage flow pattern followed the rainfall distribution in both years, the beginning and end of the 1969–70 period was much wetter with a larger proportion of the rain in increments >10 mm daily. There was only 9 mm of rain during September and October 1969, whereas in these months in 1968 nearly 190 mm of rain fell, much of it in increments >10 mm daily. The soil, 30 cm deep, was colder from March to June 1969 than in 1968 but was warmer for the succeeding three months, when evaporation was greater. In November 1969, after two dry months, nearly 60 mm of rain was needed to start drainage; total soil moisture in the 0 to 23 cm horizon was then 20% v/v and 30% v/v 45–92 cm deep. Estimations of the moisture deficit at these two depths by the end of September, together with the observed volume of drainage during November, suggested that, when rainfall at Saxmundham is largely in increments >10 mm daily, the subsoil below plough depth does not take up the extra water and prevent rapid drainage, so there are losses of soluble nutrients, especially N. This is one feature of the considerable difference in behaviour between the Saxmundham and Rothamsted soils; at Rothamsted roots penetrate deeper, which improves subsoil condition and permits plants to use more subsoil moisture. Of the relationships between mean monthly flow-rates, total monthly rain, rain >10 mm weekly, rain >10 mm daily, or >2·5 daily, the closest was between flow rate and rain >10 mm weekly, especially during the winter (September–February). Rainfall intensities and drainage were less well related during summer (March–August) because of the greater evaporation during these months. As mean annual concentrations of nutrients in drainage at Saxmundham fluctuated less than mean annual flowrate, flowrate dominated the quantities lost in drainage each year.

**Woburn.** Rainfall during March, April and May of 1969 was more than in 1968 but drainage flowrates were similar in both years. Heavy rain from June–September 1968 maintained larger flow than in 1969 when the monthly rainfall was much less. The dry months of September and October 1969, when only 15 mm of rain fell, contrasted sharply with the 149 mm that fell during the comparable period in 1968. The flows from the land

Fig. 1. Plans of Saxmundham and Woburn (see opposite page). Drain outfalls numbered.

Key to the soil types at Woburn.

- A. Brown earths on resorted Lower Greensand.
- C., D., E. Gley soils:
  - C. On colluvial Lower Greensand/Oxford clay.
  - D. On reworked Lower Greensand and Oxford clay.
  - E. On resorted Oxford clay.
- G., H., J. Alluvial complexes:
  - G. Heavy.
  - H. Light.
  - J. Undifferentiated and made ground.

**TABLE 1**

*Rates of flow from individual drains at Saxmundham and Woburn. Averages for the two periods (l/min)*

| Drain | Woburn, 1968–69 Mean | Max. | Min. | Drain | | Saxmundham, 1968–69 Mean | Max. | Min. |
|---|---|---|---|---|---|---|---|---|
| 1 | 13·4 | 22·5 | 8·7 | 1 | Harwood's Field | 3·1 | 80·0 | 0·0 |
| 2 | 10·1 | 25·0 | 1·7 | 2 | Harwood's Field | 3·9 | 80·0 | 0·0 |
| 3 | 3·3 | 15·0 | 1·0 | 3 | Harwood's Field | 1·7 | 20·0 | 0·0 |
| 4 | 1·9 | 8·7 | 0·12 | 4 | Harwood's Field | 0·7 | 60·0 | 0·0 |
| 5 | 3·6 | 15·0 | 0·62 | | | | | |
| 6 | 5·5 | 15·0 | 1·7 | 6 | West Field | 0·9 | 60·0 | 0·0 |
| Stream | 130·0 | 130·0 | 130·0 | | | | | |

| Drain | 1969–70 Mean | Max. | Min. | Drain | | 1969–70 Mean | Max. | Min. |
|---|---|---|---|---|---|---|---|---|
| 1 | 9·0 | 22·5 | 1·0 | 1 | Harwood's Field | 4·9 | 60·0 | 0·0 |
| 2 | 2·3 | 2·5 | 1·0 | 2 | Harwood's Field | 7·6 | 120·0 | 0·0 |
| 3 | 2·8 | 15·0 | 0·25 | 3 | Harwood's Field | 2·0 | 80·0 | 0·0 |
| 4 | 1·1 | 8·7 | 0·0 | 4 | Harwood's Field | 1·4 | 50·0 | 0·0 |
| 5 | 3·3 | 15·0 | 0·25 | | | | | |
| 6 | 18·3 | 80·0 | 2·5 | 6 | West Field | 1·1 | 15·0 | 0·0 |
| Stream | 75·0 | 130·0 | 15·0 | | | | | |

**TABLE 3**

*Relationships between rainfall, its intensity, soil temperature, and drainage at Woburn*

| Year | Month | Rainfall (mm) Total | Rainfall (mm) >10 mm daily | Rainy days (>0·25 mm) | Soil temperature 30 cm (°C) | Flowrate (l/min) Drains 1–6 | Flowrate (l/min) Spring |
|---|---|---|---|---|---|---|---|
| 22 March 1968–10 March 1969 | | | | | | | |
| 1968 | March | 5 | 0 | 4 | 7·0 | 8·2 | — |
| | April | 51 | 11 | 13 | 8·1 | 6·7 | — |
| | May | 55 | 15 | 17 | 10·9 | 4·8 | 130 |
| | June | 78 | 37 | 15 | 15·3 | 3·5 | 130 |
| | July | 109 | 77 | 13 | 16·6 | 3·3 | 130 |
| | August | 75 | 34 | 14 | 15·9 | 3·7 | 130 |
| | September | 108 | 66 | 19 | 15·0 | 4·2 | 130 |
| | October | 41 | 12 | 13 | 13·1 | 4·1 | 130 |
| | November | 53 | 20 | 15 | 10·3 | 5·5 | 130 |
| | December | 47 | 12 | 12 | 4·8 | 9·1 | 130 |
| 1969 | January | 76 | 11 | 22 | 4·5 | 11·8 | 130 |
| | February | 57 | 22 | 15 | 2·1 | 12·1 | 130 |
| | March | 4 | 0 | 1 | 2·2 | 6·4 | 130 |
| Total | | 759 | 317 | 173 | — | — | — |
| Mean | | — | — | — | 9·7 | 6·4 | 130 |
| 11 March 1969–23 March 1970 | | | | | | | |
| 1969 | March | 52 | 34 | 12 | 3·8 | — | — |
| | April | 34 | 14 | 15 | 7·2 | 6·3 | 130 |
| | May | 75 | 28 | 17 | 11·9 | 5·3 | 130 |
| | June | 30 | 14 | 10 | 14·9 | 4·1 | 130 |
| | July | 40 | 13 | 7 | 17·6 | 4·5 | 130 |
| | August | 60 | 24 | 14 | 17·0 | 4·0 | 130 |
| | September | 12 | 0 | 9 | 15·1 | 3·7 | 80 |
| | October | 3 | 0 | 4 | 12·9 | 3·2 | 15 |
| | November | 65 | 18 | 15 | 7·8 | 2·1 | 15 |
| | December | 49 | 0 | 18 | 4·6 | 8·2 | 30 |
| 1970 | January | 56 | 11 | 22 | 4·2 | 6·0 | 15 |
| | February | 57 | 0 | 20 | 3·4 | 25·7 | 80 |
| | March | 50 | 12 | 13 | 3·3 | 6·9 | 15 |
| Total | | 583 | 168 | 176 | — | — | — |
| Mean | | — | — | — | 9·5 | 6·7 | 75·0 |

**TABLE 2**

*Relationships between rainfall and its intensity, evaporation, soil temperature and drainage at Saxmundham*

21 March 1968–11 March 1969

| | | Rainfall | | | | Drainage | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Drains 1–4 | | | |
| Year | Month | Total (mm) | Daily > 10 mm | Evaporation Eo (mm) | Soil temperature at 30 cm depth (°C) | Observations (days) | Flowrate (l/min) | Total (as % of rain) | West Field Flowrate (l/min) |
| 1968 | March | 7 | 0 | — | 5·1 | 9 | 1·0 | 6·5 | 0·3 |
| | April | 27 | 0 | 87 | 8·3 | 21 | 0·1 | 0·5 | 0·0 |
| | May | 42 | 18 | 64 | 11·4 | 27 | 2·5 | 7·8 | 0·0 |
| | June | 56 | 10 | 93 | 16·1 | 27 | 0·1 | 0·3 | 0·0 |
| | July | 64 | 17 | 84 | 16·8 | 27 | 0·2 | 0·4 | 0·0 |
| | August | 73 | 33 | 76 | 16·3 | 28 | 1·0 | 1·9 | 0·0 |
| | September | 138 | 106 | 62 | 14·8 | 24 | 46·5 | 38·4 | 1·2 |
| | October | 51 | 11 | 28 | 12·5 | 27 | 8·2 | 20·9 | 0·2 |
| | November | 41 | 0 | — | 8·0 | 26 | 11·9 | 36·3 | 1·9 |
| | December | 45 | 27 | — | 4·8 | 22 | 13·2 | 30·9 | 3·5 |
| 1969 | January | 49 | 0 | — | 4·8 | 27 | 22·9 | 59·4 | 2·7 |
| | February | 73 | 25 | — | 2·5 | 24 | 12·5 | 19·6 | 1·3 |
| | March | 12 | 0 | — | 3·7 | 9 | 2·4 | 8·2 | 0·3 |
| Total | | 678 | 247 | — | — | 298 | — | — | — |
| Mean | | — | — | — | 9·6 | — | 9·4 | 17·8 | 0·9 |
| | | | | 12 March 1969–16 March 1970 | | | | | |
| 1969 | March | 43 | 19 | — | 3·7 | 17 | 29·7 | 55·9 | 1·3 |
| | April | 36 | 0 | 55 | 7·3 | 25 | 2·4 | 7·9 | 0·4 |
| | May | 92 | 46 | 83 | 11·7 | 27 | 24·3 | 34·0 | 0·9 |
| | June | 39 | 13 | 100 | 15·1 | 24 | 1·9 | 5·4 | 0·1 |
| | July | 99 | 98 | 119 | 19·0 | 23 | 5·5 | 6·0 | 0·0 |
| | August | 73 | 42 | 82 | 16·7 | 27 | 8·5 | 14·9 | 0·2 |
| | September | 2 | 0 | 62 | 15·5 | 27 | 0·0 | 0·0 | 0·0 |
| | October | 7 | 0 | 33 | 13·0 | 27 | 0·0 | 0·0 | 0·0 |
| | November | 99 | 73 | — | 7·1 | 27 | 15·7 | 20·3 | 0·5 |
| | December | 76 | 33 | — | 3·7 | 21 | 31·4 | 41·3 | 2·8 |
| 1970 | January | 71 | 13 | — | 4·2 | 24 | 36·2 | 57·9 | 3·0 |
| | February | 55 | 11 | — | 2·8 | 17 | 28·7 | 41·9 | 4·4 |
| | March | 23 | 0 | — | 3·8 | 13 | 24·2 | 24·7 | 0·9 |
| Total | | 715 | 348 | — | — | 299 | — | — | — |
| Mean | | — | — | — | 9·5 | — | 16·0 | 23·9 | 1·1 |

41

**TABLE 4(a)**

*Concentrations of $NH_4$–N, $NO_3$–N, $PO_4$–P, $SO_4$–S and Cl (mg/l) in drainage water from Harwood's Field, Saxmundham, from 21 March 1968 to 11 March 1969 and from 12 March 1969 to 16 March 1970, averaging values from drains 1–4*

| | | $NH_4$–N | | | $NO_3$–N | | | $PO_4$–P | | | $SO_4$–S | | | Cl | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| 1968 | March | 0·21 | 0·90 | | 6·1 | 8·2 | 4·0 | 0·06 | 0·70 | | 116 | 153 | 90 | 55 | 72 | 42 |
| | April | 0·22 | 1·40 | | 6·4 | 10·7 | 3·7 | 0·07 | 0·15 | | 143 | 176 | 107 | 54 | 71 | 47 |
| | May | 0·01 | 0·15 | | 41·9 | 91·5 | 9·7 | 0·06 | 0·25 | | 66 | 136 | 34 | 59 | 71 | 48 |
| | June | 0·22 | 0·60 | | 25·5 | 30·0 | 19·3 | 0·00 | 0·00 | | 47 | 55 | 34 | 34 | 43 | 22 |
| | July | 0·00 | 0·00 | | 41·7 | 56·5 | 29·8 | 0·00 | 0·00 | | 66 | 84 | 51 | 46 | 54 | 36 |
| | August | 0·00 | 0·00 | | 14·3 | 49·1 | 4·9 | 0·05 | 0·20 | | 36 | 67 | 21 | 38 | 52 | 27 |
| | September | 0·25 | 2·40 | 0·00 | 12·3 | 29·5 | 4·3 | 0·07 | 0·18 | 0·00 | 31 | 70 | 7 | 41 | 60 | 24 |
| | October | 0·09 | 0·40 | | 7·8 | 11·0 | 5·8 | 0·00 | 0·00 | | 39 | 61 | 23 | 46 | 55 | 36 |
| | November | 0·00 | 0·00 | | 10·6 | 16·1 | 7·7 | 0·00 | 0·00 | | 53 | 67 | 43 | 63 | 113 | 53 |
| | December | 0·00 | 0·00 | | 10·7 | 13·3 | 7·4 | 0·06 | 0·20 | | 52 | 70 | 39 | 59 | 67 | 50 |
| 1969 | January | 0·00 | 0·00 | | 10·2 | 14·2 | 7·0 | 0·17 | 0·17 | | 28 | 49 | 11 | 38 | 50 | 27 |
| | February | 0·00 | 0·00 | | 5·8 | 8·1 | 4·2 | 0·00 | 0·00 | | 46 | 79 | 17 | 40 | 73 | 16 |
| | March | 0·05 | 0·30 | | 6·9 | 14·5 | 5·3 | 0·00 | 0·00 | | 81 | 130 | 65 | 52 | 75 | 35 |
| Mean 1968–69 | | 0·08 | 0·47 | 0·00 | 15·4 | 27·1 | 8·7 | 0·04 | 0·14 | 0·00 | 62 | 92 | 42 | 48 | 66 | 36 |
| 1969 | March | 0·09 | 1·45 | | 10·9 | 25·6 | 5·5 | 0·04 | 0·30 | 0·00 | 40 | 95 | 15 | 46 | 81 | 34 |
| | April | 0·06 | 1·20 | | 10·0 | 27·5 | 5·5 | 0·00 | 0·00 | 0·00 | 96 | 114 | 80 | 58 | 80 | 43 |
| | May | 0·11 | 0·65 | | 25·5 | 91·2 | 5·5 | 0·00 | 0·00 | 0·00 | 56 | 120 | 32 | 48 | 78 | 27 |
| | June | 0·01 | 0·20 | | 12·6 | 31·0 | 6·1 | 0·40 | 0·40 | 0·40 | 89 | 127 | 50 | 58 | 62 | 54 |
| | July | 0·00 | 0·00 | | 6·2 | 22·6 | 2·4 | 0·00 | 0·00 | 0·00 | 26 | 28 | 24 | 32 | 31 | 20 |
| | August | 0·08 | 0·50 | | 4·5 | 7·5 | 0·5 | 0·00 | 0·00 | 0·00 | 29 | 30 | 25 | 36 | 41 | 32 |
| | September | — | — | 0·00 | — | — | — | — | — | — | — | — | — | — | — | — |
| | October | — | — | | — | — | — | — | — | — | — | — | — | — | — | — |
| | November | 0·00 | 0·00 | | 26·9 | 40·3 | 13·0 | 0·11 | 1·20 | 0·00 | 63 | 72 | 50 | 102 | 129 | 62 |
| | December | 0·55 | 2·40 | | 13·7 | 18·7 | 8·0 | 0·09 | 0·30 | 0·00 | 54 | 104 | 30 | 43 | 33 | 26 |
| 1970 | January | 0·34 | 2·30 | | 8·6 | 10·6 | 0·0 | 0·00 | 0·00 | 0·00 | 51 | 57 | 46 | 30 | 49 | 22 |
| | February | 0·12 | 1·50 | | 7·8 | 9·7 | 6·1 | 0·00 | 0·05 | 0·00 | 43 | 76 | 29 | 23 | 40 | 17 |
| | March | 0·43 | 3·00 | | 7·7 | 9·6 | 6·0 | 0·00 | 0·00 | 0·00 | 60 | 70 | 54 | 38 | 56 | 28 |
| Mean 1969–70 | | 0·16 | 1·20 | 0·00 | 12·2 | 26·7 | 5·3 | 0·06 | 0·20 | 0·04 | 55 | 81 | 40 | 47 | 62 | 33 |

**TABLE 4(b)**

*Concentrations of cations (mg/l) in drainage water from Harwood's Field, Saxmundham, from 21 March 1968 to 11 March 1969 and from 12 March 1969 to 16 March 1970, average values from drains 1–4*

| | | Ca | | | Mg | | | K | | | Na | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| 1968 | March | 222 | 256 | 192 | 14·9 | 23·0 | 9·8 | 1·8 | 4·4 | 0·4 | 30·4 | 38·0 | 24·0 |
| | April | 246 | 270 | 212 | 19·9 | 27·5 | 12·6 | 1·5 | 3·9 | 0·6 | 35·4 | 41·0 | 31·0 |
| | May | 245 | 280 | 215 | 11·2 | 16·8 | 8·5 | 1·2 | 2·6 | 0·5 | 24·0 | 28·0 | 18·5 |
| | June | 197 | 237 | 150 | 7·7 | 9·2 | 6·3 | 1·8 | 2·6 | 1·0 | 18·9 | 22·0 | 15·0 |
| | July | 246 | 277 | 218 | 9·6 | 12·7 | 7·4 | 1·2 | 1·6 | 1·0 | 23·5 | 30·0 | 19·2 |
| | August | 197 | 245 | 128 | 6·4 | 10·0 | 3·7 | 1·9 | 3·9 | 0·6 | 16·2 | 23·5 | 9·4 |
| | September | 152 | 225 | 84 | 5·6 | 12·7 | 3·0 | 1·8 | 4·8 | 0·8 | 16·0 | 36·0 | 10·8 |
| | October | 174 | 222 | 105 | 7·1 | 12·9 | 3·8 | 1·9 | 3·4 | 1·0 | 18·3 | 23·5 | 11·6 |
| | November | 165 | 204 | 116 | 8·2 | 9·9 | 5·7 | 1·3 | 2·7 | 0·7 | 18·3 | 22·0 | 15·0 |
| | December | 155 | 168 | 137 | 8·5 | 10·6 | 6·2 | 1·3 | 3·6 | 0·6 | 21·6 | 28·0 | 15·6 |
| 1969 | January | 133 | 163 | 108 | 4·7 | 8·9 | 4·1 | 1·5 | 2·2 | 1·0 | 14·6 | 18·0 | 11·6 |
| | February | 156 | 232 | 62 | 7·7 | 7·1 | 2·7 | 0·9 | 1·7 | 0·4 | 17·8 | 29·2 | 7·4 |
| | March | 210 | 244 | 194 | 12·6 | 21·4 | 9·5 | 0·7 | 1·2 | 0·5 | 26·2 | 32·4 | 17·4 |
| Mean 1968–69 | | 192 | 232 | 148 | 9·5 | 14·0 | 6·4 | 1·4 | 3·0 | 0·7 | 21·6 | 28·6 | 15·9 |
| 1969 | March | 151 | 222 | 114 | 7·7 | 18·3 | 4·2 | 1·5 | 3·3 | 0·6 | 19·8 | 44·8 | 12·0 |
| | April | 214 | 236 | 188 | 14·9 | 28·8 | 12·1 | 1·1 | 1·3 | 0·8 | 26·1 | 28·8 | 23·0 |
| | May | 195 | 260 | 144 | 8·9 | 16·1 | 4·5 | 1·7 | 4·2 | 0·6 | 18·9 | 31·2 | 11·0 |
| | June | 206 | 206 | 206 | 10·8 | 10·8 | 10·8 | 3·8 | 3·8 | 3·8 | 22·4 | 22·4 | 22·4 |
| | July | 111 | 124 | 98 | 4·2 | 4·6 | 3·9 | 1·5 | 2·9 | 1·0 | 13·0 | 14·2 | 12·0 |
| | August | 133 | 150 | 118 | 4·2 | 4·3 | 3·9 | 1·4 | 1·6 | 1·4 | 13·2 | 14·0 | 11·8 |
| | September | — | — | — | — | — | — | — | — | — | — | — | — |
| | October | — | — | — | — | — | — | — | — | — | — | — | — |
| | November | 210 | 236 | 160 | 7·2 | 9·3 | 4·7 | 2·6 | 5·2 | 1·6 | 17·2 | 20·8 | 12·6 |
| | December | 146 | 217 | 102 | 6·1 | 10·3 | 3·3 | 2·2 | 4·2 | 0·8 | 16·5 | 24·8 | 12·0 |
| 1970 | January | 175 | 270 | 166 | 4·3 | 14·0 | 0·8 | 1·1 | 1·4 | 0·8 | 15·6 | 20·8 | 12·8 |
| | February | 140 | 140 | 88 | 3·9 | 4·7 | 3·2 | 1·4 | 2·3 | 0·8 | 13·4 | 22·0 | 10·0 |
| | March | 163 | 176 | 148 | 7·9 | 8·7 | 7·3 | 1·7 | 3·1 | 0·7 | 21·1 | 24·0 | 19·2 |
| Mean 1969–70 | | 168 | 203 | 139 | 7·3 | 11·8 | 5·3 | 1·8 | 3·0 | 1·2 | 17·9 | 24·3 | 14·4 |

drains diminished from September 1969 and their rates, and that of the stream, remained small until March 1970; the stream had a larger and constant flow throughout 1968. There was little association between rainfall >10 mm daily and drainage flowrates, which depended more on longer periods of dry or wet weather. This is because the soil profiles are much deeper and the areas drained much larger than at Saxmundham. The large flowrate from Drain 6 during February 1969 is not readily explained, but it is a shallow drain and may have gathered some surface water. Drain 5, which originated nearby, also had a large flowrate during this month. The larger mean annual flowrate for 1968–69, especially of the stream, is the cause of larger estimated losses of nutrients than during 1969–70.

The contrasts between the drains at Woburn and at Saxmundham (other than No. 4, which has its source in resorted Oxford Clay and resembles the Saxmundham drains), are: (1) that flowrates from Woburn drains were less affected by daily rainfall; (2) the concentrations of nutrients did not show the sharp maxima, especially of $NH_4$/N, $NO_3$/N and K, found in drainage water at Saxmundham during early spring and summer.

### The effects of rainfall and volume of drainage on composition of the water

Tables 4a and b give the monthly means and ranges of concentrations of nutrients in drainage water at Saxmundham during 1968–70. Table 5 shows the relationships between the individual drains, expressed as mean annual concentrations of ions, together with values for pH and specific conductivity. Tables 6a, b and 7 give the corresponding measurements from the sources examined at Woburn. Of the major plant nutrients, nitrogen is

**TABLE 5**

*Average concentrations of ions (mg/l), conductivities, and pH values in water from five drains and one static source at Saxmundham 1968–69 and 1969–70*

| | | Harwood's Field | | | | West Field | |
|---|---|---|---|---|---|---|---|
| | | Drain 1 | Drain 2 | Drain 3 | Drain 4 | Drain 6 | Pond |
| Calcium | 1968–69 | 190 | 190 | 201 | 155 | 124 | 133 |
| | 1969–70 | 175 | 152 | 161 | 153 | 120 | 124 |
| Magnesium | 1968–69 | 8·9 | 9·8 | 10·9 | 6·0 | 7·7 | 10·3 |
| | 1969–70 | 6·9 | 7·2 | 7·6 | 5·2 | 7·7 | 10·6 |
| Potassium | 1968–69 | 1·9 | 1·2 | 1·1 | 1·9 | 2·0 | 17·7 |
| | 1969–70 | 2·2 | 1·6 | 1·4 | 1·5 | 2·1 | 18·9 |
| Sodium | 1968–69 | 23 | 22 | 22 | 15 | 15 | 29 |
| | 1969–70 | 20 | 17 | 18 | 13 | 13 | 29 |
| Ammonium-N | 1968–69 | 0·13 | 0·06 | 0·05 | 0·03 | 0·09 | 1·43 |
| | 1969–70 | 0·18 | 0·17 | 0·17 | 0·13 | 0·28 | 1·47 |
| Nitrate-N | 1968–69 | 11·5 | 12·7 | 18·7 | 15·9 | 2·5 | 0·6 |
| | 1969–70 | 12·0 | 10·9 | 12·4 | 14·9 | 5·4 | 0·8 |
| Phosphorus | 1968–69 | 0·06 | 0·02 | 0·04 | 0·08 | 0·13 | 0·58 |
| | 1969–70 | 0·08 | 0·02 | 0·01 | 0·04 | 0·00 | 0·44 |
| Sulphate-S | 1968–69 | 57 | 67 | 65 | 33 | 35 | 18 |
| | 1969–70 | 52 | 52 | 64 | 37 | 46 | 22 |
| Chloride | 1968–69 | 55 | 44 | 46 | 52 | 33 | 63 |
| | 1969–70 | 59 | 43 | 41 | 38 | 30 | 63 |
| Conductivity ($\mu$ mhos/cm) | 1968–69 | 950 | 940 | 1000 | 760 | 650 | 800 |
| | 1969–70 | 940 | 850 | 870 | 720 | 650 | 790 |
| pH | 1968–69 | 7·6 | 7·6 | 7·7 | 7·7 | 7·6 | 7·7 |
| | 1969–70 | 7·8 | 7·7 | 7·8 | 8·0 | 7·8 | 7·9 |

**TABLE 6(a**

*Concentrations of $NH_4$–N, $NO_3$–N, $PO_4$–P, $SO_4$–S and Cl (mg/l) in drainage water from Woburn, from 22 March 1968 to 10 March 1969 and from 12 March 1969 to 16 March 1970; average values from drains 1–6*

| | | $NH_4$–N | | | $NO_3$–N | | | $PO_4$–P | | | $SO_4$–S | | | Cl | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| 1968 | March | 0·00 | — | — | 12·0 | — | — | 0·14 | — | — | — | — | — | 29·5 | — | — |
| | April | 0·00 | — | — | 11·1 | — | — | 0·14 | — | — | 69·9 | — | — | 37·1 | — | — |
| | May | 0·02 | 0·30 | 0·00 | 11·2 | 21·9 | 1·2 | 0·15 | 0·55 | 0·00 | 61·4 | 130·6 | 36·0 | 32·7 | 55·0 | 12·2 |
| | June | 0·53 | 3·20 | 0·00 | 15·6 | 23·7 | 1·8 | 0·37 | 0·75 | 0·00 | 53·8 | 87·8 | 37·7 | 44·4 | 126·0 | 16·0 |
| | July | 0·03 | 0·30 | 0·00 | 11·8 | 24·8 | 2·0 | 0·15 | 0·63 | 0·00 | 55·5 | 105·0 | 32·7 | 28·8 | 54·5 | 13·0 |
| | August | 0·00 | 0·00 | 0·00 | 12·0 | 24·7 | 1·2 | 0·18 | 0·53 | 0·00 | 48·7 | 130·0 | 23·0 | 26·9 | 45·5 | 11·3 |
| | September | 0·00 | 0·00 | 0·00 | 12·7 | 25·6 | 2·0 | 0·14 | 0·53 | 0·00 | 47·8 | 121·0 | 16·5 | 27·0 | 47·5 | 11·8 |
| | October | 0·00 | 0·00 | 0·00 | 11·0 | 25·2 | 1·2 | 0·16 | 0·65 | 0·00 | 32·9 | 78·5 | 15·0 | 27·3 | 47·5 | 11·5 |
| | November | 0·00 | 0·00 | 0·00 | 12·8 | 26·2 | 1·9 | 0·14 | 0·52 | 0·00 | 54·8 | 119·0 | 30·8 | 27·0 | 45·5 | 12·5 |
| | December | 0·04 | 0·50 | 0·00 | 12·2 | 25·5 | 1·5 | 0·11 | 0·50 | 0·00 | 61·5 | 117·0 | 32·0 | 30·2 | 51·5 | 12·5 |
| 1969 | January | 0·00 | 0·00 | 0·00 | 13·7 | 23·8 | 4·8 | 0·22 | 0·85 | 0·00 | 55·3 | 102·0 | 23·0 | 30·2 | 55·0 | 14·5 |
| | February | 0·00 | 0·00 | 0·00 | 12·1 | 20·0 | 6·5 | 0·08 | 0·45 | 0·00 | 51·3 | 99·5 | 28·0 | 29·2 | 51·0 | 17·0 |
| | March | 0·26 | — | — | — | — | — | 0·00 | — | — | 56·4 | — | — | 27·7 | — | — |
| Mean 1968–69 | | 0·07 | 0·43 | 0·00 | 12·3 | 24·1 | 2·4 | 0·15 | 0·60 | 0·00 | 54·1 | 109·0 | 27·5 | 30·6 | 57·9 | 13·2 |
| 1969 | March | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| | April | 0·00 | 0·00 | 0·00 | 13·3 | 22·0 | 7·5 | 0·16 | 0·50 | 0·00 | 51·4 | 84·7 | 35·3 | 26·8 | 40·0 | 16·0 |
| | May | 0·01 | 0·15 | 0·00 | 12·3 | 21·0 | 4·5 | 0·06 | 0·50 | 0·00 | 52·0 | 108·0 | 30·8 | 26·1 | 42·5 | 14·2 |
| | June | 0·07 | 0·80 | 0·00 | 12·9 | 24·0 | 4·5 | 0·17 | 0·50 | 0·00 | 48·5 | 107·8 | 33·0 | 26·0 | 42·0 | 13·0 |
| | July | 0·03 | 0·20 | 0·00 | 14·5 | 24·3 | 4·5 | 0·19 | 0·55 | 0·00 | 50·7 | 103·5 | 37·0 | 35·3 | 126·0 | 14·5 |
| | August | 0·00 | 0·00 | 0·00 | 12·8 | 24·0 | 2·4 | 0·10 | 0·50 | 0·00 | 56·4 | 136·0 | 35·5 | 31·2 | 64·5 | 12·5 |
| | September | 0·00 | 0·00 | 0·00 | 14·7 | 25·3 | 3·5 | 0·12 | 0·40 | 0·00 | 45·0 | 59·5 | 39·0 | 24·0 | 40·0 | 14·0 |
| | October | 0·02 | 0·10 | 0·00 | 16·4 | 26·2 | 5·9 | 0·26 | 0·60 | 0·00 | 44·1 | 53·0 | 38·0 | 25·2 | 40·5 | 16·0 |
| | November | 0·23 | 0·60 | 0·00 | 16·4 | 26·0 | 4·5 | 0·19 | 0·40 | 0·00 | 57·5 | 141·0 | 37·5 | 34·5 | 81·0 | 12·0 |
| | December | 0·00 | 0·00 | 0·00 | 15·4 | 24·5 | 4·0 | 0·14 | 0·50 | 0·00 | 67·5 | 148·0 | 37·5 | 36·6 | 99·5 | 10·5 |
| 1970 | January | 0·00 | 0·00 | 0·00 | 13·8 | 25·0 | 3·0 | 0·06 | 0·40 | 0·00 | 70·9 | 163·0 | 41·0 | 29·2 | 47·0 | 12·5 |
| | February | 0·00 | 0·00 | 0·00 | 17·3 | 26·6 | 5·6 | 0·00 | 0·00 | 0·00 | 63·9 | 132·0 | 38·0 | 30·6 | 50·5 | 16·5 |
| | March | 0·00 | 0·00 | 0·00 | 17·4 | 32·2 | 8·6 | 0·00 | 0·00 | 0·00 | 62·3 | 132·0 | 36·5 | 29·6 | 44·0 | 18·0 |
| Mean 1969–70 | | 0·03 | 0·15 | 0·00 | 14·8 | 25·1 | 4·9 | 0·12 | 0·40 | 0·00 | 55·8 | 114·0 | 36·6 | 29·6 | 59·8 | 14·1 |

TABLE 6(b)

*Concentrations of cations in drainage water from Woburn, from 22 March 1968 to 10 March 1969 and from 12 March 1969 to 16 March 1970; average values from drains 1–6*

| | | Ca | | | Mg | | | K | | | Na | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| 1968 | March | 149 | — | — | 9·5 | — | — | 2·1 | — | — | 11·1 | — | — |
| | April | 167 | — | — | 10·8 | — | — | 5·8 | — | — | 12·8 | — | — |
| | May | 159 | 242 | 77 | 10·0 | 20·0 | 5·3 | 3·6 | 16·0 | 0·5 | 12·0 | 20·5 | 8·5 |
| | June | 129 | 231 | 44 | 7·9 | 10·9 | 4·8 | 12·9 | 64·0 | 0·6 | 11·5 | 15·6 | 9·4 |
| | July | 144 | 261 | 82 | 8·2 | 15·2 | 4·1 | 3·7 | 15·0 | 0·5 | 11·2 | 17·9 | 7·4 |
| | August | 151 | 333 | 41 | 9·6 | 18·5 | 5·2 | 3·2 | 9·6 | 0·5 | 11·0 | 18·0 | 8·3 |
| | September | 153 | 302 | 67 | 9·7 | 17·6 | 5·7 | 3·6 | 10·1 | 0·6 | 11·3 | 15·6 | 8·4 |
| | October | 163 | 288 | 75 | 9·2 | 17·0 | 5·2 | 3·5 | 13·6 | 0·6 | 10·9 | 15·0 | 8·0 |
| | November | 130 | 195 | 69 | 9·9 | 22·0 | 4·7 | 3·9 | 13·8 | 0·5 | 11·0 | 15·8 | 8·4 |
| | December | 144 | 177 | 55 | 9·3 | 18·0 | 5·0 | 4·2 | 13·6 | 0·4 | 10·8 | 15·2 | 8·0 |
| 1969 | January | 140 | 264 | 64 | 8·3 | 15·6 | 4·8 | 4·5 | 20·0 | 0·4 | 11·1 | 17·6 | 7·2 |
| | February | 147 | 242 | 65 | 9·0 | 18·0 | 5·0 | 4·0 | 18·0 | 0·4 | 11·1 | 18·4 | 8·0 |
| | March | 144 | — | — | 9·1 | — | — | 2·9 | — | — | 10·9 | — | — |
| Mean 1968–69 | | 148 | 253 | 64 | 9·3 | 17·3 | 5·0 | 4·4 | 19·4 | 0·5 | 11·3 | 17·0 | 8·2 |
| 1969 | March | — | — | — | — | — | — | — | — | — | — | — | — |
| | April | 128 | 182 | 69 | 9·7 | 17·8 | 5·1 | 2·9 | 5·8 | 0·5 | 10·6 | 15·4 | 8·0 |
| | May | 135 | 214 | 66 | 9·2 | 17·4 | 5·2 | 3·3 | 8·0 | 0·6 | 9·7 | 13·2 | 7·6 |
| | June | 134 | 220 | 69 | 9·5 | 19·8 | 5·1 | 3·4 | 9·6 | 0·6 | 10·7 | 16·0 | 8·4 |
| | July | 129 | 234 | 68 | 10·3 | 28·8 | 4·1 | 11·4 | 90·0 | 0·6 | 13·1 | 28·4 | 9·2 |
| | August | 129 | 232 | 72 | 9·8 | 25·2 | 4·3 | 7·5 | 31·0 | 0·6 | 12·6 | 26·4 | 8·8 |
| | September | 101 | 138 | 63 | 7·1 | 10·7 | 4·8 | 3·2 | 6·8 | 0·6 | 9·8 | 12·6 | 8·8 |
| | October | 106 | 136 | 64 | 7·1 | 10·7 | 4·9 | 3·4 | 6·7 | 0·6 | 9·7 | 12·4 | 8·6 |
| | November | 139 | 244 | 72 | 10·2 | 28·4 | 4·4 | 6·9 | 25·6 | 0·6 | 12·7 | 28·0 | 8·4 |
| | December | 137 | 256 | 67 | 10·7 | 34·0 | 3·3 | 7·8 | 40·8 | 0·8 | 12·0 | 26·4 | 7·2 |
| 1970 | January | 154 | 362 | 71 | 9·6 | 23·1 | 4·2 | 4·0 | 12·2 | 0·5 | 9·4 | 21·2 | 6·8 |
| | February | 147 | 256 | 86 | 7·8 | 15·3 | 4·3 | 4·9 | 19·2 | 0·6 | 10·8 | 18·0 | 7·4 |
| | March | 145 | 264 | 80 | 9·0 | 16·9 | 4·2 | 4·9 | 14·0 | 0·6 | 12·6 | 18·4 | 8·4 |
| Mean 1969–70 | | 132 | 228 | 70 | 9·2 | 20·7 | 4·5 | 5·3 | 22·5 | 0·6 | 11·1 | 19·7 | 8·1 |

**TABLE 7**

*Average concentrations of ions (mg/l), conductivities, and pH values of water from six drains, a permanent stream and one static source at Woburn, 1968–69 and 1969–70*

| | | Drain 1 | Drain 2 | Drain 3 | Drain 4 | Drain 5 | Drain 6 | Stream | Lake |
|---|---|---|---|---|---|---|---|---|---|
| Calcium | 1968–69 | 167 | 152 | 70 | 231 | 130 | 127 | 77 | 126 |
| | 1969–70 | 146 | 146 | 72 | 237 | 121 | 92 | 87 | 111 |
| Magnesium | 1968–69 | 9·5 | 6·8 | 10·3 | 16·7 | 5·2 | 7·0 | 8·6 | 11·3 |
| | 1969–70 | 8·4 | 6·2 | 9·9 | 21·3 | 4·6 | 5·8 | 8·7 | 10·5 |
| Potassium | 1968–69 | 1·9 | 0·7 | 4·4 | 15·7 | 0·6 | 3·4 | 3·7 | 8·6 |
| | 1969–70 | 2·2 | 0·6 | 4·7 | 19·2 | 0·7 | 5·3 | 4·7 | 9·0 |
| Sodium | 1968–69 | 14·3 | 9·7 | 8·7 | 16·1 | 8·7 | 10·1 | 11·6 | 15·5 |
| | 1969–70 | 13·3 | 8·9 | 8·9 | 19·4 | 8·4 | 9·3 | 11·6 | 15·8 |
| Ammonium-N | 1968–69 | 0·13 | 0·00 | 0·00 | 0·25 | 0·01 | 0·03 | 0·05 | 0·29 |
| | 1969–70 | 0·00 | 0·04 | 0·02 | 0·06 | 0·01 | 0·07 | 0·15 | 0·54 |
| Nitrate-N | 1968–69 | 20·4 | 12·2 | 20·4 | 8·2 | 3·2 | 7·9 | 10·8 | 2·0 |
| | 1969–70 | 24·5 | 12·2 | 21·4 | 11·7 | 5·0 | 10·9 | 9·0 | 1·9 |
| Phosphorus | 1968–69 | 0·08 | 0·02 | 0·43 | 0·09 | 0·07 | 0·22 | 0·15 | 0·01 |
| | 1969–70 | 0·02 | 0·00 | 0·33 | 0·03 | 0·05 | 0·22 | 0·05 | 0·01 |
| Sulphate-S | 1968–69 | 59 | 50 | 33 | 104 | 33 | 41 | 23 | 58 |
| | 1969–70 | 53 | 48 | 41 | 119 | 38 | 43 | 39 | 54 |
| Chloride | 1968–69 | 46 | 29 | 24 | 47 | 15 | 19 | 35 | 46 |
| | 1969–70 | 43 | 24 | 27 | 53 | 14 | 18 | 39 | 48 |
| Conductivity ($\mu$ mhos/cm) | 1968–69 | 880 | 770 | 470 | 1200 | 630 | 650 | 480 | 730 |
| | 1969–70 | 810 | 730 | 500 | 1230 | 610 | 530 | 550 | 680 |
| pH | 1968–69 | 7·1 | 7·3 | 6·3 | 7·4 | 7·2 | 7·1 | 7·1 | 7·5 |
| | 1969–70 | 7·2 | 7·4 | 6·6 | 7·8 | 7·5 | 7·2 | 7·3 | 7·5 |

most affected by leaching and, for this reason and because the amount leached depends on fertiliser–N applied, nitrate concentrations are discussed separately, with particular reference to the effects of rainfall intensity and evaporation on leaching.

### Nitrate in drainage

**Saxmundham.** Figure 2 shows the relationships between monthly rainfall, rainfall greater than 10 mm daily, evaporation from open water surface ($E_0$) from May to September, and mean monthly flowrates (l/minute) from Drains 1–4, with corresponding mean monthly concentrations of nitrate in drainage for the three years 1967, 1968 and 1969. During 1967, rainfall during the first four months (158 mm) was less than in 1968 (178 mm) or in 1969 (213 mm). Evaporation ($E_0$) was greater in 1967 than in the two succeeding years and there was an accumulated moisture deficit (0·75 $E_0$ *minus* rainfall) of 166 mm by the end of September 1967. In 1968 the monthly deficit never exceeded 51 mm and by October there was a surplus of 89 mm of rain over evaporation from the heavy rainfall during August–September. In 1969 the accumulated moisture deficit was very small, rising only to 48 mm by the end of October, after two months of exceptionally dry weather. The relationships of rainfall and evaporation were reflected in the pattern of land drainage. When rainfall was small and evaporation large during May–September 1967, drainage stopped; by contrast, the drains ran throughout the summer of 1968. Exceptionally heavy rain in September 1968 induced very rapid flows containing large concentrations of nitrate. Very little rain fell during September 1969 and there was no

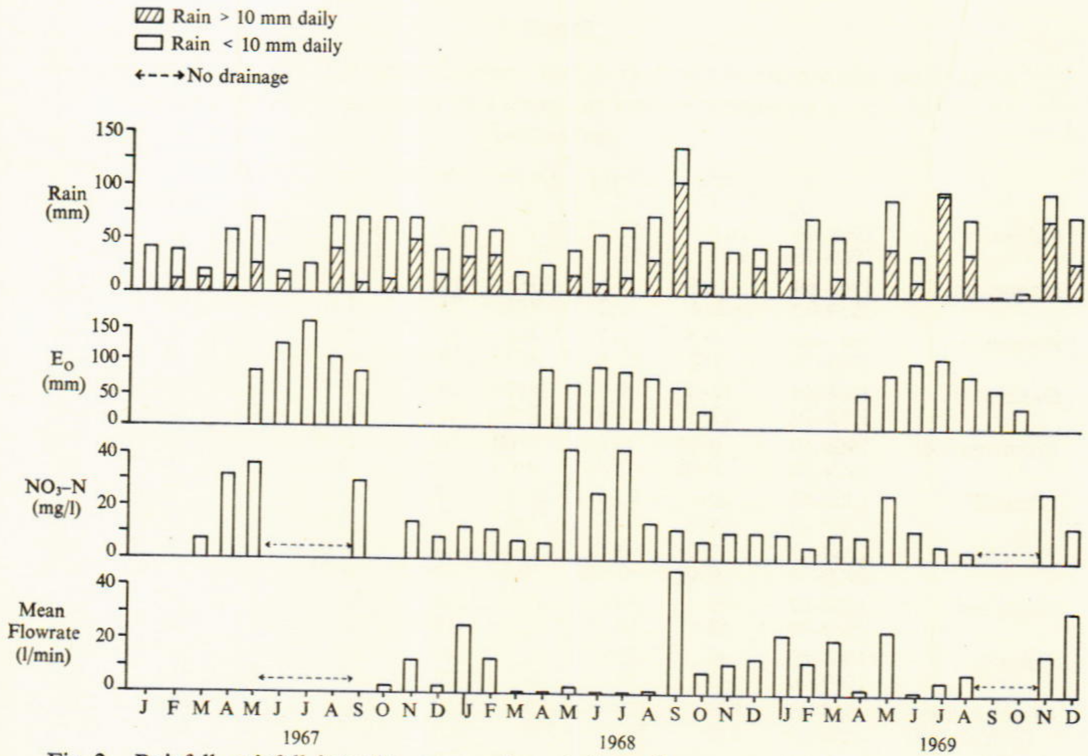



Fig. 2. Rainfall, rainfall intensity, evaporation, drainage flowrate, and $NO_3$-N concentration, in drainage at Saxmundham 1967–69.

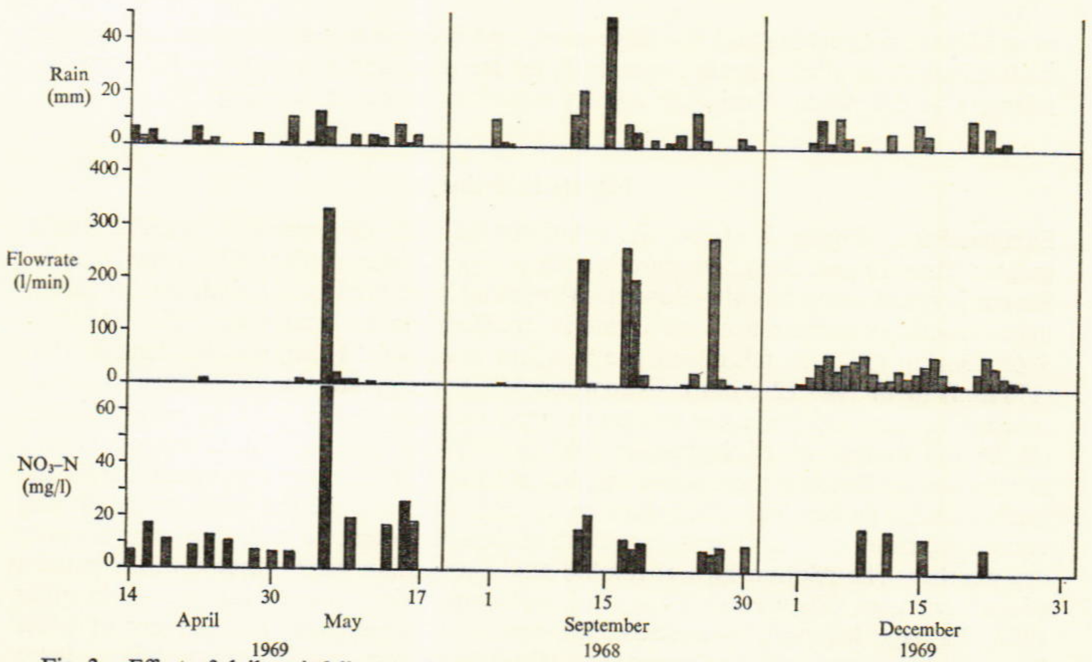



Fig. 3. Effect of daily rainfall upon drainage flowrate and corresponding $NO_3$-N in drainage water at Saxmundham.

drainage during September and October. Spring rainfall determined whether freshly applied fertiliser nitrogen was leached. There were considerable falls in all three years and the drainage water contained much nitrate. There were large flows during the winter of 1967–68 and the water contained much nitrate. More was lost during May 1968 when moderate flows were rich in nitrate, indicating that leaching was still very active. Much nitrate was leached during the winter of 1968–69 when the drains flowed fast until March. Heavy, and at times intense, rain during March to August 1969 caused further large losses of nitrate, and fast flowrates were sometimes coupled with large concentrations of nitrate. Many crops grown in 1969 appeared deficient in nitrogen, and this was confirmed by tissue tests and responses to supplementary top-dressings of N-fertiliser.

Figure 3 shows that large amounts of rain falling in a day or less were associated with fast flowrates at Saxmundham. However, the amount of nitrate lost depended on weather patterns and times of applying N-fertiliser. In the first week of May 1969 there was a very large flow containing much nitrate, but before and after this, flowrates and concentrations of nitrate were much smaller. More than 10 mm of rain on each of two days before 6 May caused much drainage from the soil, which was already close to field capacity; these flows were responsible for the total loss (or transport into subsoil) of much freshly-applied N-fertiliser. In contrast, during December 1969, when the drains ran rapidly for most of the month, the flows caused by similar intensities of rain did not contain much nitrate. Freshly applied N-fertiliser, and nitrate derived from residues, are leached in different ways. September 1969 was very dry and there was no drainage. Figure 3 shows how the very wet September of 1968 caused large flows containing much nitrate, ranging from 7 to 20 mg/l $NO_3$–N, and although these flows in autumn removed much nitrate from the land, they differed in character from those in spring when the mean concentration in large flows was about 70 mg/l of $NO_3$–N.

**Woburn.** Most of the drains had large and relatively constant flows and nitrate concentrations did not show the large spring and autumn maxima found at Saxmundham. However, Drain 4 at Woburn, which serves an area of heavier textured soil, behaved similarly to Saxmundham drains. Figure 4 illustrates the differences during the two years between Drain 4 and Drain 1 at Woburn; Drain 1 originates in deep sandy soil in the higher part of Great Hill Field (Fig. 1). Drain 4 showed seasonal maxima in flowrates similar to the smaller peaks from Drain 1. The nitrate concentrations in water from Drain 1 did not vary greatly during the two years, but tended to increase when drainage was least. During the first two months of 1970, increased flow was accompanied by an increase in nitrate concentration in Drain 1. This could have been because residual nitrogen, accumulated during the dry September and October of 1969, was removed by the unusually large flows in February 1970; the smaller flow in March 1970 had a usual nitrate concentration.

**Woburn, Saxmundham and Rothamsted compared.** Figure 4 also compares Drain 2 on Harwood's Field and West Field Drain 6 for Saxmundham. During the two years, maximum flowrates from the West Field drain were much smaller. Comparatively small flows from Drain 2 had much nitrate during the spring and summer of 1968, and West Field drain did not run; both drains had maximum flows in May 1969. Although the concentration of nitrate in the West Field drainage exceeded that in the drainage from Harwood's Field, the flow from the West Field drain was only one-eighth as large. The nitrate concentrations in Drain 4 at Woburn and the West Field drain at Saxmundham were generally similar, but the Saxmundham drain had less nitrate during

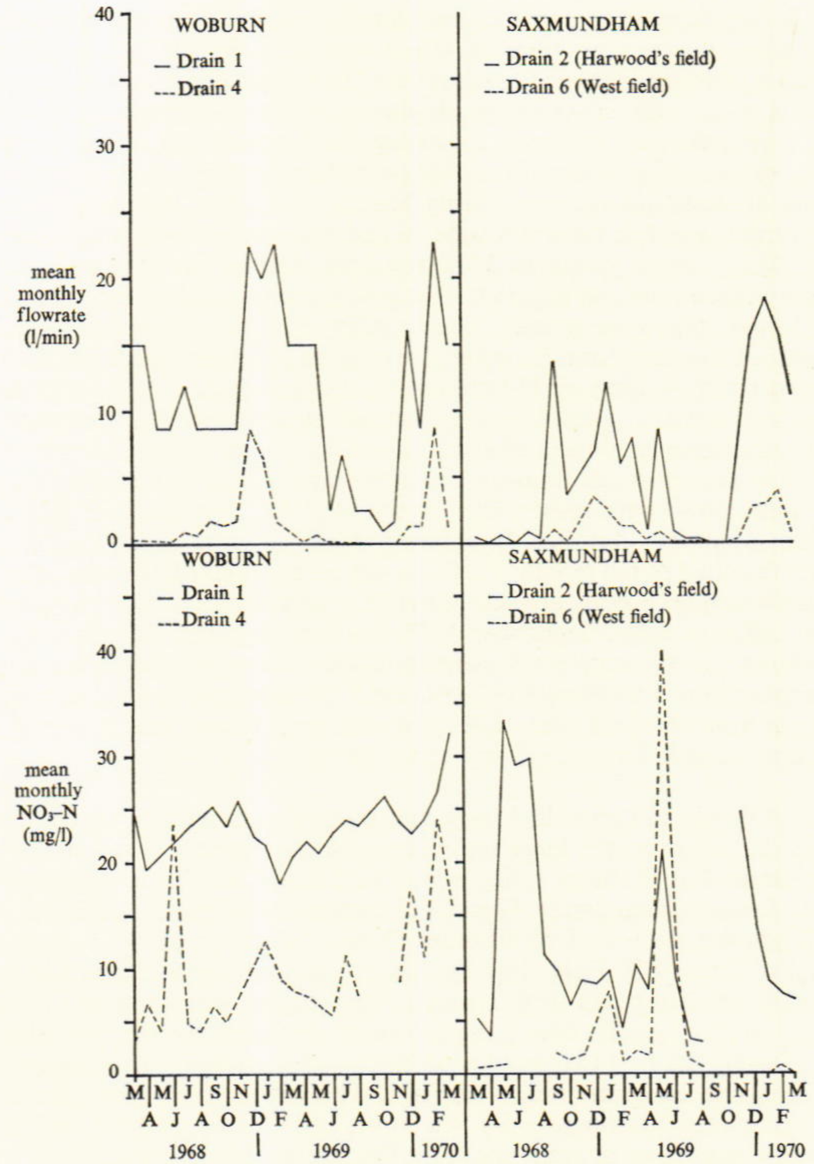



Fig. 4. Seasonal variation in drainage flowrates and corresponding $NO_3$-N concentrations at Woburn and Saxmundham 1968–70.

the first three months of 1969 and 1970. Tables 4 and 6 show that the mean annual concentrations of nitrate in Saxmundham drainage was 15·4 mg/l in 1968–69 and 12·2 mg/l in 1969–70; these are very similar to the corresponding figures for Woburn of 12·3 and 14·8 mg/l. However, at Saxmundham the daily concentrations ranged from <0·01 to 90 mg/l $NO_3$–N in very variable flows, whereas at Woburn, they were from 1·2 to 32·2 mg/l $NO_3$–N, with more constant flows. Table 5 shows concentrations of $NO_3$–N in water from the individual drains at Saxmundham. Drains 1 and 2 gave similar nitrate concentrations, which were less than those from Drains 3 and 4, and

Drain 4 had smaller flowrates. On average, water from Drain 6 (West Field) had much smaller nitrate concentrations than water from the Harwood's Field drains, which also produced much larger flows.

These new measurements of nitrate concentrations in drainage confirm the work of a century ago on Broadbalk Field at Rothamsted, where a separate drain under each of the plots collects water; the experiment provided a unique opportunity of measuring losses of nitrate from plots fertilised with different amounts and kinds of N-fertilisers. The Broadbalk experiment is in 17 long parallel strips each of 0·2 ha; winter wheat has been grown each year since 1843. Tile drains 0·6 m deep were laid in the centre of each plot in 1849; they run for only a few hours after heavy rain and are dry most days of the year. Drainage water analyses begun in 1866 were continued for 15 years and were reported in several papers (Lawes & Gilbert, 1874; Lawes, Gilbert & Warington, 1882). Until 1872–73 ammonium salts were applied in autumn and nitrate in spring. Table 8

**TABLE 8**

*Drainage from Broadbalk: average analyses for 1866–73 and seasonal changes measured in 1878–81*

| Plot | Annual manuring, kg N/ha | Average $NO_3$-N in drainage 1866–73 mg/l | 1878–81; $NO_3$-N in drainage, mg/l: Spring fertilising to 31 May | 1 June to harvest | Harvest to autumn sowing | Autumn to spring fertilising | Whole year |
|---|---|---|---|---|---|---|---|
| 2 | Farmyard manure (35 tons/ha) | 12 | 4 | 1 | 6 | 10 | 8 |
| 3 | None | 4 | 3 | 0 | 5 | 5 | 4 |
| 5* | None | 5 | 3 | 0 | 5 | 6 | 4 |
| 6* | 48 } as ammonium salts, in | 9 | 15 | 1 | 6 | 5 | 5 |
| 7* | 96 } autumn until 1873; in | 16 | 27 | 1 | 7 | 5 | 7 |
| 8* | 144 } spring 1878–81 | 20 | 28 | 4 | 14 | 8 | 9 |
| 9* | 96 as nitrate in spring | 16 | 50 | 9 | 15 | 8 | 12 |
| 15* | 96 as ammonium in autumn | — | 7 | 3 | 8 | 28 | 19 |

* These plots also receive annual dressings of PKNaMg fertilisers.

gives results for a later period (1878–81), when both ammonium salts (Plots 6, 7 and 8) and nitrate (Plot 9) were applied in spring. Much nitrate was lost from the 'natural' supply in farmyard manure, and water from this plot was richest in nitrate during autumn and winter. Drainage from land not given fertiliser (Plot 3), or not given nitrogen (Plot 5), contained 4–5 mg/l $NO_3$–N. From fertilised plots, spring drainage was richest in nitrate and there was a second peak early in autumn. During the second period (1878–81), when autumn and spring dressings were compared, the largest losses were from plots given ammonium salts in autumn (Plot 15); more nitrate was lost from nitrate fertiliser (Plot 9) than from equivalent ammonium salts (Plot 7) when both were applied in spring.

At both Saxmundham and Woburn, concentrations averaged 12–15 mg/l for the whole year, about the same as the amounts in Broadbalk drainage when 96 kg N/ha were applied as ammonium salts in autumn or all as nitrate in spring.

### Other nutrients in drainage

Tables 4a and b show the monthly means, maximum and minimum concentrations of calcium, magnesium, potassium, sodium, ammonium-N, phosphate-P, sulphate-S and chloride, found in Saxmundham drainage water. Table 5 shows the mean annual concentrations of these ions, together with conductivity and pH of water from the individual drains. Tables 6a, b and 7 provide corresponding values for the Woburn drainage.

**Calcium.** The largest concentrations in the drainage water for both Woburn and Saxmundham were of calcium. Maximum and minimum concentrations in daily samples at Saxmundham were 280 mg/l and 62 mg/l, but monthly mean concentrations ranged much less. Exceptionally small values were associated with large rainfall. The mean annual values of 192 mg/l for the first year and 168 mg/l for the second year were larger than those for Woburn drainage (148 mg/l and 132 mg/l respectively). At Woburn, however, the concentration of calcium in Drain 4 from the Oxford Clay sometimes exceeded 360 mg/l, whereas Drain 3 had consistently less calcium (<86 mg/l). Larger variations in the composition of the water from different drains at Woburn than at Saxmundham show clearly how water composition depends on soil type. However, management of land can affect the relative concentrations of ions in drainage from the same kind of soil; less calcium was found in drainage water from Saxmundham West Field, which has poor drainage, than in Harwood's Field drainage during 1968–70. The stream at Woburn, which seems to be fed from an extensive and varied catchment, had less calcium than the land drains observed (except for No. 3), and its composition fluctuated less than the composition of land drainage during the two years, but flows greatly exceeded the flows from the land drains.

**Magnesium**

***Saxmundham.*** The concentration of magnesium in Saxmundham drainage water ranged from 0·8 mg/l to 28·8 mg/l; more was present in 1968–69 than in 1969–70, which was wetter and drain flows were larger. Concentrations of magnesium diminished during winter, when flows were large, and increased during summer and autumn, except when there was much rain as during September 1968. Mean annual concentrations of magnesium were 9·5 mg/l for 1968–69 and 7·3 mg/l for 1969–70. The concentrations of magnesium in water from the separate drains at Saxmundham did not differ much, except that water from Drain 3, which had a smaller average flow than Nos. 1 and 2, contained slightly more Mg.

***Woburn.*** Magnesium concentrations in the drainage ranged from 3·3 mg/l to 34·0 mg/l during the two-year period, but mean annual concentrations were almost the same. The least concentrations were in drainage during the very dry months of September and October 1969; these were followed in November and December by some of the largest values recorded. Large flows in February 1969, and in 1970, did not diminish magnesium concentrations much below the mean annual level. Concentrations in the individual drains differed. Water from Drain 4 from the Oxford Clay had most Mg, water from 5 and 6 had least, and that from Drains 1 and 3 had intermediate amounts. The large concentrations of magnesium in drainage at Woburn may derive from glauconite in the Lower Greensand, which is the parent material of the lighter soils at Woburn. Concentrations of magnesium in the stream resembled those in the drainage, except from Drain 4, which contained more.

**Potassium**

***Saxmundham.*** Potassium in Saxmundham drainage ranged from 0·4 to 4·8 mg/l K. Usually there was less in the larger flows, although the largest concentration was in a flow of 60 l/minute from Drain 2 on 17 September 1968 (perhaps because there was dispersed clay in the water). Concentrations of K in the water from different drains were similar, which was expected as water comes from the same soil type; mean annual concentrations were 1·8 mg/l and 1·4 mg/l of K.

***Woburn.*** By contrast, the concentration of potassium at Woburn differed between drains. Drain 4 from the Oxford Clay gave the most and Drains 2 and 5 the least. Drain No. 4 produced the largest individual concentrations in June of each year (up to 90 mg/l K), perhaps because its flow was always least and the water was longest in contact with soil. Mean annual concentrations of potassium in all the drains at Woburn (Table 6) were similar for both years, averages of 4·4 and 5·3 mg/l. Mean concentrations in the stream were 3·7 and 4·7 mg/l, with little change during the whole period.

**Sodium**

***Saxmundham.*** The sodium in drainage during 1968–70 ranged from 7·4 mg/l to 44·8 mg/l Na; mean annual values were 21·6 mg/l for 1968–69 and 17·9 mg/l for 1969–70. Most was in water during March and April in both years, and mean monthly concentrations were least when rainfall, and drainage flows, were largest. After dry weather during autumn 1969 drainage ceased; the concentrations of sodium were not very large when drains ran again. Analyses of rain at Saxmundham (Williams, 1968) showed that sodium was the dominant cation and the amount in rain falling between December 1966 to November 1967 was equivalent to 8 kg/ha. Concentrations were larger during spring and autumn, especially when the wind was from the east, i.e. from the sea, which is 8 km away. Sodium can accumulate in soil when rain is not enough for drainage to occur.

***Woburn.*** Woburn drainage contained only about half as much sodium as drainage at Saxmundham. Mean annual concentrations were 11·3 for 1968–69 and 11·1 mg/l for 1969–70. The maximum concentration found in the two years was 28·4 mg/l and the smallest 6·8 mg/l. Most was in water from Drain 4, which flows from the heavier land, possibly because flows from this drain were least. Pollution of drainage water by animals did not increase sodium, because Drain 6, which runs under land often grazed, gave rather less than the other drains from land that carries no stock. Sodium concentrations were not associated with rainfall or flowrates; the stream had almost the same mean annual concentration of sodium in both years, although total rainfall and its distribution differed greatly.

**Ammonium-N.** At both sites drainage water contained little $NH_4$–N, ranging from $<$0·05 mg/l to 3·0 mg/l $NH_4$–N at Saxmundham and from $<$0·05 to 3·2 mg/l $NH_4$–N at Woburn, but most measurements were less than 1 mg/l.

Mean annual concentrations at Saxmundham were 0·08 mg/l in 1968–69 and 0·16 mg/l in 1969–70, and at Woburn 0·07 mg/l and 0·03 mg/l; the largest value at Woburn was from Drain 4 serving the heavy soil. All four drains on Harwood's Field at Saxmundham and the West Field drain gave water containing more $NH_4$–N than usual in September 1968 when 108 mm of rain fell; this very wet period may have caused temporary waterlogging that inhibited nitrification and the rapid drainage removed ammonium-N (Fig. 3). Anhydrous ammonia was applied in March 1969 to an experiment on grass near Drain 3. Much rain next day caused large drainage flows of 40–60 l/minute and these contained unusually large amounts (1·4 mg/l) of ammonium-N, suggesting that freshly-applied ammonia can be leached from this soil soon after it is applied.

The stream at Woburn usually contained less than 0·05 mg/l of $NH_4$–N but had 0·5 mg/l from December to February, probably because there was little nitrification of soluble organic matter when soil temperatures were near freezing point.

**Phosphorus.** Concentrations of phosphate in the drainage water at Saxmundham and Woburn resembled those of ammonium-N and never exceeded 1·2 mg/l. At Saxmundham the range was $<$0·05 to 1·2 mg/l $PO_4$–P and mean annual concentration was 0·04 mg/l for 1968–69 and 0·06 mg/l for 1969–70; corresponding figures for Woburn were $<$0·05 to 0·85 mg/l $PO_4$–P, 0·15 and 0·12 mg/l $PO_4$–P.

At Saxmundham in 1968–69 the West Field drainage contained more phosphate than water from Harwood's Field but none was detected during the second year. At Woburn (Table 8), in contrast to other nutrients, Drain 4 did not give the most phosphate; mean annual concentrations of 0·09 mg/l and 0·03 mg/l for 1968–69 and 1969–70 were smaller than those from Drain 3 (0·43 and 0·33 mg/l) and Drain 6 (0·22 and 0·22 mg/l) respectively for the two years. We do not know the origin of the larger concentrations of phosphate (0·2 to 0·6 mg/l) in water from Drain 3, but the mains water at Woburn Farm, which comes from boreholes in the Greensand strata of the Birchmoor source, contains similar amounts. Water from Drain 3 but not from the others was slightly acid, and perhaps this makes native phosphate more soluble.

Water from Drain 6 probably contained some phosphate because the pipes are shallow and animal excreta may have penetrated to them. Drains 5 and 6 serve the same area but Drain 5 does not cross grazed land and always had less phosphate.

Much soluble phosphate in drainage was often associated with dispersed soil particles in the water. Drainage water at Saxmundham was turbid after autumn cultivations and after periods of severe frost followed by a thaw. Samples of water from Drains 2, 3 and 4 at Saxmundham on 26 September 1968 contained 255 to 490 mg/l of suspended solids and had 0·10 and 0·16 mg/l P. Twelve days later, there was less than 0·05 mg/l of P, although there were still 160 mg/l of suspended solids. During the same period, drainage from West Field had 622 mg/l of suspended solids; these diminished to 363 mg/l by 8 October, but soluble phosphate remained almost the same (0·36 mg/l). West Field is poorly drained and structure may degrade when the subsoil is anaerobic; reduction of ferric compounds may allow phosphate to dissolve, and these small (but larger than usual) amounts of soluble P to be leached.

## Sulphur

***Saxmundham.*** Sulphate in drainage water at Saxmundham averaged 62 mg/l in 1968–69 and 55 mg/l in 1969–70; during the two years the range was from 7 to 176 mg/l $SO_4$–S. Least sulphate was in water from Drain 4 after exceptionally heavy rain caused a large flow during mid-September 1968 (58 mm of rain fell during the previous three days). Most was lost in late April 1968 in water from Drain 3, after a period of dry weather, when the flow was very small (0·05 l/minute). Variations in sulphate in Saxmundham drainage water are discussed below in relation to changes in nitrate. Water from Drains 1, 2 and 3 of Harwood's Field contained larger concentrations of sulphate than water from No. 4 or from the West Field drain. Mean monthly sulphate concentrations were not closely related to mean monthly rainfall or to volume of drainage.

***Woburn.*** The mean annual concentrations of sulphate were 54 mg/l in 1968–69 and 56 mg/l in 1969–70, similar to those at Saxmundham. Concentrations also fluctuated similarly, from 15 to 163 mg/l $SO_4$–S, but there were contrasts between individual drains. Mean monthly concentrations in water from Drain 4 ranged from 85 to 156 mg/l of $SO_4$–S, and for the other drains from 15 to 103 mg/l, with the mean annual concentrations shown in Table 7. Monthly mean sulphate concentrations varied little during the two years although monthly rainfall and rainfall distribution varied greatly. The stream at Woburn contained less sulphate than the drainage water in both years, but concentrations were smaller and more varied during the first year when the flow was more constant. Least sulphate was recorded in September and October 1968 when there was much rain, and largest concentrations in December 1969 when flows increased again after the dry September and October.

### Chloride

***Saxmundham.*** Chloride in the drainage water averaged 48 mg/l in 1968–69, and 47 mg/l in 1969–70; the range for the two years was 16–129 mg/l Cl. Individual drains on Harwood's Field had similar concentrations, which were larger than those in West Field drainage.

***Woburn.*** Chloride averaged 30·6 mg/l in 1968–69 and 36·6 mg/l in 1969–70, the range for the two years was 11·4 to 126 mg/l, very similar to the range at Saxmundham. The concentrations depended on the source, water from Drains 1 and 4 had most chloride and from Drains 5 and 6 least. The stream contained about as much chloride as water from Drain 1, giving a range of 29 to 46 mg/l during the two years.

## Physical measurements on drainage water

**Conductivity.** The mean specific conductivity of the drainage water from Harwood's Field at Saxmundham was 949 $\mu$ mhos/cm in 1968–69 and 874 $\mu$ mhos/cm in 1969–70. The range during the two years was from 340 to 1420 $\mu$ mhos/cm. Water from individual drains differed; in the first year Drain 3, which gave the smallest and most intermittent flow, gave water with the largest conductivity, but in the second year conductivity was less, except for some large values in November 1969 after two dry months. Water from West Field had the smallest conductivities in both years; this drain flows slowly (resembling Nos 3 and 4 on Harwood's Field), but contains less soluble salts; this is unusual for drainage that flows slowly when the water is more nearly in equilibrium with soil constituents.

At Woburn, water from Drain 4 had largest conductivities in both years, 1200 $\mu$ mhos/cm in 1968–69 and 1230 $\mu$ mhos/cm in 1969–70. Water from Drains 3, 5 and 6 had least conductivity, ranging from 470 to 646 $\mu$ mhos/cm; Drains 5 and 6 gave similar results, especially during the first year. Drains 1 and 2 had intermediate values, ranging from 734 $\mu$ mhos/cm to 883 $\mu$ mhos/cm during the two years. The stream water had larger and slightly more variable conductivities in 1969–70 than in 1968–69, when flows were larger and more constant. Measurements of conductivity were very useful when considered with analyses for individual ions in the drainage waters; they were a check on composition, especially when there were large concentrations of individual ions while other ions remained relatively constant.

**Hydrogen ion concentration.** The pH of drainage water at Saxmundham ranged only from 7·1 to 8·6, as the soil is calcareous. The values were close to the maximum associated with equilibrium calcium bicarbonate solutions. Differences between individual drains were very small.

At Woburn, water from Drain 3 had a smaller mean pH (6·3 and 6·6) in both years than from the other five drains or the stream, which averaged from pH 7·1 to 7·8 during the two years. Drain 3 varied from pH 5·8 to 6·9 in the first year and from 6·0 to 7·6 in the second year. The largest value recorded (8·2) was from Drain 4 in November 1969 after two dry months.

### Relationships between the concentrations of nitrate and of the other ions in drainage water

Large drainage flows at Saxmundham during spring were always accompanied by sudden increases in nitrate concentration resulting from the rapid leaching of recently applied fertiliser. Changes in nitrate were associated with changes in the concentrations of ions other than the dominant calcium ion, which remained relatively constant at 250 mg/l. Figure 5 shows the relationships between $SO_4^{--}$, $Cl^-$, $Na^+$, and $Mg^{++}$, with increasing concentrations of $NO_3^-$.

Sulphate was more concentrated than other ions, except calcium; it was affected most by the changes that also caused nitrate to change, and diminished as nitrate increased. However, the sulphate concentration also showed a smaller, but significant, increase before the maximum concentration of nitrate was reached. When nitrate diminished after reaching a peak, sulphate concentration increased again to a near usual value. Because the drainage flow also diminished sharply with fall in nitrate concentration and sulphate had not increased enough to compensate, the conductivity of the drainage water was at a minimum. Sodium and magnesium concentrations, which were much less than those of sulphate, were affected similarly by the increase in nitrate, but the relative decreases were much smaller. Chloride behaved differently and showed a small peak coinciding with that of nitrate.

Potassium was much less concentrated than the other ions discussed; it fluctuated during the period when nitrate increased, but the fluctuations were not clearly related to changes in concentration of other ions, or to dilution and solubility effects. Saxmundham soil contains much readily exchangeable potassium and its solubility seemed to alter in the same way as that of calcium. Ca concentrations varied only from 212 to 280 mg/l during the period illustrated in Fig. 5 and the only large changes for this ion were after exceptional rain. On 16 September 1968, after 58 mm of rain during the previous three days, calcium fell to 115 mg/l and again to 86 mg/l on 26 September 1968 when a further 31 mm of rain had fallen. These small concentrations were presumably the result of the mass flow of rainwater, containing very little calcium, through leached and saturated soil; drainage was too fast for calcium salts in soil to reach equilibrium with the soil solution. In these conditions concentrations of sodium, magnesium, nitrate, chloride, and sulphate diminished and the corresponding conductivities were exceptionally small.

There were similar effects with Woburn drainage water, especially from the heavy land (Drain 4), but sampling was less frequent than at Saxmundham so the effects of rapid changes in nitrate concentration on the concentrations of other ions could not be examined.

The concentration of sulphate ions in drainage reached a peak that *preceded* the large

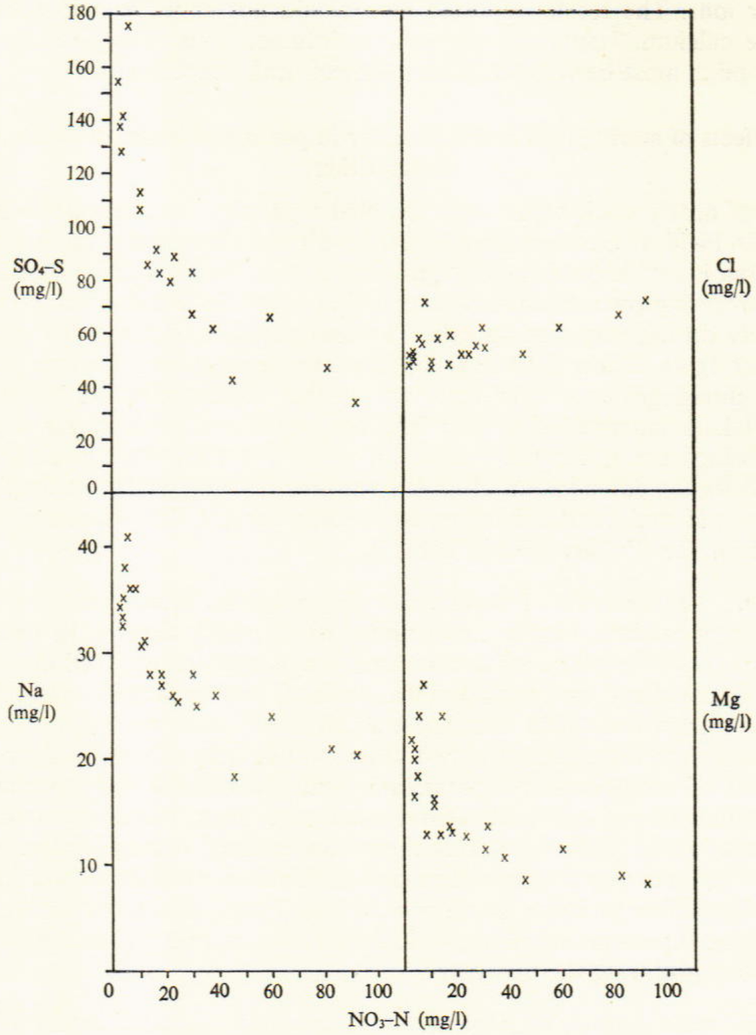



Fig. 5. Relationship between $NO_3$-N and $SO_4$-S, Cl, Na, and Mg in drainage at Saxmundham 3 April–10 May 1968.

peak in nitrate. This effect is similar to that in column chromatography when displaced molecules or ions occur in a band of greater concentrations detectable by collecting fractions of the solution. This band is followed by a peak concentration of the displacing species (in Saxmundham soil the very mobile nitrate ion in combination with the major soil cation (Ca)). Soil solutions cannot contain as much sulphate as nitrate, because the concentration of sulphate is governed by the solubility product of sparingly soluble calcium sulphate, which may not dissolve quickly enough to maintain normal concentrations of $SO_4$ during the rapid flows that leached the nitrate. Slower flows allow sulphate concentrations to become normal by solution from sites in the soil; but nitrate cannot be immediately renewed in the same way, so its concentration decreases rapidly. Cation/anion interactions in the solutions moving down soils in the field where modern fertilising is used should be studied more, especially the effects of much nitrate, and of calcium, on the other ions. The results reported here would not apply to acid soils with little exchangeable calcium. Important changes in drainage water composition occur very quickly; sampling must be very frequent to detect peak concentrations.

### The effects of storing land drainage water in ponds and lakes on its chemical composition

Two bodies of nearly static water were sampled regularly. The farm pond 200 m south of Harwood's Field at Saxmundham is fed by ditches that receive land drainage. The catchment area is arable land, mostly growing cereals, which receive 70–120 kg N/ha/year; beans are also grown. No stock is kept and no animal effluent enters the pond, which overflows only during very wet periods. The artificial lake of about 0·4 ha at Woburn receives water from Drain 1 (it may have other underground sources we have not detected); it discharges only after very wet weather during summer, but often during winter. The lake is surrounded by our farmland, mostly in experiments in which large fertiliser dressings are used; the composition of its water was especially interesting because we knew the composition of its main source (Drain 1). Mean annual concentrations of ions, pH and conductivity measurements for the Saxmundham pond are in Table 5, and for the Woburn lake in Table 7.

**Saxmundham.** The analyses of pond water differed little between the two years. The concentrations of calcium, nitrate, and sulphur were smaller than in the drainage water from Harwood's Field; pH, conductivity and magnesium concentrations were similar but the pond contained more potassium, sodium, ammonium-N, phosphate-P and chloride. The nitrate from field drainage was no doubt removed by water plants. The water remained clear throughout the two years, without any bloom of algae. The larger concentrations of ammonium-N, potassium, and phosphorus were probably caused by decomposition of organic matter from weeds and trees, which surround the pond, and from water weeds. These ions were more concentrated during winter, when it was cold and water plants did not grow than during summer. Sulphate-S was least concentrated from September to December (down to 6 to 7 mg/l) and most during late winter and early spring (up to about 70 mg/l). Chloride was more constant, and ranged only from 50 to 70 mg/l during the two years.

**Woburn.** The mean annual concentrations of the ions measured in the Woburn lake water were also similar in the two years. The differences between land drainage composition and that of lake water were generally similar to those at Saxmundham; concentrations of sulphate and chloride were similar, but sulphate varied less than at Saxmundham. Calcium concentrations in Woburn lake were small during the dry September and October of 1969 and remained small until December. During the preceding (wetter) year calcium concentration fluctuated less. Monthly concentrations of ions in water from Drain 1 and the lake are interesting comparisons. Conductivity, calcium, phosphate, and especially nitrate, were smaller in the lake water. Magnesium, potassium, ammonium-N, and pH, were larger whereas sulphate and chloride were similar to the concentrations in water from Drain 1. Although 20 to 24 mg/l of $NO_3$–N entered the lake from this drain and there was enough soluble phosphate in the lake water to support algal growth (the minimum amount is thought to be 0·01 mg/l), no algal bloom occurred during the two years, the concentration of nitrate never exceeded 5 mg/l and was mostly less than 2 mg/l. The fate of the nitrate is not known but large water plants may remove it. The lake contains trout that thrive.

## LOSSES OF PLANT NUTRIENTS IN DRAINAGE WATER

### Composition of water lying on the surface of land at Saxmundham

After heavy rain at Saxmundham, samples of water from shallow pools lying on Harwood's Field were analysed and their content of nutrients compared with that in drainage water sampled at the same time. The results show how nutrients can be lost in surface run-off from this land, which slopes to the south. Since 1964 the field has been ploughed deeply and accepts rainfall better, but before 1964 nutrients were probably carried in surface run-off to lower parts of the field or were lost altogether. Until recently the field was cultivated in the 'stetches' traditionally used in parts of East Anglia. Beds of land 3 m wide were shallowly ploughed and had surface drainage furrows between to remove the excess rain unable to penetrate into the cultivated layer.

Table 9 gives mean concentrations and ranges of ions in the surface water samples taken in 1968–69 and 1969–70. Only magnesium and sodium were less than the corresponding values for water from land drains. All the other ions (which were applied in fertiliser salts) varied considerably; nitrogen, phosphorus and potassium were very concentrated, especially during March to May of each year. The Saxmundham soil quickly 'caps' when there is much rain and plant nutrients, especially nitrate, whether added as fertiliser, or dissolved from the soil, could be easily lost by surface run-off down the field. Transport of this kind has occurred on the site of Rotation I Experiment, because crops on plots in the lower blocks have responded to nutrients washed over a central headland, and extra nutrients have been detected by soil analyses where fertilisers have not been applied. Small concentrations of nutrients in the drainage water from West Field may be partly because they are lost by the surface run-off, which has been observed.

### Removal of crop nutrients in land drainage

The amounts of plant nutrients lost in land drainage depend not only on their concentrations and the corresponding flowrates of the land drains, but even more on how long the flows last. Large and protracted flows containing smaller concentrations may often be more significant in removing nutrients than spectacularly large concentrations in a short flow. Both composition and the flowrate of drainage water at Saxmundham differed from that at Woburn. At Saxmundham very large flows were often brief, but sometimes concentrations of ions were large. At Woburn continuous flows at moderate rates, and with moderate concentrations of ions, were recorded from deeper drains serving a much larger catchment.

The difficulties associated with estimating losses of nutrients in land drainage were well understood by Lawes and Gilbert when they investigated the composition of the drainage water from Broadbalk Field nearly 100 years ago. On Broadbalk the drains, laid 60 cm deep and overlying pervious subsoil over the chalk, receive only a small proportion of the total drainage as most of the water percolates between lines of tiles. To study the effect of flow on composition of the drainage, Lawes and Gilbert used a simple visual assessment of flows from the individual drains (Grey, 1922), similar to the one used here. Visual assessments were periodically checked by measuring the volume of drainage water collected during a known period. Mean monthly flowrates were calculated from daily records at Saxmundham, and from bi-weekly samplings at Woburn. These were used, together with the mean concentrations of the elements determined, to estimate nutrients lost in *observed* drainage. Lawes and Gilbert based their estimates of losses on *total* drainage occurring during the periods investigated, but the drainage was collected from an uncropped lysimeter 1·8 m × 2·2 m (0·0004 ha) and 1·5 m deep situated on

## TABLE 9

*Composition of surface water at Saxmundham (Harwood's Field) 1968–70*

| Year | | Na | K | Ca | Mg | $NH_4$–N | $NO_3$–N | $PO_4$–P | Cl | $SO_4$–S | K 25°C ($\mu$ mhos/cm) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1968–69 | Mean | 11·8 | 8·3 | 108 | 3·9 | 3·0 | 7·2 | 1·24 | 62 | 35 | 689 | 7·7 |
| | Range | 6·2–21·2 | 1·0–33·5 | 30–242 | 1·5–8·7 | 0–30·2 | 0–39·7 | 0–9·70 | 14–175 | 11–112 | 200–1280 | 7·4–8·1 |
| 1969–70 | Mean | 7·0 | 3·8 | 77 | 2·2 | 0·5 | 13·2 | 0·18 | 22 | 22 | 430 | 7·7 |
| | Range | 3·8–10·8 | 1·2–11·2 | 37–107 | 1·3–4·2 | 0–2·1 | 0·9–47·6 | 0–1·67 | 4–73 | 9–41 | 200–710 | 7·0–8·6 |

## TABLE 10

*Total losses of nutrients from individual drains at Saxmundham (kg/year)*

| | Drain | Ca | Mg | K | Na | $NH_4$–N | $NO_3$–N | $PO_4$–P | $SO_4$–S | Cl |
|---|---|---|---|---|---|---|---|---|---|---|
| (1968–69) | | | | | | | | | | |
| Harwood's Field | 1 | 253 | 12 | 2·5 | 31 | 0·17 | 15 | 0·08 | 76 | 73 |
| | 2 | 318 | 16 | 2·0 | 37 | 0·10 | 21 | 0·03 | 112 | 73 |
| | 3 | 147 | 8 | 0·8 | 16 | 0·04 | 14 | 0·03 | 47 | 33 |
| | 4 | 46 | 2 | 0·6 | 5 | 0·01 | 5 | 0·02 | 10 | 16 |
| | Total | 764 | 38 | 5·9 | 89 | 0·32 | 55 | 0·16 | 245 | 195 |
| West Field | 6 | 48 | 3 | 0·8 | 6 | 0·03 | 1 | 0·05 | 14 | 13 |
| (1969–70) | | | | | | | | | | |
| Harwood's Field | 1 | 369 | 14 | 4·6 | 42 | 0·37 | 25 | 0·17 | 109 | 125 |
| | 2 | 497 | 24 | 5·2 | 57 | 0·56 | 36 | 0·06 | 171 | 142 |
| | 3 | 139 | 6 | 1·2 | 15 | 0·15 | 11 | 0·01 | 55 | 35 |
| | 4 | 92 | 3 | 0·9 | 8 | 0·08 | 9 | 0·02 | 22 | 23 |
| | Total | 1097 | 47 | 11·9 | 122 | 1·16 | 81 | 0·26 | 357 | 325 |
| West Field | 6 | 57 | 4 | 1·0 | 6 | 0·10 | 3 | 0·00 | 22 | 14 |
| Harwood's Field 1968–69 Total (kg/ha/year*) | | 252 | 12 | 1·9 | 29 | 0·1 | 18 | 0·05 | 81 | 64 |
| 1969–70 Total (kg/ha/year) | | 361 | 15 | 3·9 | 40 | 0·4 | 27 | 0·08 | 118 | 107 |

* Harwood's Field 3·03 hectares.

Barnfield and not on Broadbalk. This lysimeter was continuously fallowed, and they were aware that the drainage recorded was greater than from land that grew crops, although it might be similar for parts of the year when Broadbalk was bare or the crop very small.

At Saxmundham and at Woburn the drains are deeper than on Broadbalk; they overlie less pervious strata and must gather more of the total drainage. Flowrates at Saxmundham may have been over- or under-estimated, as they sometimes varied within one day; flowrates at Woburn were relatively constant and less frequent observations were satisfactory. More sophisticated measuring devices could have been used to measure the very small and very large flows, but it is questionable whether these would have been justified, because the proportion of *total* drainage collected by a tile drainage system is never known and it probably differs from season to season as subsoil drainage channels vary in capacity in dry and wet weather. In spite of these uncertainties, approximate estimates of nutrient losses seemed worth calculating to compare with those made for Broadbalk by Lawes and Gilbert. The figures are useful because they record the total amounts lost as surface drainage into ditches and streams. At Saxmundham *all* the other nutrients that are leached from Harwood's Field enter the deep subsoil and mobile ions may reach underground water reserves. The same is true at Woburn, but there may be other drainage channels to springs and streams that we have not detected. Tables 10 and 11 show estimated losses of nutrients. The losses at Saxmundham are also estimated as kilogrammes per hectare per year, because the drain outfalls on Harwood's are all known and they serve only this field; this could not be done for Woburn.

The greatest difference between nutrients lost in drainage at the two sites was that they were much greater for *individual* drains at Woburn. This resulted from the more constant, and on average larger, flowrates at Woburn. At Saxmundham the order of the amounts of individual ions lost was $Ca > SO_4\text{–}S > Cl > Na > NO_3\text{–}N > Mg > K > NH_4\text{–}N > PO_4\text{–}P$. At Woburn the order was similar except that more $NO_3$ was lost than Na, and more phosphate-P than ammonium-N. Saxmundham is close to the sea and receives extra sodium in rain, whereas Woburn is well inland. (The concentrations of sodium in the rain at Saxmundham and Woburn average 2·2 mg/l and 0·5 mg/l respectively). At Woburn the subsoils contain some phosphorus compounds that are more soluble and are leached more readily when the drainage water is acid (as with the Drain 3). The stream at Woburn removes considerable amounts of nutrients, with the proportions of individual ions in the same order as in drainage water at Saxmundham. The large amounts of calcium and nitrate removed each year by this small stream indicate the major losses there must be in larger rivers. The amount of nutrients removed by individual drains at Saxmundham reflect their different flowrates. Drain 2 carried most and Drain 4 least. The West Field drain removed much less as its flow is very small; the drainage was poor in nitrate and more magnesium and sodium than $NO_3$–N were lost in the two years.

Lawes and Gilbert (1882) constructed a balance sheet for Broadbalk showing relative losses and gains of nitrogen, but, as stated above, the absolute magnitude of their figures is uncertain because the amounts of drainage are unknown. However, these measurements are relevant to pervious soils overlying Chalk, which are common in Southern and Eastern England. Winter wheat is sown during autumn each year and Plot 7 receives about as much N-fertiliser as farmers apply (95 kg N/ha on average for England and Wales in 1969). For the year as a whole, drainage water passing into the Chalk will contain 7 mg/l of $NO_3$–N and, when there are 250 mm of drainage, 17 kg/ha of N from fertiliser will be lost. Where only organic manure is used (as in Plot 2), losses of nitrate might be larger. Even without fertiliser-N or organic manure (Plots 3 and 5), drainage

TABLE 11

*Total losses of nutrients from individual drains at Woburn (kg/year)*

| Drain | Ca | Mg | K | Na | $NH_4$–N | $NO_3$–N | $PO_4$–P | $SO_4$–S | Cl |
|---|---|---|---|---|---|---|---|---|---|
| | | | | (1968–69) | | | | | |
| 1 | 1176 | 67 | 13 | 101 | 0·91 | 144 | 0·56 | 414 | 327 |
| 2 | 807 | 36 | 4 | 52 | 0·00 | 65 | 0·11 | 263 | 155 |
| 3 | 121 | 18 | 8 | 15 | 0·00 | 35 | 0·74 | 57 | 42 |
| 4 | 230 | 17 | 16 | 16 | 0·25 | 8 | 0·09 | 104 | 47 |
| 5 | 370 | 20 | 10 | 29 | 0·09 | 23 | 0·63 | 118 | 56 |
| 6 | 246 | 10 | 1 | 16 | 0·02 | 6 | 0·13 | 63 | 29 |
| 1–6 | 2950 | 168 | 52 | 229 | 1·27 | 281 | 2·26 | 1019 | 656 |
| Stream | 5261 | 588 | 253 | 792 | 3·42 | 738 | 10·20 | 1558 | 2419 |
| | | | | (1969–70) | | | | | |
| Drain | | | | | | | | | |
| 1 | 690 | 40 | 10 | 63 | 0·00 | 116 | 0·10 | 252 | 204 |
| 2 | 176 | 7 | 1 | 11 | 0·05 | 15 | 0·00 | 57 | 29 |
| 3 | 106 | 14 | 7 | 13 | 0·03 | 31 | 0·48 | 60 | 39 |
| 4 | 137 | 12 | 11 | 11 | 0·03 | 7 | 0·02 | 69 | 30 |
| 5 | 885 | 56 | 51 | 89 | 0·67 | 105 | 2·12 | 413 | 178 |
| 6 | 210 | 8 | 1 | 15 | 0·02 | 9 | 0·09 | 66 | 25 |
| 1–6 | 2204 | 137 | 81 | 202 | 0·80 | 283 | 2·81 | 917 | 505 |
| Stream | 3429 | 343 | 185 | 457 | 5·91 | 345 | 1·60 | 1553 | 1545 |

water would contain 4 mg/l of $NO_3$–N (average for the year), 11 kg N/ha would be lost (and yields would be less than a third of those with N-fertiliser or FYM). Losses of nitrate from spring-sown cereals given all their fertiliser-N between February and early April will probably exceed these on Broadbalk. (The average dressing for barley in England and Wales in 1969 was 80 kg N/ha.) Winter wheat transpires some water during spring, and drainage is less than from land under a spring-sown crop; the wheat also begins to take up nitrate by March and removes much in April, whereas spring-sown cereals take up little N until May. Losses of nitrate from Broadbalk Field from 1878 to 1881 were calculated by Lawes, Gilbert and Warington (1882). They estimated that 78 kg/ha N was lost during 1879–80 when 96 kg/ha N was applied as ammonium salts in autumn. When the same amount was applied as nitrate in spring, 68 kg/ha was lost in drainage. During 1880–81 the respective losses were 88 kg/ha and 63 kg/ha of nitrogen. The first winter was dry, the second very wet. The unfertilised soil lost 17 kg/ha N in 1879–80 and 21 kg/ha in 1880–81.

Raney (1960), who analysed leachates from lysimeters filled with Lakeland sand, concluded that the loss of cations was more closely related to the increase in nitrate than to the amount of water passing through the soil, when these were expressed as equivalent weights. Chloride and sulphate showed less association. Losses of nitrate in this work (Tables 10 and 11), were associated with the amount of total bases (Ca, Mg, Na, K) and with $SO_4$–S and Cl expressed as kilogramme equivalents a year. These relationships, shown in Fig. 6, were closer for Saxmundham than for Woburn drainage. Work on eight different soils from Illinois, used in the form of large, undisturbed, uncropped, and unfertilised cylinders was reported by Stauffer (1942). Surface run-off as a percentage of total rainfall on Muscatine silt loam was 22·4%, from Cowden loam it was 36·2%, drainage was 22·7% and 3·6% respectively. Loss of calcium was 95 kg/ha/year from the Muscatine soil and only 3·5 kg/ha/year from the Cowden loam. These results, although referring to lysimeter studies, illustrate the variations found in losses from different soil types, and emphasise the need for more information of this kind on field soils in the U.K.

For most British conditions, the total amounts of nutrients leached from farmland

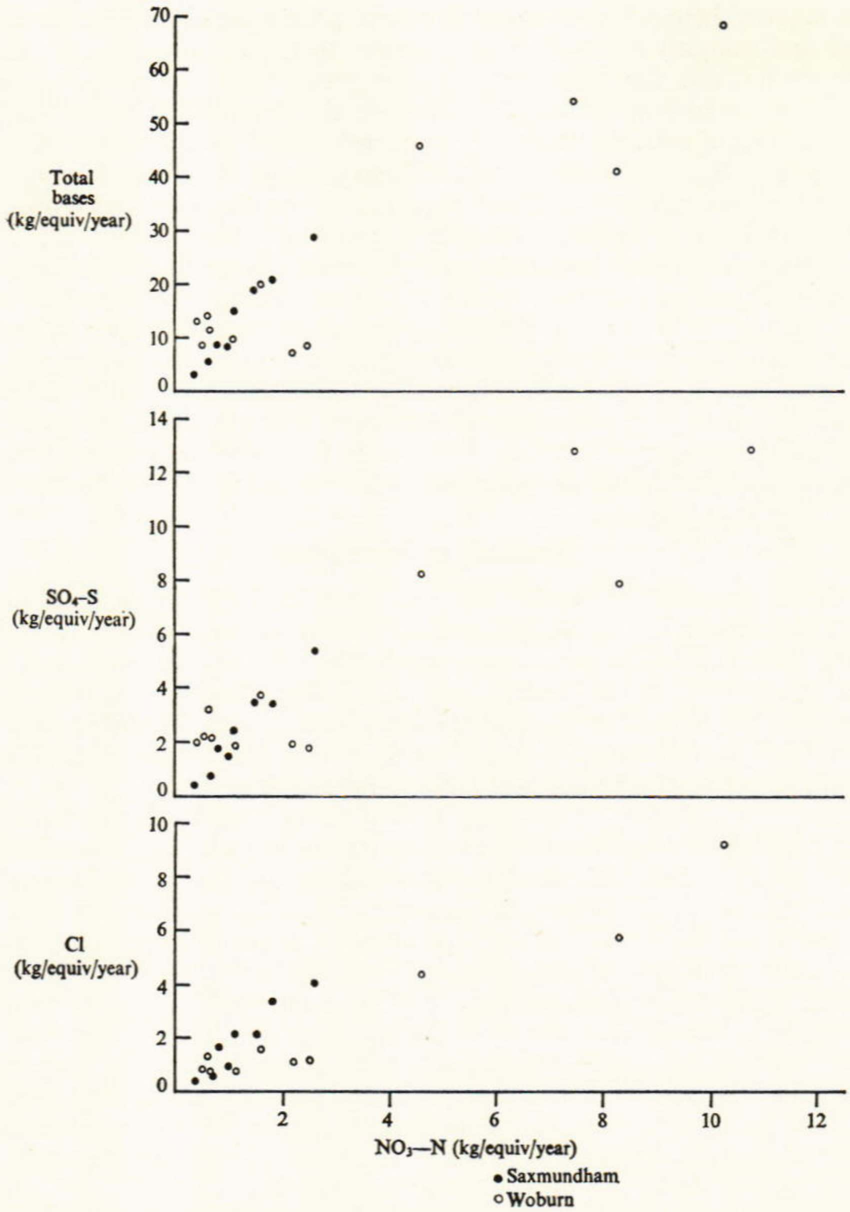



Fig. 6. Relationship between $NO_3$-N and total bases, $SO_4$-S, and Cl, in drainage at Woburn and Saxmundham 1968–70.

cannot be estimated accurately; percolating water, which displaces the soil solution, is never completely collected by any drainage system providing a flow that can be measured and sampled. The areas drained by ditches and streams can be assessed only rarely. On well-drained farmland, some of the water passes between the tiles into the deeper subsoil to reach a permanent water table. The proportion of water 'lost' in this way cannot be determined, but it must depend on the type of subsoil and parent material, and their physical condition (size and nature of cracks and fissures).

Losses reported here can be regarded only as approximate, as they are based on flows measured and sampled intermittently. However, they serve to emphasise how much nutrients *are* lost and they show the need for greater care in fertiliser use and land management to avoid waste of fertilisers. The intensity of rainfall, which is the important factor in leaching of nutrients, cannot be predicted; but all that is practicable should be done to increase the proportion of rainfall that is accepted and retained by soils. Increasing the water-holding capacity of soils and the rooting depth of crops, by good management, helps to use both rain and soluble nutrients in soil solutions more efficiently. As more fertilisers are used, it becomes more important to use them efficiently. Nitrate–nitrogen and lime are the principal nutrients lost in drainage. Lime is cheap and costs British farmers only a few million pounds a year, but nitrogen fertilisers cost them about £70 million. If advisory officers assess drainage flows (which can be done visually) and measure the nitrate they contain (this is possible with a field test (Williams, 1969)), they can gauge the losses of nitrate. Assessments made through the winter could help in planning spring dressings of nitrogen; they would be even more valuable for assessing the losses from fertilised land in spring and indicating the need for extra top-dressings.

### Summary and conclusions

Land drainage water from tile drains and from a pond and lake was sampled during two years at Saxmundham in East Suffolk, and at Woburn in Bedfordshire. A small stream at Woburn, and water from surface pools on fertilised land at Saxmundham, were also analysed, mainly by automated methods, for K, Ca, Mg, Na, $NH_4$–N, $NO_3$–N, $PO_4$–P, $SO_4$–S and Cl. Specific conductivity and pH were also measured. The influence of weather (mainly rainfall and its intensity) on the volume and the concentrations of all these ions was examined, but most attention was given to nitrate-N.

Drainage from a field of 3 ha of soil derived from boulder clay at Saxmundham, overlying a relatively impervious subsoil, was compared with the flows from deeper and more pervious soil derived from Lower Greensand overlying Oxford Clay at Woburn. Drainage flows from the boulder clay soil varied widely and depended on short periods with much rain (>10 mm/day). At Woburn, drainage flow was more constant and continuous, and depended on longer periods of dry or wet weather. A heavy Oxford Clay soil at Woburn gave drainage flows similar to the boulder clay at Saxmundham.

Drainage from the boulder clay and Oxford Clay soils showed sharp maxima in $NO_3$–N concentrations during spring; at Saxmundham these peaks were related to recently applied fertiliser–N. Much was lost in drainage at Saxmundham during spring when nitrate was more concentrated than during autumn and winter, when the nitrate came from residues of fertilisers or crops or from soil reserves. There was no marked nitrate maximum in drainage from the Greensand soils at Woburn. The mean concentration of nitrate 13·8 mg/l (at Saxmundham) and 15·5 mg/l (at Woburn) for the two years resemble those in drainage from Broadbalk Field at Rothamsted during the last century (12 mg/l) on the plot given 96 kg N/ha $NO_3$–N in spring. Sudden increases in nitrate concentration in drainage from the calcareous Saxmundham boulder clay soil caused corresponding decreases in $SO_4$–S, Cl, Na and Mg; Ca and K concentrations were not affected. Sulphate-S concentrations increased just before nitrate reached its maximum; chloride also increased (but less than sulphate) at the same time as nitrate.

The mean annual concentration of ions in the drainage water from Saxmundham (near the sea) were in the order

$$Ca > SO_4\text{–}S > Cl > Na > NO_3\text{–}N > Mg > K > NH_4\text{–}N > PO_4\text{–}P$$

at Woburn (inland) $NO_3$–N > Na and $PO_4$–P > $NH_4$–N. The concentrations of ions in drainage diminished when flows were large, except when freshly applied nitrogen was being rapidly leached. Soil type influenced drainage composition at Woburn; ionic concentrations other than $PO_4$–P were greater in the Oxford Clay drainage than in Greensand drainage.

Soil management changed the composition of drainage water on the same soil type at Saxmundham, as the result of the imperfect working of recently laid tile drains. Phosphate-P and ammonium-N were usually less than 1 mg/l in drainage but phosphate was usually more than 0·01 mg/l recognised as being necessary for algal growth. Blooms of algae were not observed in the pond at Saxmundham or in the lake or stream water at Woburn.

The waters collected from a pond at Saxmundham and a lake at Woburn had different compositions from the drainage that fed them. Calcium, nitrate-N and sulphate-S were less; potassium, ammonium-N, phosphate-P and chloride were more in the pond and lake.

Surface water from shallow pools left after rain on boulder clay at Saxmundham contained less Mg and Na than drainage water, but more of other ions contained in fertilisers.

Estimates of the nutrients lost in *observed* drainage were calculated from mean annual flows and concentrations, but total losses cannot be determined as the proportion of drainage water that passes into subsoil between the tile drains is always unknown. The losses recorded emphasised that large amounts of nutrients were removed by drainage, especially lime and nitrogen, both of which farmers have to buy. Much more is spent on nitrogen than on lime, and using N efficiently becomes increasingly important as dressings increase. Also, lessening the nitrate that enters water used for public supply will help water authorities. Drainage flows can be estimated visually and their nitrate concentrations can be measured in the field; doing so might be a valuable aid in planning nitrogen fertilising.

## APPENDIX

### Methods of analysis and sampling used for the drainage water

**Sampling and flowrate measurement.** All samples of drainage water were collected in clean polythene bottles, stored in a cool place in the dark, and delivered as soon as possible to Rothamsted for analysis. Ammonium- and nitrate-nitrogen were measured immediately and the samples were stored in a refrigerator until other analyses were completed.

Flows from tile drains were first calibrated by measuring the volume in a known time. Subsequently, visual estimates of flow were found to agree closely with these volume/time measurements; these assessments were used later with periodical checks. It is immaterial how the visual estimates are made, so long as a constant scale is used that is not so fine that there is a risk of confusion between adjacent values. Rates slower than 30 l/minute are easy to estimate visually; larger flows, which transport much nutrients, even during a day and with concentrations of >25 mg/l, should be verified by measurement. Grey (1922) described the empirical equivalents used by Lawes, Gilbert and Warington (1882) for visually assessing the flows from the Broadbalk drains to investigate the effect of flow on drainage composition.

**Potassium and sodium.** By 'EEL' flame photometer.

**Calcium and magnesium.** By a 'Unicam' SP 900 flame spectrophotometer with radiation buffers (Salt, 1967). Magnesium by atomic adsorption.

**Ammonium-N.** Absorptiometrically, using a 'Technicon AutoAnalyzer' and the method of Varley (1966) modified by adding a citrate/tartrate buffer; forty samples an hour were done and the limit of detection was 0·05 mg $NH_4$–N/l.

**Nitrate-N.** Absorptiometrically, using a 'Technicon AutoAnalyzer' and Litchfield's (1967) method. Twenty samples an hour were done with a limit of detection of 0·01 mg $NO_3$–N/l.

**Phosphorus.** Absorptiometrically, using a 'Technicon AutoAnalyzer', by Fogg and Wilkinson's (1958) method. Sixty samples an hour were measured with a limit of detection of 0·05 mg $PO_4$–P/l.

**Chloride.** Absorptiometrically, using a 'Technicon AutoAnalyzer' and Henriksen's (1966) method. Forty samples an hour were measured with a limit of detection of 0·5 mg Cl/l.

**Sulphate.** Turbimetrically, using a 'Technicon AutoAnalyzer' by the method of Williams and Twine (1967). Twenty samples an hour were measured with a limit of detection of 0·1 mg $SO_4$–S/l.

**Conductivity.** Using a 'Mullard' conductivity meter.

**pH.** Using a 'Pye' pH meter and a glass electrode.

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