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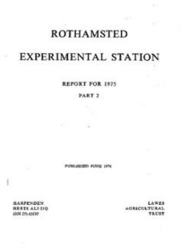
Rothamsted Experimental Station Report for 1975 Part 2


ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1975

PART 2

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The Chemical Composition of Water from Land Drainage at Saxmundham and Woburn (1970-1975)

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The Chemical Composition of Water from Land Drainage at Saxmundham and Woburn (1970–75)

R. J. B. WILLIAMS

Introduction

The chemical composition of drainage water from Saxmundham and Woburn Experimental Stations for the period March 1968–March 1970 and the influence of weather upon nutrient losses has been reported previously (Williams, 1971). The measurements now described are for the subsequent period until March 1975.

Saxmundham

A new system of five pipe drains was installed in October 1972 at Saxmundham, on a calcareous clay loam belonging to the Beccles Series (Hodge, 1972). These drains traverse the field in an east–west direction and discharge into the ditch at the eastern boundary. The positions of the outfalls are given on the map of Saxmundham Experimental Station appearing at the end of this Report. The drains (7·5 cm diameter) were laid 0·8 m deep. with washed shingle backfill to within 30 cm of the soil surface. The field was mole-drained 0·6 m deep and at 2·7 m spacings at right angles to the drain lines. Drain 1 collects water from the headland at the northern end of the field next to the road. Drainage from this outfall was recorded but not chemically analysed, neither was the water from the two spur drains that gather water from the southern headland. Drains 2 and 3 take drainage from land that contains the Rotation 2 experiment and an area to the west, under arable crops (roots and cereals). Drains 4 and 5, at the southern half of Harwood's Field, drain an area largely occupied by the Rotation I experiment which had been under herbage crops (half under lucerne receiving no N fertiliser and half under grass receiving 100 kg ha^{-1} for each of, on average, two annual cuts) since the new drains were installed. Chemical composition of drainage from these two differently cropped areas enabled concentrations and amounts of nutrients lost in their drainage to be compared.

Measurements made from March 1970–March 1972 on drainage from the old system described previously (Williams, 1971) are compared with those made for the period 1968–70. The nutrient content and flowrates of the new drains are discussed with particular reference to annual weather.

When the new drainage system was laid in 1972, information was obtained about the nature of the original system on Harwood's Field, the plan of which had been lost. A system of 5-cm pipe drains about 0·7 m deep running diagonally from north-west to south-east with the incline of the land and at approximately 19·5 m (65 ft) spacings, were uncovered in the trenches cut for the new drains. This system was in addition to the ones previously described (Williams, 1971). Most of these earliest drains showed little evidence of having functioned recently and, being laid without porous backfill, the dense subsoil was firmly consolidated around them. All the pipes exposed when the new system was installed were effectively sealed before the new ones were laid.

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TABLE 1(a)

Mean annual flowrates (litre min⁻¹) of drains at Saxmundham

Drain	Mean	Maximum	Minimum
Old Drainage System			
17/3/70–19/3/71			
1	1·5	30·0	0·0
2	2·5	30·0	0·0
3	0·6	15·0	0·0
4	0·6	15·0	0·0
20/3/71–19/4/72			
1	1·9	60·0	0·0
2	2·9	60·0	0·0
3	0·5	15·0	0·0
4	0·3	15·0	0·0
New Drainage System			
6/12/72–12/3/73			
2	0·6	2·5	0·0
3	0·8	15·0	0·0
4	0·6	2·5	0·0
5	0·7	2·5	0·0
13/3/73–16/3/74			
2	1·0	30·0	0·0
3	1·0	30·0	0·0
4	1·1	30·0	0·0
5	1·3	60·0	0·0
17/3/74–26/3/75			
2	4·1	136	0·0
3	3·8	136	0·0
4	4·1	136	0·0
5	4·1	136	0·0

Woburn

The drainage system at Woburn has remained unchanged since measurements were reported previously. It is composed of six land drains, a spring arising from an underground source in Mill Dam Close near the farm buildings, and a lake fed with drainage water. The latter two sources discharge into a stream that passes Woburn Farm and later joins the River Ouzel. Drains 1, 2 and 3 discharge from the base of Great Hill. Drains 1 and 2 are situated at the north side of Great Hill Bottom 2; Drain 1 discharges into the lake, Drain 2 into the ditch that separates this field from Broad Mead. Drain 3 is at the south-west corner of Honey Pot Field and discharges into a ditch that runs northwards towards Broad Mead. Drains 5 and 6 both originate in a spring on land to the east of Honey Pot Field. Drain 5 discharges into a shallow ditch that runs northwards to Broad Mead. Drain 6 traverses shallowly a cattle watering point in an adjacent field outside Woburn Experimental Station. The soils of this area of Woburn Farm have been described in detail (Catt, King & Weir, 1975) and belong to the Flitwick, Rowsham and Evesham Series overlying Lower Greensand and Ampthill Clay.

Effects of weather on drainage

Tables 1(a) and 1(b) give the mean annual flowrates and range of flows of drains at Saxmundham and Woburn respectively. Table 2 gives information on the effects of rainfall and evaporation upon the mean monthly flowrates and percentage of rain in *observed* drainage (see Appendix) from all the drains of the old system on Harwood's

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TABLE 1(b)

Mean annual flowrates (litre min^{-1}) of drains at Woburn

Drain	Mean	Maximum	Minimum
	23/3/70–22/3/71		
1	9·1	30	0
2	9·1	30	0
3	1·7	15	0·25
4	1·3	15	0
5	1·8	15	0·1
6	16·5	30	2·5
Spring	81·8	130	2·5
	23/3/71–15/3/72		
1	6·2	15	1
2	6·4	30	1
3	2·1	2·5	1
4	0·9	2·5	0
5	0·7	2·5	0
6	15·0	—	—
Spring	66·9	130	15
	16/3/72–1/3/73		
1	3·7	15	1
2	2·9	2·5	0·25
3	0·9	2·5	0
4	0·2	1	0
5	0·2	1	0
6	13·2	15	2·5
Spring	130	—	—
	2/3/73–19/3/74		
1	4·3	15	0
2	4·3	30	0
3	0·6	2·5	0
4	0·5	2·5	0
5	0·4	2·5	0
6	12·4	30	0
Spring	55·7	130	15
	20/3/74–14/3/75		
1	19·1	130	0
2	10·4	30	0
3	3·5	30	0
4	4·1	30	0
5	4·0	30	0
6	25·6	130	0
Spring	111·8	130	30

Field from March 1970 to October 1972. Table 3 gives corresponding information for the drains of the new system from October 1972 until March 1975, with the flows from Drains 2 and 3 (under arable cropping) treated separately from those from Drains 4 and 5 (under herbage crops). Table 5 gives similar information for the Woburn drains including the spring which is a more constant source of aquifer water. The percentage of rain appearing in observed drainage could not be calculated for Woburn as the drains serve an undefined area. Table 4 gives information on periods of continuous and discontinuous drainage at Saxmundham from 1968 to 1974.

Drainage at Saxmundham

The total mean flow from Drains 1–4 of the old system at Saxmundham for the period 17 March 1970 to 19 April 1972 was one-half to one-third of the values reported for 1968–69 when rainfall was larger. Flows from the new drains commenced on 6 December 1972 after they had been laid in dry weather the previous October and virtually no

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TABLE 2

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

Old Drainage System

Year	Month	Rainfall (mm) Total	Rainfall (mm) >10 mm daily Days	Rainfall (mm) >10 mm daily mm	Evaporation (E_0) (mm)	Soil temperature at 30 cm depth (°C)	Drains 1–4 Drainage Observations (days)	Drains 1–4 Drainage Flow-rate (litre min^{-1})	Drains 1–4 Drainage Total (as % of rain)
	(17/3/70–15/3/71)								
1970	March	15	0	0	—	5·0	11	6·3	29·9
	April	53	1	11	40	6·2	26	7·7	20·7
	May	18	0	0	105	12·8	26	1·1	9·3
	June	8	0	0	133	17·6	26	0	0
	July	28	0	0	98	17·2	23	0	0
	August	21	0	0	113	17·8	27	0	0
	September	62	2	53	83	15·3	26	0	0
	October	25	0	0	49	11·6	27	0	0
	November	151	4	86	28	8·1	25	11·3	10·7
	December	34	0	0	—	5·7	20	10·6	45·9
1971	January	86	1	17	—	4·3	24	20·7	35·5
	February	20	0	0	—	5·0	24	6·1	40·3
	March	20	0	0	—	4·0	13	2·8	9·5
	Total	541	8	167	—	—	298	—	—
	Mean	—	—	—	—	9·9	—	5·2	15·5
	(16/3/71–15/3/72)								
1971	March	20	0	0	—	6·2	14	9·8	37·3
	April	15	0	0	13	7·9	24	0·2	1·9
	May	23	0	0	105	12·6	26	0	0
	June	83	5	72	102	12·7	22	0·5	0·9
	July	76	2	56	140	18·2	27	0·2	0·4
	August	60	2	30	113	17·2	27	0·1	0·2
	September	39	1	23	70	15·3	26	0·1	0·4
	October	62	2	44	50	11·8	27	7·4	17·6
	November	102	2	44	—	7·0	26	18·4	25·7
	December	29	0	0	—	6·3	26	9·5	48·3
1972	January	62	2	28	—	4·3	22	17·3	41·1
	February	32	0	0	—	4·0	25	10·5	43·7
	March	27	0	0	—	4·8	12	8·2	21·7
	Total	630	16	297	—	—	304	—	—
	Mean	—	—	—	—	9·9	—	6·3	18·4
	(16/3/72–5/10/73)								
1972	March	4	0	0	—	6·7	13	1·8	34·2
	April	45	0	0	64	8·3	25	3·1	9·8
	May	39	0	0	100	11·3	27	0	0
	June	44	2	23	90	13·2	26	0	0
	July	51	1	19	96	17·4	27	0	0
	August	10	0	0	97	15·9	21	0	0
	September	66	1	45	69	13·1	27	0·1	0·2
	October	0	0	0	9	11·1	5	0	0
	Total	259	4	87	—	—	171	—	—
	Mean	—	—	—	—	12·2	—	0·7	5·5

(New drainage system installed 5–6/10/72)

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TABLE 3 *Relationships between rainfall and its intensity, evaporation, soil temperature and drainage at Saxmundham*

New Drainage System

Year	Month	Rainfall (mm) Total	Rainfall >10 mm daily Days	Rainfall >10 mm daily mm	Evaporation (E_0) (mm)	Soil temperature at 30 cm depth (°C)	Observations (days)	Drainage: Drains 2 and 3 Flowrate (litre min^{-1})	Drainage: Drains 2 and 3 Total (as % of rain)	Drainage: Drains 4 and 5 Flowrate (litre min^{-1})	Drainage: Drains 4 and 5 Total (as % of rain)
1972	October (6/10/72)	6	0	0	29	10·9	21	0	0	0	0
	November	49	1	19	17	6·9	26	0	0	0	0
	December	30	1	10	—	5·9	22	1·7	19·5	1·2	14·3
1973	January	17	0	0	—	4·8	26	0·5	10·1	0·7	14·7
	February	28	0	0	—	4·0	24	1·8	20·0	1·6	18·4
	March (15/3/73)	10	0	0	—	5·2	13	1·8	30·1	1·9	32·8
	Total	140	2	29	—	—	132	—	—	—	—
	Mean	—	—	—	—	6·2	—	1·0	13·2	0·9	13·3
1973	March (16/3/73)	3	0	0	—	6·2	14	0·2	11·8	0·2	12·2
	April	62	2	26	—	6·9	23	4·6	24·8	7·5	41·7
	May	62	1	11	79	11·5	27	1·3	8·4	1·1	6·3
	June	25	1	12	120	17·1	26	0	0	0	0
	July	73	4	54	92	18·5	21	0	0	0	0
	August	26	1	11	106	17·8	26	0	0	0	0
	September	86	4	66	93	15·7	26	0	0	0	0
	October	39	1	12	39	10·5	27	0	0	0	0
	November	28	1	11	9	6·0	26	0	0	0	0
	December	35	1	11	—	4·4	23	1·5	14·8	2·7	27·5
1974	January	38	0	0	—	5·3	26	4·3	39·1	4·2	39·4
	February	50	1	14	—	5·6	24	11·6	72·3	12·8	82·4
	March (15/3/74)	24	0	0	—	4·5	14	2·6	18·0	2·4	18·6
	Total	551	17	228	—	—	303	—	—	—	—
	Mean	—	—	—	—	10·0	—	2·0	14·5	2·4	17·5
1974	March (16/3/74)	2	0	0	—	5·2	15	4·7	418	4·4	405
	April	12	0	0	88	8·7	26	0·2	5·6	0·2	5·8
	May	10	0	0	131	11·9	27	0	0	0	0
	June	31	0	0	125	15·5	26	0	0	0	0
	July	46	1	12	127	15·9	25	0	0	0	0
	August	67	2	27	93	16·5	26	0	0	0	0
	September	106	4	63	78	13·5	26	0·4	1·3	0·4	1·3
	October	84	3	33	33	8·5	27	7·5	30·8	4·4	18·7
	November	121	2	65	28	7·7	26	37·3	103·0	34·9	99·5
	December	33	0	0	—	6·1	23	5·8	60·7	7·1	76·7
1975	January	94	2	36	—	6·1	24	36·6	133·0	45·6	171·1
	February	13	0	0	—	4·8	24	1·8	43·2	2·2	54·5
	March (15/3/75)	41	0	0	—	5·1	13	15·2	61·9	15·5	65·2
	Total	660	14	236	—	—	308	—	—	—	—
	Mean	—	—	—	—	9·6	—	8·4	65·9	8·8	69·0

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drainage had occurred since April. Their mean annual flowrates until March 1974 were similar to those recorded for the old system, with Drain 5 of the new system situated at the southern end of the field close to the position of old Drain 2 giving the largest mean and maximum flow. From September 1974 until March 1975, 492 mm of rain fell, equivalent to about 75% of that in the period from March 1974 until March 1975 (Table 3). Drainage was continuous from the beginning of October until early May (Table 4). Maximum flowrates during this period were the largest recorded for this site and the mean total annual flowrate (16·1 litre min^{-1}) for Drains 2–5 for 1974–75 was as large as in 1969–70 when there was more drainage during the spring and summer months. This is evidence for the larger capacity offered by the new system. Flows are larger in very wet weather and smaller flows last longer than those recorded for the old drains.

Estimates of percentage of rain appearing as observed drainage (Tables 2 and 3) show that these are larger for the drains of the new system. The discontinuous nature of drainage at Saxmundham and the influence of the amount and distribution of annual rainfall upon the extent of the periods of continuous and discontinuous drainage from 1967 to 1975 are shown in Table 4. From 17 October 1967 to 3 May 1975 the drains did not run during 40% of the time. Estimates of losses of NO_3-N in continuous drainage were calculated from monthly mean concentrations and flowrates from the entire systems. During autumn and winter when land is often cultivated and uncropped, even moderate rainfall can produce long periods of continuous drainage because evaporation is small. Excessive rainfall at that time can produce flows of large volume containing much residual N. When these periods of continuous drainage extend into spring, larger losses of freshly applied N can be lost. However, drainage between April and October can be small and intermittent due to the combined effects of greater crop growth and evaporation, and N losses are restricted. These general conclusions, applicable to many soils,

TABLE 4

Drainage and rainfall at Saxmundham (1967–75)

Continuous drainage

Period		Days	Rainfall (mm)	Rain days (>0·25 mm)
17/10/67–8/4/68		174	306	75
11/9/68–23/6/69		285	588	135
15/11/69–4/6/70		201	385	103
11/11/70–4/4/71		144	329	63+
8/11/71–29/4/72		172	276	67
15/1/73–29/5/73		134	176	49
5/12/73–16/4/74		132	142	43
4/10/74–3/5/75		211	454	113
1967–75	Total	1453	—	—
	Mean	182	332	81+

Discontinuous drainage (1 April–1 October)

Year	Days without drainage	% of period	Days with drainage	% of period	Rainfall (mm)	Rain days (>0·25 mm)
1968	102	56	81	44	401	87+
1969	68	37	115	63	340	64+
1970	117	64	66	36	190	57+
1971	148	81	35	19	296	51
1972	157	86	26	14	255	62+
1973	122	67	61	33	334	59+
1974	162	89	21	11	272	54
Mean	125	69	58	31	298	62+
Range	68–162	37–89	21–115	11–63	190–401	51–87+

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are illustrated by measurements made at Saxmundham of losses of nitrate in continuous drainage during 1968–75.

The longest period of continuous drainage (285 days) was recorded between 11 September 1968 and 23 June 1969 when the rainfall was 588 mm. The next longest period (211 days) was between 4 October 1974 and 3 May 1975 when rainfall was 454 mm. Between 15 November 1969 and 4 June 1970 when the rainfall was 385 mm there were 201 days of continuous drainage. Mean flowrates for the old drainage system in 1968–69 and 1969–70, were similar (about 19 litre min^{-1}). In the 1974–75 period the mean flowrate for the new drains was much larger (33 litre min^{-1}) and more nitrate (68 kg ha^{-1}) was lost in drainage than in 1968–69 or 1969–70 when the losses were 30 and 22 kg ha^{-1} respectively. Losses of NO_3-N for November 1970 to 4 April 1971, 8 November 1971 to 29 April 1972 and 5 December 1973 to 16 April 1974 were 12, 9·6 and 16·4 kg ha^{-1} respectively. In these three periods continuous drainage was less (132–144 days). The smallest loss of NO_3-N (8·5 kg ha^{-1}) was measured in the period 15 January to 29 May 1973 when mean flowrate was least (4 litre min^{-1}) and flows during May were very small and little spring-applied N was lost. The rainfall during January to March 1973 (58 mm) was only about 40% of the mean value for all the other years since 1968.

Most nitrate was lost during periods of continuous drainage when monthly rainfall and flowrates were largest. At these times concentrations of nitrate in drainage water moderated, being rarely greater than 25 mg $litre^{-1}$ and often below 15 mg $litre^{-1}$, except in early May 1969 when large flows leached much spring-applied N and concentrations were greater than 90 mg $litre^{-1}$ NO_3-N from individual drains. A more detailed account of losses of nitrate-N from under arable and herbage crops in 1974–75 is given below (Fig. 1). Table 4 also gives periods of discontinuous drainage from 1 April until 1 October from 1968 to 1974. On average, 70% of this period was associated with no drainage but this varied greatly from year to year. In 1969 the percentage was 37%, in 1974 it was 89%. In 1969 rainfall from January to March was 177 mm and from April to October 341 mm, 199 mm of which fell in amounts $>$10 mm daily. In 1974, 114 mm of rain fell from January to March and only 272 mm from April to October, of which only 102 mm occurred as $>$10 mm daily. Accumulative moisture deficits were 32 mm by the end of September 1969 and 149 mm in 1974. In 1970 and 1973 the proportions of time without drainage from April to October were similar. Rain from January to March was 178 mm in 1970 and 58 mm in 1973, between April and October it totalled 190 mm and 334 mm respectively, of which 64 mm fell in amounts $>$10 mm daily in 1970 and 180 mm in 1973. Accumulative moisture deficits by the end of September were 252 mm in 1970 and 82 mm in 1973. The effect of larger early rainfall in 1970 was annulled by less total rain of smaller intensity later, associated with larger evaporation. More rain occurred later in 1973 particularly after July when evaporation was larger.

These results illustrate the dependence of the restriction of drainage from April to October, which is critical for the retention of spring-applied N fertiliser on this soil, upon the extent of rainfall during the first three months of the year and the balance between evaporation and the distribution and intensity of rain during the summer months.

Comparisons of the drainage from the two sections of the new system at Saxmundham (Table 3) indicates that Drains 4 and 5 at the lower end of this gently sloping field had larger flowrates than the section above, particularly during the period of exceptionally wet weather from September 1974 until March 1975 when very large flows were recorded. It is known that in periods of large rainfall some lateral movement of water can occur at this site and this may have enhanced the flows from Drains 4 and 5, although the chemical compositions of the drainage from these two drains was always markedly different from those from Drains 2 and 3. In Table 3, drainage expressed as a proportion

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of the monthly rain sometimes exceeds 100%. Selection of drainage periods from March to March as being of greater relevance to the relationships between nutrient losses and crop growth has meant that the percentages for the latter half of March 1974 are very large. Before 15 March, 94% of the month's rain had fallen. If the percentages of drainage

TABLE 5

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

		Rainfall (mm)					Mean flowrate (litre min⁻¹)	
			>10 mm daily		Rainy days	Soil temperature		
Year	Month	Total	Days	mm	(>0·25 mm)	30 cm (°C)	Drains 1–6	Spring
				23/3/70–22/3/71				
1970	March	10	0	0	3	4·7	5·8	15
	April	71	3	36	22	6·9	13·1	23
	May	7	0	0	9	12·9	4·4	66
	June	33	0	0	8	16·6	2·7	130
	July	42	0	0	16	15·9	0·6	130
	August	63	1	26	11	16·4	2·7	130
	September	39	1	13	11	14·7	2·8	30
	October	18	0	0	8	11·6	2·7	30
	November	131	6	86	20	8·7	4·8	30
	December	38	2	24	12	5·9	7·5	80
1971	January	87	2	31	18	4·5	8·1	130
	February	15	0	0	7	4·7	11·0	130
	March	44	1	14	11	4·4	8·3	130
	Total	598	16	230	156	—	—	—
	Mean	—	—	—	—	9·8	5·7	81
				23/3/71–15/3/72				
1971	March	4	0	0	2	6·1	10·8	130
	April	33	2	27	7	7·9	4·8	30
	May	35	0	0	13	12·2	3·7	30
	June	84	4	70	13	13·6	3·4	30
	July	37	1	13	6	17·6	3·4	23
	August	86	2	24	19	16·8	3·6	30
	September	16	0	0	5	14·8	3·5	30
	October	79	3	53	8	12·0	3·0	30
	November	67	3	45	13	7·2	5·3	130
	December	21	0	0	10	6·5	4·2	130
1972	January	59	1	10	20	4·9	8·6	130
	February	38	0	0	16	4·1	10·0	130
	March	25	0	0	9	4·7	8·5	30
	Total	584	16	242	141	—	—	—
	Mean	—	—	—	—	9·8	5·6	68
				16/3/72–1/3/73				
1972	March	18	0	0	7	7·1	—	—
	April	49	0	0	18	8·5	8·3	130
	May	40	0	0	20	11·1	2·9	130
	June	27	0	0	12	13·3	3·3	130
	July	67	1	45	13	15·8	0·9	130
	August	15	0	0	4	15·6	3·0	130
	September	36	1	21	6	13·3	2·7	130
	October	22	1	14	8	10·9	2·7	130
	November	52	2	26	13	7·8	3·1	130
	December	46	0	0	14	6·3	8·4	130
1973	January	20	0	0	13	4·9	3·6	130
	February	19	0	0	11	4·7	5·8	130
	March	3	0	0	1	3·8	3·4	130
	Total	414	3	106	140	—	—	—
	Mean	—	—	—	—	9·6	4·0	130

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TABLE 5 (*continued*)

Year	Month	Rainfall (mm) Total	>10 mm daily Days	>10 mm daily mm	Rainy days (>0·25 mm)	Soil temperature 30 cm (°C)	Mean flowrate (litre min⁻¹) Drains 1–6	Mean flowrate (litre min⁻¹) Spring
				2/3/73–19/3/74				
1973	March	8	0	0	4	5·4	3·4	130
	April	46	2	21	13	7·3	3·4	130
	May	111	1	52	14	11·4	2·8	130
	June	71	3	68	5	15·9	0·6	73
	July	37	2	25	9	16·7	2·9	15
	August	32	0	0	7	17·1	2·6	15
	September	36	1	10	10	15·2	2·8	15
	October	30	0	0	11	10·7	3·1	15
	November	32	1	12	6	7·1	2·7	73
	December	32	0	0	15	4·5	1·4	53
1973	January	64	0	0	18	5·3	11·3	130
	February	63	2	23	14	5·6	9·8	30
	March	34	1	14	10	5·0	4·1	30
	Total	596	13	225	136	—	—	—
	Mean	—	—	—	—	9·8	3·9	65
				20/3/74/14/3/75				
1974	March	5	0	0	1	6·7	8·5	130
	April	16	0	0	6	7·9	6·4	30
	May	33	0	0	10	10·9	2·8	30
	June	68	3	52	10	14·4	1·8	130
	July	41	1	17	13	15·4	0·6	130
	August	110	4	80	14	15·5	3·4	130
	September	109	3	44	23	13·6	3·1	130
	October	90	5	69	19	9·2	29·6	130
	November	121	3	69	22	7·2	53·8	130
	December	34	0	0	15	6·9	7·5	130
1975	January	62	1	12	21	6·4	4·1	130
	February	33	1	17	7	5·8	12·5	130
	March	81	3	55	12	5·8	46·7	130
	Total	803	24	415	173	—	—	—
	Mean	—	—	—	—	9·6	13·9	115

are calculated for the entire month they are both approximately 48%. Again, in January 1975 the percentage was large when the month's rain was large and was preceded by two wet months. These results reinforce the possibility mentioned above for a lag in the flows from the drains by water held up in ploughed land at this site. Free water at plough depth at Saxmundham had been noticed in very wet winter weather.

Drainage at Woburn

At Woburn, drainage has been continuous since measurements were commenced in 1968 although individual drains have ceased to flow for short periods. Drain 4 from the heavier textured soil in Honey Pot Field had the smallest flows and the longest periods without drainage. The mean annual flowrates of the drains at Woburn (Tables 1(b) and 5) were similar to those reported for 1968–70 (Williams, 1971) but since 1969 the flows from Drain 6 have accounted for nearly 50% of the flow from all the land drains. In 1968 it accounted for only 15%. There has been a corresponding decrease in the amount from Drain 5 that originates in the same spring source. Clearly much water once entering this drain has become diverted to Drain 6. The large annual flows recorded for 1974–75 were, as at Saxmundham, the result of much rain (449 mm) falling between September

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1974 and March 1975. The mean annual flow from the spring at Woburn Farm was about 30% less in drier years when rainfall was less than 600 mm than in wetter years when it exceeded 720 mm. The flowrates of the land drains excluding Drain 6 showed greater annual variation being on average halved in drier years. Flows from Drain 6, a spring-fed source, behaved differently. Mean total annual flowrates from the land drains were on average four times as much as at Saxmundham. This is a reflection of the different kinds of source and soil series at these two sites and is relevant to the estimations of annual losses of nutrients presented later.

Drainage water composition

Table 6 gives the average monthly concentrations of nutrients in drainage from the old system at Saxmundham during 1970–72, Table 7 shows the relationships between the individual drains expressed as mean annual concentrations of ions together with values for pH and specific conductivity. Tables 8(a), 8(b) and 9 give corresponding measurements on drainage from the new system of drains from December 1972 to March 1975. The chemical compositions of water from Drains 2 and 3 under arable crops are presented separately from those from Drains 4 and 5 under herbage crops. Fig. 1 shows the relationships between weekly rainfall, rain days (>0·25 mm), mean weekly flowrates (drains 2–5) and weekly concentrations of nitrate-N in drainage corresponding to losses of nitrate in drainage from September 1974 until May 1975. Tables 10 and 11 give corresponding measurements for the Woburn drainage systems to those in Tables 6 and 7.

TABLE 6

Chemical composition of drainage water from Harwood's Field, Saxmundham. Average values from Drains 1–4 of the Old System (1970–72)

Year	Month	Mean concentration (mg litre^{-1})								
		Na	K	Ca	Mg	NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S
1970	March (23/3/70)	24·9	0·6	235	13·9	0·26	6·3	0·00	57	112
	April	35·4	1·0	204	11·5	1·34	10·1	0·00	61	85
	May	—	—	—	—	1·32	5·8	—	—	—
	June	—	—	—	—	1·9	5·7	—	—	—
	July	—	—	—	—	—	—	—	—	—
	August	—	—	—	—	—	—	—	—	—
	September	—	—	—	—	—	—	—	—	—
	October	—	—	—	—	—	—	—	—	—
	November	16·7	1·6	162	6·3	1·65	22·6	0·00	33	46
	December	18·8	1·7	166	7·1	0·79	20·2	0·00	41	57
1971	January	18·1	0·8	158	6·2	0·06	16·7	0·03	44	47
	February	16·5	0·6	153	5·8	0·00	11·7	0·00	41	38
	March (19/3/71)	15·6	1·6	155	5·7	0·53	7·7	0·00	33	50
	Mean 1970–71	22·3	1·1	176	8·1	0·87	11·9	0·00	44	62
1971	March (20/3/71)	—	—	—	—	—	—	—	—	—
	April	—	—	—	—	—	—	—	—	—
	May	—	—	—	—	—	—	—	—	—
	June	22·3	2·1	231	7·5	0·34	53·0	0·00	78	49
	July	11·9	3·2	138	4·6	0·65	32·3	0·00	35	34
	August	15·3	2·7	136	5·2	0·23	14·2	0·04	29	38
	September	—	—	—	—	—	—	—	—	—
	October	13·0	6·2	181	5·7	3·30	16·1	0·40	98	41
	November	13·4	4·1	158	5·2	0·77	15·1	0·16	56	34
	December	14·2	2·1	165	5·9	0·57	11·7	0·04	45	36
1972	January	13·2	2·1	145	5·0	0·66	9·9	0·13	30	28
	February	19·8	1·1	166	7·0	0·25	9·0	0·02	40	41
	March	21·3	1·3	196	8·1	0·41	10·2	0·00	49	54
	April (19/4/72)	21·9	2·1	198	9·3	0·45	12·3	0·04	52	62
	Mean 1971–72	16·6	2·7	171	6·4	0·76	18·4	0·08	51	42

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Drainage water composition at Saxmundham

Although the new drainage system was not installed until October 1972 there was no drainage from the old one from 19 April until then with the exception of a very small flow (<0.6 litre min^{-1}) from Drain 2 on 19 September. The measurements from March 1971 to 1972 include those for April as these terminated, for all practical purposes, the drainage from the old system. Some very small flows in April 1971 were recorded but no samples were taken for chemical analysis.

Mean annual compositions for the drainage water from the old system (Table 7) were similar to those found during 1968–69 except that NH_4-N was more. Concentrations of nitrate-N in 1970 differed from that in 1971. In 1970, rainfall from April to September was 190 mm and moisture deficit was 252 mm by the end of September compared with 1971 when rainfall was 296 mm and the deficit 84 mm for the same period. There was no drainage from June to the end of October but, in 1971, only May had no drainage, there being small intermittent flows until October when flows increased. Concentrations of nitrate-N $>$ 50 mg $litre^{-1}$ were measured in flows from individual drains in November 1970. These large concentrations were presumably in rapid flows down cracks that had formed in the soil during a very dry summer during which crop N responses were small, and represent unused residues from spring applications. Later in 1970 flowrates increased and concentrations of nitrate decreased until by the following March they were similar to

TABLE 7

Average annual concentrations of ions (mg $litre^{-1}$), conductivities, and pH values of drainage water from four drains of the Old System on Harwood's Field, Saxmundham (1970–72)

		Drain 1	Drain 2	Drain 3	Drain 4	Mean (1–4)
Sodium	1970–71	27·1	18·4	18·8	15·1	19·8
	1971–72	22·4	17·2	13·4	11·9	16·2
Potassium	1970–71	1·4	1·5	1·0	0·5	1·1
	1971–72	2·7	2·1	1·7	4·3	2·7
Calcium	1970–71	188	164	164	159	169
	1971–72	206	170	144	169	172
Magnesium	1970–71	7·9	7·0	7·7	6·1	7·2
	1971–72	7·9	7·4	5·0	5·5	6·5
Ammonium-N	1970–71	1·13	0·86	1·08	0·60	0·92
	1971–72	0·68	0·64	0·63	0·88	0·71
Nitrate-N	1970–71	18·6	16·0	13·5	15·3	15·8
	1971–72	24·4	8·6	7·4	16·2	14·2
Phosphate-P	1970–71	0·00	0·00	0·00	0·06	0·02
	1971–72	0·08	0·05	0·04	0·29	0·12
Chloride	1970–71	70·1	36·4	31·1	35·6	43·3
	1971–72	71·4	44·4	30·9	54·0	50·2
Sulphate-S	1970–71	66·1	53·2	78·2	38·8	59·1
	1971–72	55·5	44·6	28·4	34·2	40·6
Conductivity (μmho cm^{-1})	1970–71	955	833	804	731	831
	1971–72	1003	771	650	789	803
pH	1970–71	7·9	7·9	7·9	8·0	7·9
	1971–72	7·9	7·8	7·9	8·1	7·9

those found in drainage a year earlier. In 1971 concentrations of NO_3-N varying from 20 to 40 mg $litre^{-1}$ in small flows (0·1 to 0·6 litre min^{-1}) in mid-June drainage indicated that some of the spring-applied N had been leached. This leaching became more pronounced when flows became continuous in early November and more nitrate was lost in some large flows.

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These results illustrate the different behaviour of nitrate leaching in two consecutive years that were characterised by different rainfall distributions and other weather factors that affect evaporation, and emphasise the difficulties associated with the efficient use of fertiliser N on this soil.

The average concentrations of ions, conductivities and pH values of water from the old drains in 1970–72 were very similar to those reported previously for 1968–70. On average there was a small decrease in magnesium and a significant increase in ammonium-N during 1970–72.

The new system of drains at Saxmundham were installed to serve separate areas of Harwood's Field unlike the original systems that were gradually added to since the original one was laid possibly at the end of the last century or the beginning of this. The two systems are not comparable in position or numbering. By isolating water from the northern headland near the road, possible run-off from that direction was minimised.

Comparing the mean annual concentrations of ions in drainage from the arable section served by Drains 2 and 3 (Table 9, p. 53) with those from the old drainage system in 1968–70 (Williams, 1971) before the herbage crops were sown, the mean concentrations of Ca, Mg, NH_4-N, NO_3-N, and in particular Cl and SO_4-S, have increased whereas Na, K and PO_4-P have remained similar. The increase in chloride and sulphate was particularly noticeable in the short period from December 1972 to March 1973 (Table 8(b)) when the drains of the new system began to function after a previous dry summer and autumn. Mean concentrations of chloride three times those found in the earlier drainage and twice those of sulphate were measured. These concentrations remained larger into 1975 on the arable section even when mean monthly flowrates were large and they became less only when flowrates from individual drains were maximal ($>$100 litre min^{-1}). This effect was less pronounced in drainage from the herbage section where chloride and sulphate concentrations had become similar to those from the old drains by 1975.

The concentrations of ions in drainage from the arable and herbage sections showed some marked differences. With the exception of Na and PO_4-P, other ionic concentrations were less from under grass and lucerne. This effect was particularly noticeable for calcium, chloride, nitrate and sulphate. On average, nitrate in drainage from under herbage was only 20% of that under arable cropping; potassium, calcium, magnesium, ammonium-N and sulphate between 65% and 85% and chloride only 35%.

The Saxmundham soil is calcareous. The topsoil contains about 1% free $CaCO_3$ and the subsoil up to 20% $CaCO_3$ in localised areas (Williams & Cooke, 1971). The pH of the drainage waters varied from 7·7 to 8·1. The concentration of calcium in drainage from under herbage has decreased from 72% in 1972–73 to 68% in 1973–74 and to 62% in 1974–75 of the corresponding concentrations in drainage from the arable section. This decline in the concentration of calcium could be the result of two interacting factors: (i) the uptake of this ion from the uncultivated topsoil within the root range of permanent crops, and (ii) possible lateral leaching in the topsoil across each drain intersection. The density of the Saxmundham subsoil often exceeds 1·65 (Cooke & Williams, 1972) and water movement within it could be slow and promote preferential leaching in the topsoil. Similar considerations could apply to the differences observed with chloride and sulphate compared with the concentrations found in drainage from the arable section which is ploughed annually.

The large increases in the concentrations of chloride and sulphate in the drainage from the arable section compared with those from the old drainage system mentioned above suggests that the retention of these ions by the soil has become altered by a change in the equilibrium achieved under the original system of drainage. The shallow depth of the shingle backfill below the soil surface used when the new drains were laid, compared

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with its complete absence in the old system could accelerate the movement of soluble ions to the drain channels and outfalls.

Comparison of leaching of nitrate under arable and herbage crops at Saxmundham. Losses of nitrate-N in drainage from the two sections of the new system at Saxmundham were calculated for the three periods of continuous drainage in 1973–75 (Table 4). In the first of these from 15 January until 29 May 1973, 5·1 kg ha^{-1} NO_3-N was lost in drainage from the arable section and 3·4 kg ha^{-1} from under herbage crops. From 5 December 1973 until 16 April 1974 the losses were 13·3 and 3·1 kg ha^{-1} respectively. The period from 1 September 1974 to 3 May 1975 was one of large rainfall and after 4 October of continuous and at times excessive drainage at Saxmundham. The rainfall (564 mm) exceeded the long period average for these months for 1930–73 by 147 mm. Drainage for chemical analysis was sampled more frequently to determine the relative amounts of nitrate-N lost under the two systems of cropping. The relationships between rainfall, drainage and losses are shown in Fig. 1. Weekly rainfall and the number of rain days ($>$0·25 mm) are given with corresponding trends in mean flowrate from Drains 2 to 5. In September, although 63 mm of rain fell in the last two weeks, only very small flows were observed. This drainage however contained from 32 to 67 mg $litre^{-1}$ NO_3-N on the arable section and was the result of leaching of residues down cracks in the dry soil as described above for 1970. There was a small but significant increase in the nitrate content of drainage from the section under grass and lucerne. As evaporation diminished in October and November and much rain fell, flowrates increased sharply and concentrations of nitrate lessened. Large losses of NO_3-N occurred in drainage from the arable section in November when the monthly rainfall exceeded 100 mm. About 11 kg ha^{-1} nitrate-N was lost compared with about 2 kg ha^{-1} from the area under herbage. Similar periods associated with heavy and continuous rain occurred during the last two weeks of January 1975 when further losses of nitrate amounted to about 10 and 4 kg ha^{-1} from the arable and herbage sections respectively. Although there were large flows later in early April these contained less nitrate and were evidence for the fact that previous leaching had been severe. In this last period the amounts of nitrate lost were similar for both sections and could be due to some mineralisation of organic matter under the herbage as soil temperatures rose.

In the total period considered, losses of nitrate-N from the two drains of the arable section were 46 and 60 kg ha^{-1}, from the two drains of the section under lucerne receiving no N fertiliser and grass receiving 100 kg ha^{-1} after each of two cuts each year they were 15 and 18 kg ha^{-1}. Towards the end of the period, drainage from under the herbage section sometimes contained less than 1 mg $litre^{-1}$ NO_3-N which corresponds to the mean concentration in rainwater at this site (Williams, 1975), and provides further evidence for the completeness of leaching. The relationship between the losses of nitrate from under the arable and herbage sections was examined. For the period of continuous drainage from 4 October 1974 until 3 May 1975 estimates of NO_3-N losses based on monthly flowrates and mean concentrations were 51 kg ha^{-1} from the arable section and 18 kg ha^{-1} from under herbage crops.

During the period September 1974 until May 1975 mean weekly losses and concentrations of nitrate from Drain 4 were sometimes larger than those from Drain 5 situated on the field below. The mean flowrates from these two drains for the entire period were the same. The differences were more noticeable during the short periods of intense and continuous rainfall that produced the maximum losses of nitrate reported above. Drain 4 lies on a gentle slope from land served by Drain 3 on the arable section and separated from it by a broad grassed track. It is possible that some surface run-off occurred under

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these very wet conditions and this will be investigated in the future when weather conditions are suitable.

The relationship between the weekly losses of nitrate expressed as mean values from each pair of drains serving each section, was examined to provide a numerical comparison for future drainage measurements at this site, when Rotation I is resown with grass and lucerne. The coefficient of correlation between herbage (h) and arable (a) losses of nitrate was 0·91 and the relationship between them is expressed in the following equation

$$h = 0{\cdot}043 + 0{\cdot}284\,a\ (\pm 0{\cdot}024).$$

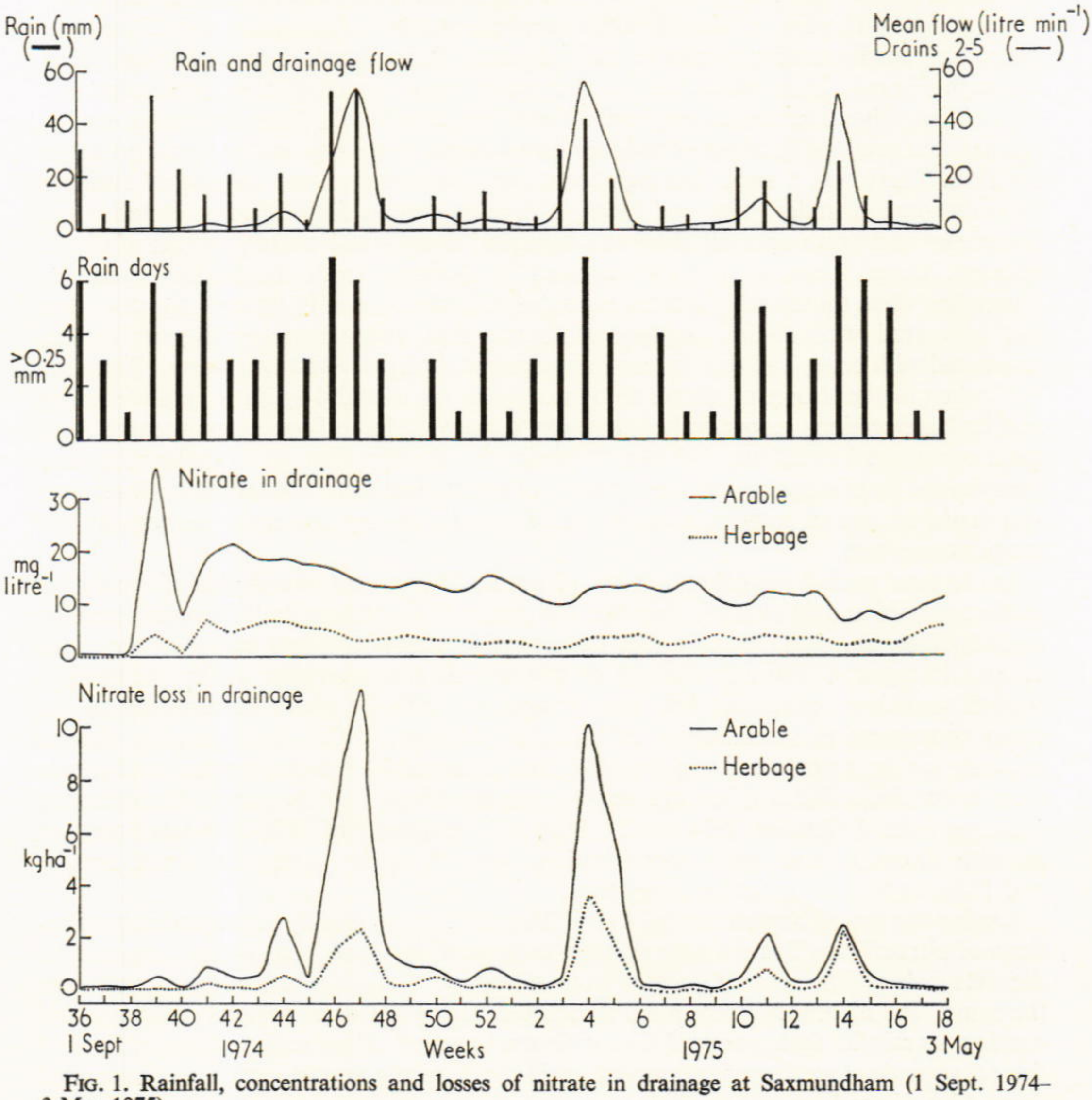

FIG. 1. Rainfall, concentrations and losses of nitrate in drainage at Saxmundham (1 Sept. 1974–3 May 1975).

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Drainage water composition at Woburn

The chemical composition of drainage at Woburn during 1970–75 (Tables 10 and 11) show similar variations between individual sources to those reported for the two preceding years. Mean annual concentrations of sodium, potassium, magnesium, ammonium-N, phosphate-P, chloride and sulphate-S for all the land drains showed little variation. During 1968–75 calcium varied between 120 and 150 mg litre^{-1} and nitrate between 12 and 19 mg litre^{-1}. Spring water had less calcium or nitrate than the land drains but its composition was otherwise similar. For individual drains, as in 1968–70, most calcium was found in drainage from Drain 4 from heavy soil and least from the sandy soil served by Drain 3. Nitrate concentrations in Drain 5 during 1973–75 were twice as large as those found in the previous three years and smaller variations were measured in water from Drains 4 and 6. Variations in nitrate concentration at Woburn were much less than at Saxmundham (Tables 7 and 8(b)). There was more sulphate in drainage from Drain 4 and more phosphate from Drain 3 than in the other sources. The spring water, in common with the mains supply at Woburn Farm that is derived from deep boreholes in the Greensand at the local Birchmoor Source (Williams, 1975), has

TABLE 8(a)

Chemical composition of drainage water from Harwood's Field, Saxmundham (1972–75). Averaging values for Drains 2 and 3 or 4 and 5 of the New System

		Mean concentration (mg litre^{-1})							
		Drains 2 and 3 (Arable)				Drains 4 and 5 (Herbage)			
		Na	K	Ca	Mg	Na	K	Ca	Mg
1972	December (6/12/72)	24·8	3·1	261·4	9·4	23·8	3·0	183·4	6·8
1973	January	23·4	1·6	227·1	8·8	25·8	1·7	178·1	7·4
	February	21·9	1·3	221·8	8·8	24·0	1·5	158·9	7·2
	March (12/3/73)	22·6	1·9	203·1	9·2	25·2	1·8	138·9	7·4
	Mean	23·2	2·0	228·4	9·1	24·7	2·0	164·8	7·2
1973	March (13/3/73)	—	—	—	—	—	—	—	—
	April	19·0	1·8	184·8	8·4	18·4	1·1	146·6	6·6
	May	24·1	1·9	210·8	10·1	24·0	1·2	173·1	8·5
	June	—	—	—	—	—	—	—	—
	July	—	—	—	—	—	—	—	—
	August	—	—	—	—	—	—	—	—
	September	—	—	—	—	—	—	—	—
	October	—	—	—	—	—	—	—	—
	November	21·6	6·8	212·0	8·1	23·4	2·0	185·0	7·3
	December	21·1	1·7	218·1	8·5	21·5	1·5	126·8	6·4
1974	January	23·2	1·1	211·7	9·6	22·5	0·7	98·8	6·7
	February	21·9	1·2	228·5	9·6	21·7	0·8	132·8	7·0
	March (16/3/74)	24·0	0·8	240·0	10·6	23·9	0·8	161·6	7·9
	Mean	22·1	2·2	215·0	9·3	22·2	1·2	146·4	7·2
1974	March (17/3/74)	24·8	0·9	240·6	12·0	25·2	0·9	180·0	9·6
	April	27·9	1·3	253·5	13·1	27·8	0·8	205·0	11·4
	May	—	—	—	—	—	—	—	—
	June	—	—	—	—	—	—	—	—
	July	—	—	—	—	—	—	—	—
	August	19·6	4·6	318·0	11·9	—	—	—	—
	September	12·7	3·0	172·3	6·4	14·6	1·4	114·7	4·4
	October	17·2	1·7	198·1	7·2	17·4	1·1	131·0	4·8
	November	13·9	1·8	216·8	7·1	13·3	1·2	124·6	4·8
	December	16·8	1·2	238·5	8·5	16·4	0·7	132·5	6·0
1975	January	16·0	1·6	200·6	7·8	15·4	1·0	122·0	5·5
	February	20·5	1·4	229·4	9·4	19·7	1·0	142·0	6·9
	March (26/3/75)	18·8	1·2	191·7	8·2	18·5	0·8	119·4	6·4
	Mean	18·8	1·9	226·0	9·2	18·7	1·0	141·2	6·6

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TABLE 8(b)

Chemical composition of drainage water from Harwood's field, Saxmundham (1970–72). Averaging values from Drains 2 and 3 or 4 and 5 of the New System

		Mean concentration (mg litre⁻¹)									
		Drains 2 and 3 (Arable)					Drains 4 and 5 (Herbage)				
		NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S	NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S
1972	December (6/12/72)	0·46	25·4	0·00	160·9	102·5	0·62	3·3	0·00	55·7	101·5
1973	January	0·59	18·9	0·00	119·0	79·6	0·49	2·5	0·00	48·4	87·6
	February	0·53	18·2	0·00	119·3	89·4	0·48	2·9	0·00	42·0	90·3
	March (12/3/73)	1·21	15·5	0·00	111·6	85·3	0·85	3·1	0·00	32·1	74·5
	Mean	0·70	19·5	0·00	127·7	89·2	0·61	3·0	0·00	44·6	88·5
1973	March (13/3/73)	—	—	—	—	—	—	—	—	—	—
	April	0·56	17·1	0·01	76·4	78·3	0·56	11·0	0·01	39·5	62·4
	May	0·28	16·9	0·00	86·0	86·7	0·20	6·4	0·00	36·5	85·6
	June	—	—	—	—	—	—	—	—	—	—
	July	—	—	—	—	—	—	—	—	—	—
	August	—	—	—	—	—	—	—	—	—	—
	September	—	—	—	—	—	—	—	—	—	—
	October	—	—	—	—	—	—	—	—	—	—
	November	1·35	11·8	0·00	78·0	92·0	1·12	5·8	0·00	31·8	93·3
	December	1·05	22·9	0·06	130·2	82·7	0·78	3·3	0·06	36·6	63·4
1974	January	0·62	22·6	0·01	141·4	82·4	0·62	3·8	0·00	35·1	55·4
	February	0·36	19·0	0·04	120·3	86·4	0·33	4·2	0·03	29·6	55·6
	March (16/3/74)	0·34	16·6	0·00	122·5	91·4	0·29	4·3	0·07	35·6	64·7
	Mean	0·65	18·1	0·02	107·8	85·7	0·57	5·5	0·02	35·0	68·6
1974	March (17/3/74)	0·03	12·5	0·00	112·6	101·6	0·06	4·5	0·00	37·6	88·9
	April	0·30	9·3	0·00	123·8	119·0	0·00	4·2	0·00	45·8	123·8
	May	—	—	—	—	—	—	—	—	—	—
	June	—	—	—	—	—	—	—	—	—	—
	July	—	—	—	—	—	—	—	—	—	—
	August	0·80	110·0	0·15	64·0	81·5	—	—	—	—	—
	September	0·40	35·0	0·11	54·0	52·3	0·15	4·5	0·00	36·0	50·3
	October	0·35	18·7	0·02	98·5	55·9	0·25	5·6	0·00	38·4	39·4
	November	0·17	15·1	0·12	99·2	61·7	0·26	4·5	0·04	28·6	31·9
	December	0·19	13·4	0·00	112·2	79·2	0·15	3·3	0·00	29·2	41·7
1975	January	0·37	11·6	0·07	81·9	69·9	0·35	2·7	0·03	22·8	37·4
	February	0·30	13·0	0·00	92·3	81·8	0·34	3·2	0·00	25·0	49·5
	March (26/3/75)	0·13	11·0	0·01	68·4	73·7	0·14	3·6	0·08	24·9	37·9
	Mean	0·30	25·0	0·05	90·7	77·7	0·19	4·0	0·02	32·0	55·6

always contained some PO_4-P (0·05–0·27 mg litre^{-1}) since measurements were started in 1968. This phosphate is presumably of mineral origin.

The water from Drain 1 discharges into the lake at Woburn yet their chemical compositions, as reported before, are different and have remained relatively constant during the last seven years. Conductivity of the lake water was less than that from Drain 1 and concentrations of calcium, phosphate, and in particular nitrate, were smaller. Magnesium, potassium, ammonium-N and pH were larger but chloride and sulphate similar. The mean annual concentration of nitrate in the lake water since 1968 has varied from 0·9 to 3·0 mg litre^{-1} with a mean value of 1·8 mg litre^{-1}, whereas that of drainage from Drain 1 has varied from 16·5 to 27·5 mg litre^{-1} with a mean value of 22·5 mg litre^{-1}. PO_4-P in the lake varied from 0·01 to 0·05 with a mean of 0·02 mg litre^{-1} and from the drain 0·02 to 0·19 with a mean of 0·11 mg litre^{-1}. The amount of phosphate present in the drainage water may limit the use of other ions by free living aquatic organisms (Williams, 1974) but plants rooted in the bottom mud may be responsible for removing some of the nitrate conveyed to the lake.

TABLE 9

Average annual concentrations (mg litre^{-1}), conductivities, and pH values of drainage water from four field drains of the New System on Harwood's Field, 1972–75

Drain	Na	K	Ca	Mg	NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S	Conductivity (μmho cm^{-1})	pH
					16/12/72–12/3/73						
Arable (2)	22·3	1·4	213	8·1	0·62	14·2	0·00	148·0	73·6	1126	7·8
(3)	23·5	2·4	244	10·0	0·66	25·1	0·00	105·5	107·6	1228	7·8
Herbage (4)	23·1	2·3	170	7·2	0·56	3·0	0·00	49·0	90·3	866	7·9
(5)	25·9	1·5	160	7·2	0·58	2·9	0·00	41·0	89·4	837	7·9
					13/3/73–16/3/74						
Arable (2)	22·6	1·7	213	8·4	0·64	19·9	0·03	121·1	75·9	1130	7·9
(3)	22·2	1·0	226	10·7	0·45	19·8	0·02	119·2	93·2	1211	7·8
Herbage (4)	20·9	1·0	134	6·9	0·45	4·8	0·03	36·9	60·0	715	7·9
(5)	23·5	0·9	131	7·3	0·52	4·5	0·03	32·0	64·3	713	7·9
					17/3/74–26/3/75						
Arable (2)	18·4	1·7	210	7·5	0·24	13·2	0·04	91·0	69·1	988	7·9
(3)	17·2	1·3	211	9·2	0·25	16·0	0·04	95·8	76·3	1033	7·7
Herbage (4)	16·6	1·0	135	6·9	0·23	4·3	0·02	30·8	43·6	648	7·8
(5)	18·1	0·9	130	6·1	0·25	3·3	0·02	26·7	45·7	588	7·8
					17/12/72–26/3/75						
Arable (2 + 3)	21·0	1·6	220	8·9	0·47	18·0	0·02	113·6	82·4	1119	7·8
Herbage (4 + 5)	21·4	1·3	143	6·9	0·43	3·8	0·02	36·0	65·6	728	7·9

Physical measurements on drainage water

Conductivity. The mean specific conductivity of the drainage water from the old system at Saxmundham (Tables 7 and 9) varied from 650 to 1003 μmhos cm^{-1} during 1968–72. Largest values were found for drainage from Drain 1 at the northern end of the field and the smallest from Drain 4 that collected drainage in a north to south direction down the field. Conductivities of drainage from the two sections served by the new system were different. Under arable crops it varied from 988 to 1228 μmhos cm^{-1}, under herbage crops it varied from 888 to 866 μmhos cm^{-1}. The mean conductivity of the drainage under the herbage crops during 1972–75 was about 65% of that for the other section which agreed with the smaller concentrations of ions measured in it.

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TABLE 10

Chemical composition of drainage water from Woburn, averaging values from Drains 1–6 (1970–75)

Mean concentration (mg litre^{-1})

		Na	K	Ca	Mg	NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S
1970	March (23/3/70)	12·6	4·9	145·4	9·0	0·00	17·4	0·00	29·5	62·3
	April	13·2	4·3	148·1	8·0	0·09	16·9	0·10	31·7	56·6
	May	11·2	4·0	119·3	8·2	0·27	17·5	0·12	24·7	54·4
	June	10·9	4·5	97·3	7·4	0·13	17·5	0·19	25·3	44·1
	July	10·3	5·5	81·0	7·6	0·35	17·8	0·52	24·4	39·7
	August	10·9	4·8	93·0	7·8	0·00	18·1	0·37	25·9	44·4
	September	10·6	4·3	96·6	7·6	0·12	15·7	0·43	25·2	45·1
	October	10·9	4·5	95·8	7·6	0·01	17·3	0·38	26·3	43·8
	November	12·0	11·2	132·8	9·4	0·04	19·7	0·29	37·2	63·0
	December	11·7	4·5	131·2	8·0	0·17	17·3	0·17	33·3	64·0
1971	January	11·9	4·5	146·8	8·5	0·15	15·9	0·21	31·8	67·0
	February	11·7	4·2	137·7	8·3	0·04	16·4	0·21	29·8	59·6
	March (21/3/71)	11·0	3·6	142·5	10·1	0·00	16·0	0·19	29·3	69·9
	Mean 1970–71	11·5	5·0	120·6	8·3	0·11	17·1	0·24	28·8	54·9
1971	March (22/3/71)	11·3	4·6	143·2	7·7	0·00	14·7	0·13	30·2	59·7
	April	10·9	3·1	123·5	7·8	0·00	15·1	0·17	25·9	62·0
	May	10·8	3·4	126·3	8·2	0·13	15·0	0·22	27·0	54·3
	June	11·0	4·1	117·3	8·7	0·03	14·7	0·23	26·7	46·6
	July	10·3	4·3	105·8	7·8	0·00	17·5	0·32	27·3	47·8
	August	11·1	8·5	105·1	7·9	0·79	17·6	0·30	28·6	46·1
	September	10·7	4·2	103·0	7·9	0·00	17·2	0·31	27·2	52·1
	October	10·0	4·8	100·5	8·0	0·18	15·7	0·31	26·5	42·4
	November	10·6	3·5	127·8	7·3	0·04	14·4	0·16	28·3	51·8
	December	11·3	4·6	157·0	8·7	0·05	15·7	0·20	32·5	64·7
1972	January	11·2	4·1	152·4	8·6	0·03	16·8	0·11	31·9	60·7
	February	11·4	3·9	148·3	8·5	0·01	18·7	0·12	29·9	57·2
	March (15/3/72)	11·5	4·4	144·5	8·4	0·00	17·3	0·12	29·9	57·6
	Mean 1971–72	10·9	4·4	127·3	8·1	0·10	16·2	0·21	28·6	54·1
1972	March (16/3/72)	—	—	—	—	—	—	—	—	—
	April	12·9	4·4	149·5	9·0	0·24	18·7	0·24	35·9	60·9
	May	11·1	3·3	152·4	8·7	0·02	15·7	0·21	29·6	54·8
	June	11·3	4·5	120·5	7·8	0·08	15·3	0·24	29·0	47·4
	July	11·1	3·6	116·1	8·2	0·07	14·5	0·26	28·7	45·1
	August	10·7	3·2	124·7	6·9	0·11	13·6	0·15	29·1	46·4
	September	9·8	4·0	115·0	7·6	0·00	16·3	0·28	26·9	45·4
	October	11·2	6·4	103·0	7·5	0·00	8·3	0·17	30·8	44·5
	November	10·3	3·4	123·1	7·3	0·03	14·4	0·15	30·1	49·1
	December	10·9	7·3	162·7	8·5	0·13	19·5	0·13	35·3	52·2
1973	January	12·0	4·1	146·8	9·8	0·00	16·6	0·17	34·6	67·0
	February	11·3	2·4	162·3	8·4	0·00	15·3	0·12	37·2	66·7
	March (1/3/73)	11·9	2·9	149·7	9·6	0·00	15·4	0·08	32·3	57·7
	Mean 1972–73	11·2	4·1	135·5	8·3	0·06	15·3	0·17	30·0	53·1
1973	March (2/3/73)	—	—	—	—	—	—	—	—	—
	April	10·0	2·9	123·5	7·4	0·01	14·4	0·21	26·8	50·3
	May	12·0	1·9	152·3	8·1	0·02	9·2	0·09	30·5	63·0
	June	11·0	2·6	142·2	7·1	0·00	12·5	0·16	25·1	64·4
	July	12·0	5·3	144·7	9·2	0·00	13·3	0·23	30·6	64·4
	August	10·2	4·0	108·0	6·5	0·05	11·4	0·08	24·0	43·8
	September	10·9	5·9	93·0	5·4	0·00	7·6	0·11	24·4	32·7
	October	11·3	4·4	101·0	6·0	0·00	8·7	0·17	24·2	34·3
	November	13·7	3·9	114·6	6·3	0·18	9·5	0·11	31·4	45·5
	December	11·9	3·6	124·0	7·0	0·00	9·7	0·25	29·7	53·5
1974	January	12·1	4·3	177·7	8·9	0·00	25·4	0·05	49·2	76·7
	February	11·6	3·8	169·7	9·1	0·00	23·5	0·09	40·0	70·6
	March (19/3/74)	14·2	3·2	175·2	8·9	0·00	23·5	0·08	46·3	74·2
	Mean 1973–74	11·7	3·8	135·5	7·5	0·02	14·1	0·14	31·9	56·1
1974	March (20/3/74)	14·1	2·9	172·2	8·8	0·00	24·5	0·08	41·8	63·3
	April	13·0	3·3	161·3	8·7	0·00	18·7	0·16	39·0	71·0
	May	10·9	3·4	140·5	7·6	0·00	16·6	0·22	32·8	53·6
	June	12·4	3·6	128·3	7·8	0·06	16·2	0·16	35·8	49·8
	July	11·6	5·0	114·4	7·0	0·06	16·3	0·21	32·6	43·3
	August	17·8	20·9	179·0	11·9	0·02	33·8	0·28	59·9	54·2
	September	11·4	3·5	138·3	7·0	0·00	14·5	0·22	34·9	50·5
	October	12·4	3·4	158·8	7·3	0·01	17·3	0·02	32·3	57·9
	November	9·3	2·6	143·0	6·4	0·00	15·1	0·11	30·2	45·6
	December	9·6	5·2	166·6	8·4	0·06	17·4	0·09	34·5	52·9
1975	January	9·1	5·0	151·5	8·7	0·00	14·4	0·17	31·3	66·4
	February	11·2	5·2	162·1	8·1	0·01	19·3	0·05	35·8	60·7
	March (14/3/75)	10·6	4·3	139·3	6·6	0·00	19·1	0·00	28·5	46·3
	Mean 1974–75	11·8	5·3	150·4	8·0	0·02	18·7	0·14	36·1	55·0
	Mean 1970–75	11·4	4·5	133·9	8·0	0·06	16·3	0·18	31·1	54·6

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TABLE 11

Average annual concentration of ions (mg litre^{-1}), conductivities and pH values of drainage water from six drains, a stream, and a lake at Woburn, 1970–75

		Drain 1	Drain 2	Drain 3	Drain 4	Drain 5	Drain 6	Spring	Lake
Sodium	1970–71	15·9	9·7	9·4	16·0	9·2	10·1	12·5	19·7
	1971–72	14·4	10·0	9·6	15·0	8·6	9·9	12·8	17·8
	1972–73	13·3	10·0	9·6	18·4	8·9	10·0	12·4	17·0
	1973–74	16·6	10·6	10·2	15·9	9·6	10·2	14·2	15·4
	1974–75	15·4	9·7	8·7	14·9	9·2	10·0	12·3	16·7
Potassium	1970–71	2·9	0·8	4·6	19·6	1·1	5·4	4·1	9·1
	1971–72	2·7	0·7	4·4	12·3	0·7	7·7	4·2	8·7
	1972–73	2·7	0·7	3·7	13·2	0·8	6·4	3·9	8·7
	1973–74	2·9	0·8	2·2	12·4	1·2	5·1	4·8	8·5
	1974–75	2·9	1·4	3·2	19·6	1·7	5·0	3·9	9·0
Calcium	1970–71	150	150	73	237	116	89	86	119
	1971–72	154	152	76	236	121	93	83	114
	1972–73	155	156	83	233	144	94	78	115
	1973–74	165	151	97	271	148	106	102	104
	1974–75	179	150	90	246	136	114	73	121
Magnesium	1970–71	9·0	7·3	10·0	16·0	4·4	5·8	8·6	11·2
	1971–72	9·0	6·2	10·0	15·6	4·5	6·0	8·8	10·9
	1972–73	8·6	6·5	9·4	18·1	7·5	6·3	7·9	12·2
	1973–74	8·5	6·6	8·6	17·2	5·6	6·5	10·1	9·8
	1974–75	9·3	6·0	7·3	15·5	5·2	6·1	7·6	9·8
Ammonium-N	1970–71	0·11	0·12	0·07	0·18	0·11	0·08	0·10	0·49
	1971–72	0·01	0·00	0·01	0·04	0·02	0·38	0·00	0·52
	1972–73	0·03	0·02	0·02	0·03	0·02	0·15	0·03	0·35
	1973–74	0·02	0·01	0·03	0·00	0·00	0·02	0·07	0·27
	1974–75	0·05	0·01	0·02	0·10	0·00	0·01	0·00	0·39
Nitrate-N	1970–71	27·5	18·1	20·3	21·7	6·2	11·6	9·6	2·6
	1971–72	21·7	13·0	19·6	32·2	4·7	11·0	10·2	1·3
	1972–73	21·5	11·8	17·0	33·3	4·8	10·1	9·4	0·9
	1973–74	16·5	11·0	18·8	38·8	11·7	13·4	9·2	1·2
	1974–75	25·4	11·4	11·7	27·1	16·7	15·9	10·3	3·0
Phosphate-P	1970–71	0·16	0·05	0·42	0·05	0·14	0·38	0·14	0·01
	1971–72	0·14	0·01	0·45	0·01	0·10	0·35	0·21	0·04
	1972–73	0·19	0·00	0·36	0·00	0·11	0·33	0·27	0·05
	1973–74	0·06	0·06	0·22	0·02	0·08	0·27	0·16	0·05
	1974–75	0·09	0·00	0·08	0·08	0·14	0·30	0·19	0·01
Chloride	1970–71	45·6	28·9	27·6	49·6	16·0	18·8	38·1	54·1
	1971–72	41·4	26·7	29·1	49·2	12·6	18·6	38·9	50·9
	1972–73	40·7	29·2	30·3	65·3	15·5	19·5	37·2	49·0
	1973–74	47·7	31·2	40·5	55·1	20·6	19·9	44·1	44·7
	1974–75	56·9	30·4	27·8	58·2	18·8	19·6	36·9	51·2
Sulphate-S	1970–71	64·3	53·1	43·9	124·4	40·0	41·7	35·8	60·6
	1971–72	66·1	53·7	43·6	99·5	40·7	42·4	31·8	59·4
	1972–73	64·2	52·1	47·9	103·4	41·0	40·3	27·9	51·5
	1973–74	68·0	54·6	46·1	131·8	47·3	48·3	39·5	45·7
	1974–75	67·8	45·4	41·2	97·2	43·4	42·1	24·2	53·0
Conductivity (μmho cm^{-1})	1970–71	805	720	482	1172	562	493	521	713
	1971–72	800	716	505	1255	576	524	514	670
	1972–73	778	729	508	1286	643	514	490	671
	1973–74	878	750	596	1312	681	585	624	614
	1974–75	977	742	523	1239	681	620	479	718
pH	1970–71	7·2	7·6	6·6	7·8	7·5	7·2	7·6	7·5
	1971–72	7·1	7·6	6·5	7·6	7·6	7·2	7·4	7·5
	1972–73	7·2	7·5	6·7	7·6	7·8	7·0	7·2	7·3
	1973–74	7·4	7·8	7·1	7·6	8·0	7·2	7·7	7·6
	1974–75	7·4	7·6	7·1	7·6	7·5	7·2	7·3	7·6

With the exception of drainage from Drain 4 at Woburn the mean specific conductivities of the other land drains (Table 11) were similar and varied from 470 to 977 μmhos cm^{-1}. Water from Drain 4 had larger values ranging from 1172 to 1286 μmhos cm^{-1}. The flows from this source are always smaller than from the other drains and the concentrations of the ions much larger. On average, water from the spring had smaller conductivity than the land drains except Drain 3 and varied from 523 to 624 μmhos cm^{-1}. Lake water had a mean conductivity of 685 μmhos cm^{-1} in the period 1968–75 and varied from 614 to 730 μmhos cm^{-1}.

Hydrogen ion concentration. The pH of drainage at Saxmundham showed little variation between 1968 and 1975. The mean annual pH from the old system of drains from 1968 to 1972 varied from 7·6 to 8·1 and from the new system from 1972 to 1975 from 7·7 to 8·1.

At Woburn, pH values were least in water from Drain 3 although this had shown an increase from 6·3 in 1968 to 7·1 in the period 1973–75. Mean annual pH was largest in water from Drains 2, 4 and 5 (7·2–8·0). Water from the spring and the lake were similar and varied from 7·1 to 7·6.

Removal of crop nutrients in land drainage

Amounts of plant nutrients lost in land drainage depend not only upon their concentrations and corresponding flowrates but also on how long flows last. Volume of drainage is a function of rainfall, evaporation and the capacity of a soil to retain water. Retention

TABLE 12

Losses of nutrients in drainage ($kg\ ha^{-1}\ year^{-1}$) at Saxmundham (1970–75)

Drain	Na	K	Ca	Mg	NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S
			Old Drainage System (2/3/70–19/3/71)						
1–4*	15	1·0	125	6	0·7	12	0·01	33	43
			(20/3/71–19/4/72)						
1–4*	15	1·9	143	6	0·5	12	0·06	42	37
			* Harwood's Field, 3·03 ha						
			New Drainage System (6/12/72–12/3/73)						
Arable (2)	3	0·2	23	1	0·07	1·6	0·00	16	8
(3)	3	0·3	35	1	0·09	3·6	0·00	15	15
Herbage (4)	2	0·2	17	1	0·06	0·3	0·00	5	9
(5)	4	0·2	22	1	0·08	0·4	0·00	6	12
			(13/3/73–16/3/74)						
Arable (2)	16	1·2	152	6	0·46	14·2	0·02	86	54
(3)	16	0·7	160	8	0·32	14·0	0·01	84	66
Herbage (4)	15	0·7	95	5	0·32	3·4	0·02	26	42
(5)	25	0·9	137	8	0·54	4·7	0·03	33	67
			(17/3/74–26/3/75)						
Arable (2)	52	4·8	590	21	0·67	37·1	0·11	256	194
(3)	47	3·6	579	25	0·69	43·9	0·11	263	209
Herbage (4)	44	2·7	361	18	0·61	11·5	0·05	82	116
(5)	59	2·9	424	20	0·82	10·8	0·07	87	149

Drains 2 and 3 served 1·29 ha under arable crops
Drains 4 and 5 served 1·25 ha under grass and lucerne

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of water is dependent on soil pore size distribution, the depth at which the drains are situated, and the nature of the underlying parent material.

At Woburn the land drains reported here are situated near to the foot of Great Hill where soils with much sand overlie less permeable clays and, with the exception of Drain 4, flow most of the year. The spring at the farm, and Drain 6 which originates in a similar source, flow at all times.

At Saxmundham, periods of continuous flow during autumn to early summer vary from year to year. Residual nutrients become leached by autumn and winter rainfall when this is large. Extension of the periods of continuous drainage into April and May leaches spring applications of nitrogen producing larger maximum concentrations than those often found in early winter drainage. As drainage volume varies greatly from season to season at this site, this and the other factors mentioned influence the estimates of annual losses of nutrients presented here.

Table 12 gives estimates of annual losses in kg ha^{-1} of nutrients in *observed* drainage at Saxmundham calculated from mean flowrates and concentrations of ions for the old drainage system from March 1970 until April 1972 and for the two sections of the new drainage system under arable or herbage crops from December 1972 until March 1975. Table 13 gives the corresponding information for the Woburn drainage system including nutrients transported in the spring source.

Losses of nutrients in land drainage at Saxmundham

The relative magnitudes of the annual losses of nutrients in drainage at Saxmundham for 1968–70 were Ca > SO_4-S > Cl > Na > NO_3-N > Mg > K > NH_4-N > PO_4P. For the last two years of the old system (1970–72) the order was the same except that in 1971–72, Cl was larger than SO_4-S by about 5 kg ha^{-1}. For the new drainage system (1972–75) there were large differences between the amounts lost under the two systems of cropping. More chloride than sulphate was lost under arable conditions than under herbage crops in 1973–75. During the same period more magnesium than nitrate was lost in drainage under herbage. Otherwise the relative magnitudes of calcium, sodium, potassium, ammonium-N and phosphate-P remained the same since 1968.

Less nutrients were lost during 1970–72 from the old drainage system than during the previous two years because total flowrates were about one-half to one-third of those measured in 1968–70 when rainfall was more and evaporation less. Similar amounts were lost in 1970–71 and 1971–72. From 1968 to 1972 the average losses (kg ha^{-1} $year^{-1}$) were about 25 of Na, 2 of K, 220 of Ca, 10 of Mg, 0·4 of NH_4-N, 17 of NO_3-N, 0·05 of PO_4-P, 62 of Cl and 70 of SO_4-S.

Comparing the losses from the old drains with the estimates from the new ones installed in 1972, much larger losses occurred, particularly during 1974–75 which included the period from September to March when rainfall was abnormally large and mean monthly drainage flows (Table 3) were amongst the largest recorded for this site. Nutrient losses during 1972–75, particularly of Cl and SO_4-S, were proportional to the increased flows and concentrations, and were larger than those measured from the original drainage system. During 1973–75 losses under arable cropping (kg ha^{-1} $year^{-1}$) were about 33 of Na, 3 of K, 370 of Ca, 15 of Mg, 0·5 of NH_4-N, 27 of NO_3-N, 0·07 of PO_4-P, 172 of Cl and 130 of SO_4-S. Under herbage crops they were about 36 of Na, 2 of K, 250 of Ca, 13 of Mg, 0·6 of NH_4-N, 8 of NO_3-N, 0·05 of PO_4-P, 57 of Cl and 94 of SO_4-S. These results indicate that the losses from the new drains as a whole were larger than those from the old system that had been installed many years ago and which, due to lack of backfill, probably functioned less efficiently. Losses from the section under herbage

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TABLE 13

Total losses of nutrients from individual drains at Woburn (kg year^{-1})

Drain	Na	K	Ca	Mg	NH_4-N	NO_3-N	PO_4-P	Cl	SO_4-S
				1970–71					
1	76	14	717	43	0·53	132	0·76	218	308
2	46	4	717	35	0·57	87	0·24	138	254
3	8	4	65	9	0·06	18	0·37	25	39
4	11	13	162	11	0·12	15	0·03	34	85
5	9	1	110	4	0·10	6	0·13	15	38
6	88	47	772	50	0·69	101	3·30	163	362
1–6	238	83	2543	152	2·07	359	4·83	593	1086
Spring	537	176	3697	370	4·30	413	6·02	1638	1539
				1971–72					
1	47	9	502	29	0·03	71	0·46	135	215
2	34	2	511	21	0·00	44	0·03	90	181
3	11	5	84	11	0·01	22	0·50	32	48
4	7	6	112	7	0·02	15	0·01	23	47
5	3	0·3	45	2	0·01	2	0·04	5	15
6	78	61	733	47	3·00	87	2·76	147	334
1–6	180	83·3	1987	117	3·07	241	3·80	432	840
Spring	450	148	2918	309	0·00	359	7·38	1368	1118
				1972–73					
1	26	5	301	17	0·06	42	0·37	79	125
2	15	1	238	10	0·03	18	0·00	45	79
3	5	2	39	4	0·01	8	0·17	14	23
4	2	1	24	2	0·00	4	0·00	7	11
5	1	0·1	15	1	0·00	1	0·01	2	4
6	69	44	652	44	1·04	70	2·28	135	280
1–6	118	53·1	1269	78	1·14	143	2·83	282	522
Spring	847	266	5330	540	2·05	642	18·45	2542	1906
				1973–74					
1	38	7	373	19	0·05	37	0·14	108	154
2	24	2	341	15	0·02	25	0·14	71	123
3	3	1	31	3	0·01	6	0·07	13	15
4	4	3	71	5	0·00	10	0·01	14	35
5	2	0·03	31	1	0·00	2	0·02	4	10
6	66	33	691	42	0·13	87	1·76	130	315
1–6	137	46·3	1538	85	0·21	167	2·14	340	652
Spring	416	141	2986	296	2·04	269	4·68	1291	1156
				1974–75					
1	155	29	1797	93	0·50	255	0·90	571	681
2	53	8	820	33	0·05	62	0·00	166	248
3	16	6	166	13	0·04	22	0·15	51	76
4	32	42	530	33	0·22	58	0·17	125	209
5	19	4	286	11	0·00	35	0·29	40	91
6	135	67	1534	82	0·13	214	4·04	264	566
1–6	410	156	5133	265	0·94	646	5·55	1217	1871
Spring	723	229	4290	447	0·00	605	11·16	2168	1422

crops showed a closer relationship with those from the old drains that were under arable crops in two years (1969–70 and 1974–75) when the mean annual flowrates were similar. However, comparing these two periods, the new drains under herbage crops transported twice as much sodium, potassium, magnesium and sulphate, but similar amounts of nitrate, ammonium-N and phosphate.

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Losses of nutrients in land drainage at Woburn

Annual losses of nutrients from the drainage system at Woburn as kg year^{-1}, since the drains serve undefined areas (Table 13) clearly show the influence of larger and more continuous flows on the estimated amounts of nutrients lost from this site compared with Saxmundham. The flow of the spring, since measurements started in 1968, has been larger than the combined flows of all the land drains. Of the land drains, Drain 6 has, since 1969, accounted for almost 50% of the flows from the other drains. These two sources were therefore associated with most of the ions transported in drainage at this site. In common with the drainage at Saxmundham the most abundant ion was calcium but the relative annual losses from the Woburn drains had the same relationships each year since measurements started and Ca > SO_4-S > Cl > NO_3-N > Na > Mg > K > PO_4-P > NH_4-N. For the spring water the same order applied except that chloride exceeded sulphate in 1970–71, magnesium exceeded nitrate-N in 1973–74 and ammonium-N exceeded phosphate in 1969–70.

The losses of nutrients in drainage at Woburn were in general related to the annual rainfall. For each of the periods March to March 1968–69 and 1974–75 the annual rainfall was nearly 760 mm. In the first of these periods rainfall in excess of the 10-year mean occurred from June to September, in the second period from August to November. Less nutrients were lost in drainage during 1968–69 than 1974–75 when flowrates were larger due to less evaporation during the period of excess rain.

The spring had a larger flow during 1972–73 than in 1974–75 although rainfall during this period (414 mm) was only half that in the second period (803 mm). More nutrients were transported in spring water in 1972–73. The reverse was true for the land drains. The reason for this is not known. The spring is recharged from deeper aquifer sources than some of the land drains and its flow could be influenced by factors other than seasonal rainfall.

Of the total losses of ammonium-N and phosphate from all the land drains during 1968–75 those from Drain 6 accounted for 53 and 58% respectively. The shallow nature of this drain after leaving its source on higher land and the use of the fields it traverses to graze cattle suggest organic pollution as being the cause. *Concentrations* of phosphate in water from Drain 3 which had small flowrates were similar to those from Drain 6 but the effective *amount* of phosphate which is the significant factor associated with pollution of river water was greatest in the latter source.

Estimates of losses of nutrients from all the land drains at Woburn during 1970–75 were as follows (in kg) Na 1083, K 422, Ca 12 470, Mg 697, NH_4-N 7, NO_3-N 1556, PO_4-P 19, Cl 2864, SO_4-S 4971. Of these amounts between 30–40% of Na, Ca, Mg, NO_3-N, Cl and SO_4-S were lost in flows from Drain 6 together with 50–75% of the K, NH_4-N and PO_4-P.

The amounts of nutrients transported in the water from the spring in the same period were larger than those lost from all the land drains including Drain 6. Losses were about one and a half times as much calcium, nitrate-N and sulphate-S, and from two to three times as much sodium, potassium, magnesium, phosphate-P and chloride. The amounts of ammonium-N were similar.

Silicon in drainage water

Determinations of silicon in rainwater, land drainage and borehole water from Woburn and Saxmundham were made during 1973–74 (Williams & Messer, 1975). Rainwater contained on average about 0·08 mg litre^{-1} Si, water from Drains 1 to 4 at Woburn about 4 mg litre^{-1} with least from Drain 4; Drains 5 and 6 contained 6–7 mg litre^{-1} and

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the spring about 11 mg litre^{-1}. The lake water contained on average about 2 mg litre^{-1} Si. At Saxmundham, drainage contained about 3 mg litre^{-1} Si. Estimated annual losses during 1973–74 were about 2·5 kg ha^{-1} at Saxmundham from the whole area served by the new drains; losses under the arable and herbage sections were similar. At Woburn, corresponding losses were 21 kg year^{-1} from drains 1 to 5, 41 kg year^{-1} from Drain 6 and nearly 100 kg year^{-1} in the water from the spring.

Summary and conclusions

The flows of land drainage from an old system of drains on a field of 3 ha at Saxmundham in East Suffolk on a soil of the Beccles Series were measured during 1970–72 and the water was chemically analysed for plant macronutrients. The influence of seasonal weather upon drainage flows and compositions was discussed and estimates made of annual losses of nutrients in *observed* drainage. The results were compared with those previously reported for 1968–70. Similar measurements were made on drainage from a new system installed in October 1972 designed to drain, separately, land under arable or herbage crops. The chemical composition and flowrates from the two sections of this new system were compared with the results obtained from the original system. Flowrates from the new system were larger and more persistent than from the old drains and annual losses of nutrients were more in wet years. More nutrients were lost under arable conditions than under leys of cut grass given fertiliser N and lucerne receiving none. Under arable conditions from the old and new drainage systems the relative magnitudes of annual losses in kg ha^{-1} were Ca > SO_4-S > Cl > Na > NO_3-N > Mg > K > NH_4-N > PO_4-P. Under herbage crops, losses of chloride were more than sulphate-S and magnesium more than nitrate N. During a period of excessive rainfall from September 1974 until May 1975 when drainage was continuous and at times large, three times as much nitrate-N (53 kg ha^{-1}) was lost in drainage under arable crops than under herbage (16 kg ha^{-1}). The influence of periods of continuous and discontinuous drainage at Saxmundham upon nutrient losses was discussed with particular reference to applied and residual N.

Corresponding flows and compositions of drainage from soils of the Flitwick, Rowsham and Evesham Series overlying Lower Greensand and Ampthill Clay at Woburn in Bedfordshire were measured during 1970–75 and the results compared with those reported earlier for 1968–70. The chemical composition of water from a lake forming part of the drainage system was also examined.

Larger and more continuous flows at Woburn compared with Saxmundham resulted in larger losses of nutrients particularly from two sources associated with natural springs. More drainage occurs in wet years but the impact of seasonal weather upon drainage flow is less than at Saxmundham and depends more upon soil variability which is greater at this site.

The order of magnitudes of the estimated losses, as kg year^{-1}, at Woburn, were similar to the Suffolk site except that nitrate exceeded sodium—a reflection of the distance of Woburn from the sea; and phosphate was greater than ammonium-N—largely due to the presence of animals grazing a catchment area and to mineral sources in the parent materials at Woburn.

Water from the lake that collects land drainage, as reported earlier for 1968–70, contained less nitrate and phosphate than the water entering it. The concentrations of these two ions limit the growth of aquatic microorganisms and algal 'blooms' are rare.

Silicon determined in drainage at Woburn and Saxmundham was largest in deeper spring sources of water and the annual losses in drainage at these two sites were similar to and slightly less than those for potassium.

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APPENDIX

Methods of analysis and sampling used for the drainage waters

Sampling and flowrate measurement. The same procedures were used for the sampling and analysis of the drainage waters as reported earlier (Williams, 1971). Visual estimates of flows, previously checked against measured volumes, were suitable for small flows but large flows required measurement on a time–volume basis, as not only are these flowrates difficult to assess, but they also transport much larger amounts of nutrients. Ideally, monitoring equipment capable of measuring the wide range of flows found in land drainage should be used, but the method described above is capable of adequate precision so long as observations are made frequently and with due regard to the variability of drainage flows from a particular site. At Saxmundham, daily observations were made, at Woburn where the drainage is more continuous, less frequent readings sufficed.

Samples of drainage were collected in polythene bottles, stored in a cool place in the dark, and delivered to Rothamsted as soon as possible. Determinations of nitrate and ammonium-N were made immediately and for other ions as soon as possible afterwards.

Methods of analysis

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; 40 samples an hour were done and the limit of detection was 0·05 mg litre^{-1} NH_4-N.

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 litre^{-1} NO_3-N.

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 litre^{-1} PO_4-P.

Chloride. Absorptiometrically, using a 'Technicon AutoAnalyzer' and Henricksen's (1966) method. Forty samples an hour were measured with a limit of detection of 0·5 mg litre^{-1} Cl.

Silicon. By the automated method of Wilson (1965) using a 'Technicon AutoAnalyzer'. Forty samples an hour were measured with a limit of detection of 0·01 mg litre^{-1} Si.

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 litre^{-1} SO_4-S.

Conductivity. Using a 'Mullard' conductivity meter.

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

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