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Potassium Concentrations in Surface and Groundwaters and the Loss of Potassium in Relation to Land Use

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Summary

Losses of potassium (K) from the rooting zone of soils are a financial loss to the farmer and the magnitude of such losses is important if it affects the quality of water intended for human consumption. Across a wide range of rainfalls, farming systems, surface soils and underlying geological strata in the UK there is little dramatic change in the range of K concentrations in drainage from either agricultural soils or soils under other land use systems. In upland areas, with less intensive farming and often greater rainfalls, the upper value for the range of K concentrations rarely exceeded 3 mg K l⁻¹. Even in areas of intensive arable production, usually associated with lower rainfalls and smaller quantities of through drainage, water taken from rivers only occasionally had K concentrations approaching 10 mg l⁻¹. From measured losses of K in lysimeters the relationship, K leached (kg ha⁻¹) = 0.012 x drainage + 0.089 ($r^2 = 0.75$) was found. It suggests that for each 100 mm through drainage about 1 kg K ha⁻¹ would be lost.

Potassium in the soil solution is at risk to loss by leaching but its rapid transfer to exchangeable and non exchangeable categories of soil K minimises this risk. Almost all sites capable of holding exchangeable and non exchangeable K would have to be saturated before there was serious risk of large amounts of K being leached from soil. To predict such losses a model (KLEACH) has been constructed to predict the retention of K by 1 cm horizons in soil and thus the risk of K eventually passing out of the soil to streams or aquifers.

Whilst there is little evidence that K in drinking water is detrimental to human health, the maximum admissible concentration of K in drinking water in the EECs Drinking Water Directive is unlikely to be exceeded in most cases. This situation is unlikely to change because most soils have a

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great capacity to retain K and the amount of KCl used as fertilizer is changing little. Increasing levels of chloride in drinking water are associated with ever increasing amounts of chloride in atmospheric deposition not increasing use of potassium fertilizers.

1. Introduction

Much of the water used for human consumption is taken either from rivers and lakes (surface water) or from deeper strata (aquifers) often many metres below the surface. At least within the European Community, there are quality standards for water intended for human consumption. For potassium, the Drinking Water Directive (80/778 EEC) imposes a maximum admissible concentration (MAC) of 12 mg K l⁻¹ with a guide level of 10 mg l⁻¹.

The chemical composition of water leaving surface soils depends on complex interactions which may or may not reach equilibrium as the water passes through air, soil, subsoil and if appropriate, deeper strata. Rain absorbs impurities introduced into the atmosphere by pollution. It then percolates at different rates through top soils of different texture which will have been enriched to varying degrees with soluble salts added to enhance crop growth. It then passes through subsoils with widely ranging chemical and physical properties before being discharged to streams and rivers or, where the lower strata are permeable, into aquifers. This paper discusses factors affecting the concentration of K in water mainly from agricultural soils.

2. Sites and soils

Much of the recent data given here is from five research stations in South Eastern England together with survey data collected from water supply organisations in England and Wales. The research stations together with their soil type and average annual rainfall are as follows. Rothamsted, silty clay loam, 700 mm; Woburn, sandy loam but some light-textured soils overlying Oxford clay, 600 mm; Saxmundham, calcareous sandy clay loam, 600 mm; Broom's Barn, soils developed in glacial drift range from sandy loams to clay loams, 500 mm; Brimstone Farm, clay with more than 93% clay plus silt, 680 mm.

Only at Saxmundham and Brimstone would artificial drainage be considered necessary because the subsoils are only slowly permeable. A new

system of clay pipe drains at 0.8 m depth with pebble (stone) backfill to plough layer was installed at Saxmundham in October 1972 to replace an older system which did not cover all the experimental site. Water was led into the backfill and pipe drains through mole channels made in the soil at 0.6 m depth and 2.7 m spacing using a mole-plough. This consisted of a rigid vertical tine with an enlarged bullet-shaped expander, about 10 cm diameter, at the base of the tine. At Brimstone Farm large, hydrologically separated plots were established in 1978 to study the interaction of cultivation, minimum γ ploughing, and mole and tile drainage γ none, on rates of water loss from soil. Surface runoff, interflow, at the junction of the Ap and subsoil horizons, and drainflow on the drained plots, can all be intercepted, collected and measured. The silty clay loams at Rothamsted do not require under drainage, the water passing through clay subsoils of varying depth into the chalk strata below. However, Lawes and Gilbert installed horseshoe and sole drains, an early form of clay pipe drain on Broadbalk, in 1849 at about 0.7 m depth to aid removal of surface water. There was no pebble backfill. Sandy loams at Woburn and Broom's Barn are free draining, but on parts of both farms surface soils of this texture overlay slowly permeable subsoils and to speed the removal of surplus water from the surface, pipe drains have been installed. Those at Woburn are without backfill.

At all five research stations mainly arable crops are grown and they are generously manured especially with P and K to ensure that these nutrients do not limit growth.

3. The K cycle in agricultural soils

A simplified potassium cycle for agricultural soils recognises various categories or pools of soil K (Figure 1). Their precise definition is less important than the realisation that K can transfer in both directions between categories. Plant roots take up K⁺ from the soil solution and this pool of readily available K can be maintained by adding soluble K fertilizers. K-rich organic manures or by transfer from the readily soluble pool as shown in Figure 1. The term readily soluble K is used here because this is the K extracted by various reagents used world-wide to estimate the availability of K to crops. All methods of analysis will include the water soluble fraction. When 1 M ammonium acetate or 1 M ammonium nitrate are used the K extracted is called exchangeable K because K⁺ held on cation exchange sites

has been replaced by NH_4^+ . But many other extractants have been suggested and a number are widely used today e.g. ammonium acetate/acetic acid at pH 4.8 (Morgan's reagent), calcium lactate, ammonium acetate-lactate (AL) and calcium acetate-lactate (CAL). In general the amounts of K extracted by these reagents are strongly correlated with exchangeable K. For a brief historical review see Johnston & Goulding (1990).

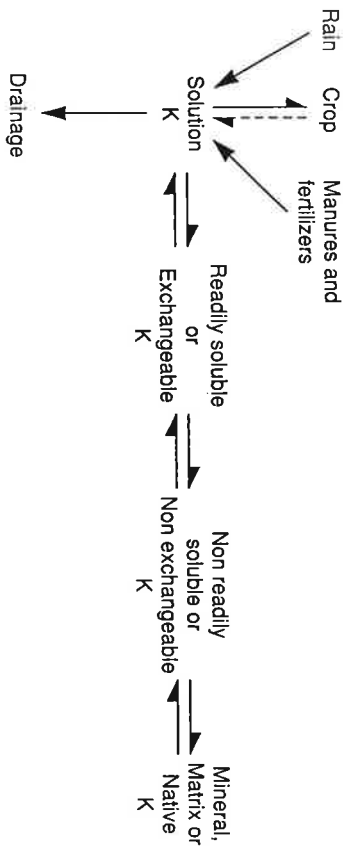


Fig. 1. Categories of soil K in a simplified potassium cycle for agricultural soils.

Figure 1 also shows that K can be lost by drainage. This is a financial loss to the farmer and the magnitude of such losses is important because of the EEC's Drinking Water Directive. However, it is important to recognise that losses in drainage will depend on how rapidly water soluble K residues from fresh applications of fertilizers or manures transfer to readily-soluble reserves, which can be measured using extractants like those listed above, and to non-soluble reserves, which cannot be measured in this way. The reversible transfer of K between the various soil pools shown in Figure 1 is discussed below. However, there is little evidence to suggest that K is released so quickly from the non-readily soluble pool in the absence of a growing crop that such a transfer could increase the risk of K leaching.

4. Transfer of K between soil pools

Examples of the transfer of K between pools were summarised by Johnston and Goulding (1990) using results from a number of long term

field experiments. One, from an experiment on a silty clay loam, is given here as an example (Table 1). This experiment was started in 1854 on a soil which contained 593 mg kg^{-1} exchangeable K. Only small amounts of K were added during the next 100 years whilst clover was grown continuously and the produce removed. This depleted soil K reserves and by 1956 the soil contained only 85 mg kg^{-1} exchangeable K, equivalent to 171 kg ha^{-1} exchangeable K in the top 23 cm (Table 1), and a test of K, applied as KCl, was made between 1956 and 1966. Where K was applied clover yields were increased but the amount of K removed was less than that applied and there was a positive K balance, (balance = amount applied minus amount removed in harvested produce). However, Table 1 shows that only about 42% of this K balance remained exchangeable. The remainder had moved into the non-exchangeable pool in Figure 1 or had been leached below 23 cm. There was little change in exchangeable K on soils not given K despite a negative K balance of nearly 250 kg ha^{-1} . This quantity of K had come from non-exchangeable or non-readily soluble reserves. In subsequent periods of the experiment changes in exchangeable K were always between 30 and 40% of the K balance (Table 1). Because not all of a positive K balance will be accounted for by an increase in exchangeable K, it is impossible to calculate K losses in drainage by subtracting the increase in exchangeable K from the K balance, the two parameters which can be most readily determined.

Table 1. Effect of K balance on exchangeable K in soil, Garden Clover experiment, Rothämsted.

Period	Average K applied annually kg ha^{-1}	Total K balance in period kg ha^{-1}	Exchangeable K, kg ha^{-1} , during each period			Change in exch. K as % of K balance
			At start	At end	Difference	
1956-66	None	-246	171	194	+23	-
	136	+617	171	431	+260	+42
1967	437	+437	194	338	+144	+33
1968-78	250	+1667	375	1065	+690	+41
1979-83	125	-1494	1065	502	-563	-38

5. Early data on losses of K in drainage

In 1868, twenty five years after the start of the Broadbalk experiment at Rothamsted, Dr A. Voelcker analysed the drainage collected from the variously manured plots. At that time very little, if any, K was applied as fertilizer on farms although some K would be recycled through occasional applications of farmyard manure (FYM). The amount of K tested on Broadbalk (90 kg ha⁻¹) is similar to that applied to cereals today so that these early results have relevance to current practice.

Table 2. Concentration of K in drainage water from Broadbalk plots, Rothamsted, in 1868 and estimated annual loss of K.

Treatment	K applied kg ha ⁻¹	K in drainage mg l ⁻¹	K lost kg ha ⁻¹
None	None	1.5	3.7
K ₂ SO ₄	90	2.7	7.0
FYM	220	4.5	11.3

The results (Lawes *et al.*, 1882), summarised in Table 2, showed that although large amounts of K were applied annually both as potassium sulphate and in FYM there was only a small increase in the K content of the drainage from fertilized plots compared to the unmanured. Soils treated annually with FYM, 35 t ha⁻¹, received much more K and, compared with the fertilized soils, the extra K lost in drainage was in proportion to the extra K applied. The amount of K lost from the fertilized soil was very small compared with the loss of Ca (only about 3%) and the authors (*ibid* page 103) commented on this as follows "... the potash and magnesia being to a large extent retained by the soil, ...". The authors (*ibid* page 104) also commented that, "In the absence of drain pipes a part of both the phosphoric acid and potash in the drainage water would doubtless be retained by the subsoil".

These results showed that K could be lost from agricultural soils receiving large amounts of K but the quantities lost were likely to be small; they also suggested that K could be retained in subsoils. Unfortunately there is no information on the proportion of the rainfall passing to these shallow drains. Other data (see Section 8) suggest that the quantities of K lost were larger than might be expected.

6. Soil factors controlling the downward movement of K

6.1. Water soluble K

Warren and Johnston (1962) found a good relationship between water soluble K and exchangeable K where the latter ranged from 100 to 900 mg kg⁻¹ in the top 23 cm of a silty clay loam at Rothamsted. Above 170 mg kg⁻¹ K about 15% of the exchangeable K was water soluble, below this value the proportion was smaller. Whether similar proportions of water soluble to exchangeable K would be found on other soils is not known, nor is it known what the proportion would be in subsoils.

However, water soluble K must be at risk to loss by leaching whenever rainfall leads to water moving downwards through the soil profile. The amount of K moving downwards will depend both on the quantity of water and the speed at which it moves downwards. Water moving quickly through large pores and channels is likely to have a smaller concentration of K than water retained for long periods in small diameter pores.

Once K enriched water has moved from one soil layer to the next the availability of cation exchange sites in the lower layer, and to a lesser extent, the residence time of water in that layer, will govern how much K is removed from the soil solution to be held on cation exchange sites. Thus K can be progressively removed from the soil solution as it passes through the soil. Provided the subsoils contain sufficient cation exchange sites, drainage passing to streams and rivers or to deep aquifers may contain little or no K (see later for further discussion).

6.2. Retention of K in soil

The relationship between movement and retention of K by soil is not a simple one. Table 3 shows the gain in exchangeable K at four depths in a silty clay loam (25% clay) after more than 100 years of applying K as fertilizer or in FYM (Warren and Johnston, 1962). With all treatments there was a much smaller increase in exchangeable K at 46-54 cm than there was in the top 23 cm. However, each soil horizon had not become saturated with exchangeable K before the enrichment of deeper horizons commenced. Table 4 shows the gain in exchangeable K at four depths in a sandy loam soil when FYM and FYM composted with additional vegetable material (FYM compost) were each added at 37.5 and 75.0 t ha⁻¹ annually for 20 years. All plots received a small application of K as fertilizer. Results from this experiment are quite different to those in Table 3. On the lighter

textured soil (10% clay) the 23-30 and 30-46 cm horizons for each treatment contain as much extra exchangeable K as the ploughed surface soil (0-23 cm), and there is only a little less in the 46-61 cm layer. In both experiments the increase in exchangeable K was related to the amount of K added and although the increases were large, the largest values were still less than 10% of the cation exchange capacity. The difference in behaviour between the two soils, the development of a K profile with depth in the Rothamsted soil compared to almost uniform enrichment in the Woburn soil, is probably related to the rate at which water flowed downwards through the profile and the speed at which K exchanged with adsorbed cations.

Table 3. Amount of K added and exchangeable K at four depths on a silty clay loam.

Depth cm	Treatment and K added, kg ha ⁻¹			
	No K none	FYM 16700	PK 20500	FYM & PK 28800
0-23	119	174	380	641
23-30	129	104	179	386
30-46	139	23	102	225
46-54	152	-2	79	152

Table 4. Amount of K added and exchangeable K at four depths on a sandy loam.

K added kg ha ⁻¹ in fertilizer in organic manure	Treatment and rate *				
	NPK	FYM 1	FYM 2	FYM compost 1	FYM compost 2
950	950	950	950	950	950
0	5450	10850	3950	950	7850
Depth cm	Exch K mg kg ⁻¹	extra exch K, mg kg ⁻¹ , over NPK			
0-23	111	163	266	144	205
23-30	101	169	265	137	213
30-46	93	174	268	134	226
46-61	83	143	226	91	186

* rate 1, 2: 37.5, 75 t ha⁻¹ fresh organic manure each year for 20 years.

6.3. Modelling K leaching

The data given above show that exchangeable K and, presumably, non-exchangeable K is increased at increasing depths within the soil profile as K moves downwards in drainage. Also each soil horizon does not become "saturated" with readily soluble K before K enrichment of the lower horizons starts. It would be of great benefit to have a model that predicted this build up of K and also the risk of K moving so far down the profile that it is lost from the soil in drainage either to streams or to aquifers.

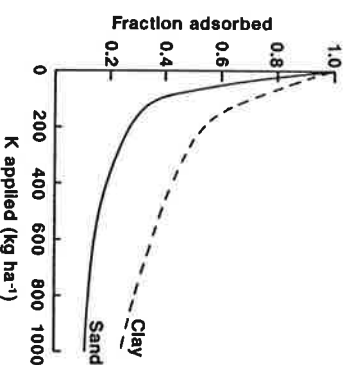


Fig. 2. The relationship between the fraction of K adsorbed by two soils and the K applied.

A model (KLEACH) has been constructed to do this. It is based on data for K adsorption (Goulding and Talbudeen, 1984) which, after modification to allow for non-equilibrium conditions during leaching, is used to generate curves like those in Figure 2. They show the fraction of an application of K that would be retained by a layer of soil 1 cm deep. As expected, the larger the amount applied, the smaller the fraction adsorbed although the amount adsorbed will be larger. The model calculates the fraction of K retained in each successive 1 cm layer as the K, less the amount retained in the previous layer, moves down through the soil. The model output is of the distribution of the applied K through the soil profile. The two examples in Table 5 show that eventually all the K is adsorbed. Depending on the depth of the soil to the field drains or to the water table the risk of K, and the amount of K, being lost can be assessed.

Table 5. Predicted K distribution from applied manures through two arable soil profiles.

Soil layer 1 cm depth	Soil type and K added, kg ha ⁻¹	
	Clay loam soil 200 kg K as KCl	Sandy soil 800 kg K as slurry
	K adsorbed, kg ha ⁻¹ , in each 1 cm layer of soil	
1	114	96
2	64	85
3	20	75
4	2	67
5		60
6		56
7		52
8		49
9		48
10		48
11		48
12		46
13		39
14		23
15		7
16		1
17		
18		
19		
20		

At present the model has been used to predict K distribution for several soils ranging in clay content from 3 to 50%, but only one set of climatic conditions. It can be modified for other climates and agricultural systems. It can be made to take account of increasing amounts of exchangeable K in surface soil from past applications of inorganic fertilizers and organic manures. It can also be extended to allow for changes in amounts of clay down the profile.

7. K in rainfall

Table 6 shows the mean K concentration and range in rainfall collected at Rothamsted, Woburn and Saxmundham during the years 1969-73 and at Rothamsted, Woburn and Broom's Barn during 1986-91 together with the amount of K added to soil each year. The K concentrations were similar at all four sites, the average ranged from 0.22 to 0.72 mg l⁻¹ and only small amounts of K, 1.4 to 4.5 kg ha⁻¹, were added to soil in rainfall. These amounts are within the range 1.1 to 9.6 kg ha⁻¹ K reported by Low and Armitage (1970) for sites in England, Germany, Sweden and Australia. They recorded one very large value, 39.3 kg ha⁻¹ K, for a site in South Africa but no explanation was offered.

Table 6. Mean annual concentration and content of K in rainfall at four experimental stations in South Eastern England.

Site	Annual rainfall mm	Concentration mean	mg l ⁻¹ K range	K added to soil kg ha ⁻¹	
Rothamsted	1969-73	619	0.72	0.1 - 3.8	4.5
	1986-91	682	0.22	0.2 - 0.4	1.5
Woburn	1969-73	548	0.39	<0.1 - 1.0	2.1
	1986-91	625	0.23	0.1 - 0.5	1.4
Saxmundham	1969-73	574	0.55	<0.1 - 2.4	3.2
	1986-91	574	0.25	0.1 - 0.4	1.4

8. K in drainage water from experimental soils

8.1. The effect of soil pH on losses of K

One consistent effect, noted in published work where comparisons were made, was that the addition of CaCO₃ to soil, liming, caused a decrease in leaching losses of K (see Munson and Nelson, 1963 and references therein). Johnston (1988) summarised data from laboratory experiments made on soils from long-term experiments at Rothamsted which had very similar clay contents and mineralogies but different pHs, range 5 to 8, and different levels of exchangeable K, range 80 to 940 mg kg⁻¹, as a result of past treatments over many years. In the laboratory increasing amounts of K were added to the soils which were put through a 12-week cycle of alternate wet

and dry periods each lasting one week. For each soil the proportion of the added K which remained exchangeable was independent of the amount of K added and about 15% of the exchangeable K was water soluble. However, a larger proportion of the added K remained exchangeable in the acid soils, pH 5 to 6, than in the neutral soils, pH 7 to 8. Therefore more of the K added to the acid soil was water soluble and at risk to leaching down the profile.

Soils of similar mineralogy are likely to have a smaller CEC when acid than when alkaline, thus acid soils can hold less exchangeable K. Also, Ca^{2+} ions occupy a larger proportion of the CEC in neutral than in acid soils and K^+ can more readily replace Ca^{2+} than Al^{3+} or H^+ ions. Thus again, more K will be retained as exchangeable K in alkaline soils.

8.2. K in drainage from lysimeters

For all their limitations lysimeters still offer an acceptable, often the only, practical way of measuring losses of plant nutrients from soil.

In 1919, 0.0004 ha monolith lysimeters 1 m deep were set up at Craibstone at the North of Scotland College of Agriculture (Hendrick and Welsh, 1927). The soil, light textured and granitic, contained 1.25% K much of which was in feldspars which had undergone little weathering. From 1921 the three lysimeters were either unmanured or received FYM with N and P fertilizers with and without limestone. These treatments were applied only to turnips, the first crop in the six-course rotation: turnips, oats, grass hay, grass cut, grass cut and oats grown between 1921 and 1926. The amount of K applied was 170 kg ha⁻¹ in 30 t ha⁻¹ FYM. Average annual rainfall was 870 mm and annual through drainage of 470 mm differed little between lysimeters. On average, the drainage from the three lysimeters contained almost identical concentrations of K, average 2.5 mg l⁻¹, range 2.2 to 2.9. Thus the amounts of K lost each year were nearly the same 9.8, 9.2 and 8.6 kg ha⁻¹ from the unmanured, manured without lime and manured with lime treatments respectively. Least K was lost in the first year when the K was applied because there was least through drainage.

In 1951 monolith lysimeters, 88 cm deep, were set up at ICT's Jealotts Hill Research Station in Southern England (Low and Armitage, 1970). The top 23 cm of soil was a sandy loam with 160 mg kg⁻¹ exchangeable K. Below 23 cm the subsoil was a coarse sand. The lysimeters were either without a crop (fallowed) or grew grass or clover. Before sowing the seeds in July

1951 all the lysimeters received the equivalent of 280 kg ha⁻¹ K. Initially the leachate was analysed mainly for mineral nitrogen but for three years 1953-55 other cations and anions were measured. The average annual loss of K was 4.7, 1.9 and 2.0 kg ha⁻¹ from the fallow, grass and clover lysimeters respectively. The volume of leachate from the fallow lysimeter was almost double that from the cropped lysimeters, thus the concentration of K in all the leachates was similar and independent of cropping. The amounts of K lost were much less than the 10 kg ha⁻¹ K deposited in the 650 mm of rainfall, even on the lysimeter without a crop. Surprised by the small losses of K in the leachate and concerned that much K might have been lost in the 17 months between the application of K fertilizer and the commencement of measurements, the authors determined the K fixation capacity of the top 15 cm of soil in the laboratory. They added the equivalent of 305 kg ha⁻¹ K, as K_2HPO_4 , to the soil and then left it to equilibrate for either three hours or nine days before leaching the soil slowly with the equivalent of 500 mm of rain. After only three hours equilibration only about 6% of the added K was in the leachate whilst after nine days the amount was less than 1% of that added. Thus it is unlikely that there had been large losses of K from the lysimeters before measurements were started and the small losses recorded are representative of what would happen on a field scale even on light textured soils.

8.3. The relationship between drainage and losses of K

Most quantitative data on losses of K from soil are from lysimeter studies. From some of the data in the literature and some given here, it was possible to construct the relationship between drainage and K losses in Fig. 3. The data are from North America and Europe between 1920 and 1990. The lysimeters were mostly monolith lysimeters ranging in depth up to 1 m. The soils varied from sands to clays; some were cropped, some fallowed; some were given K, others not. The period of measurement varied from one to ten years but only data for whole years were used here and where possible averages of a group of years were taken.

Across this wide range of soils, climates, cropping and manuring, K leached, in kg ha⁻¹, and drainage, in mm, were related:

$$\text{K leached} = 0.012 \times \text{drainage} + 0.089 \quad (r^2 = 0.75, p < 0.001)$$

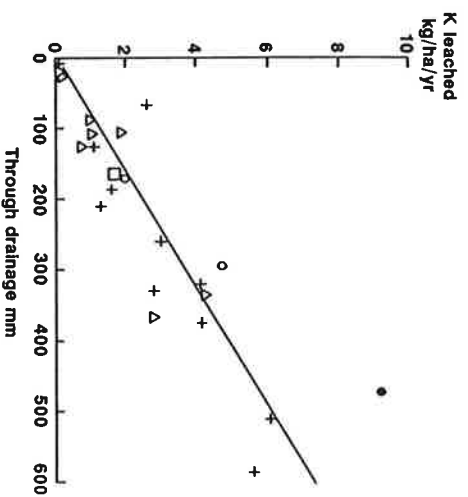


Fig. 3. The relationship between the amount of potassium leached from soil and the quantity of through drainage.

This suggests that, on average, for each 100 mm through drainage, about 1 kg ha⁻¹ K would be lost. The major outlier in the relationship is the soil from Craibstone, Scotland. Here in both manured and unmanured but cropped lysimeters, the amount of K lost was the same. One factor which seemed to distinguish this site, and was occasionally seen in other data sets, was that K losses were larger than expected when the amount of drainage exceeded 50% of the rainfall.

8.4. K in drainage from field soils

Between 1968 and 1974 drainage water was sampled regularly whenever drain flow occurred at Rothamsted, Woburn, Saxmundham and Broom's Barn (Williams, 1976). At Saxmundham, K concentrations were small and varied little throughout the period (Table 7). Six drains were sampled at Woburn and the mean concentration of K from all the drains was twice that at Saxmundham. Three of the drains which flowed regularly had a mean K concentration of 2.6 mg l⁻¹ whilst another which flowed only intermittently had about 14.9 mg l⁻¹ K. Large concentrations of K in drainage have been recorded occasionally also at Broom's Barn. They invariably followed a period of dry weather when there had been little or no drain flow.

Table 7. Mean annual concentration of K in drainage water, at four experimental stations in South Eastern England.

Site	Period	Concentration mg K l ⁻¹
Saxmundham	Mar 68 - Mar 70	1.6
	Nov 70 - Mar 72	2.4
	Dec 72 - Mar 74	1.4
	Mar 74 - Mar 75	1.2
Woburn drains	Mar 68 - Mar 70	5.0
	Mar 70 - Mar 74	5.2
Woburn stream	Mar 68 - Mar 70	4.2
	Mar 70 - Mar 74	4.3
Broom's Barn	Jan 70 - Feb 74	0.28
	Jan 86 - Dec 92*	0.26
Rothamsted	Jan 70 - Feb 74	15.8

* excluding 1990-91

In the absence of flow meters and an accurate knowledge of the area drained by each drain it was not possible to calculate losses of K in kg ha⁻¹ but they might have been more nearly the same than were the concentrations in drainage. The composition of water in a small stream at Woburn remained remarkably constant (Table 7). Water flow is maintained by a spring on the farm and it was thought that the water comes from deep drainage from soils on the farm. Drain flows at Broom's Barn during 1970-74 were extremely variable and intermittent; the range in K concentrations was 0.2 to 7.3 mg l⁻¹. In this first period three drains had an average K concentration of 0.3 mg l⁻¹ and these three drains were sampled again during the period 1986-1991 whenever possible, although drain flow was even more intermittent than previously. Average K concentrations in this second period were almost identical to that in the first period (Table 7).

There is data for only one drain at Rothamsted in Table 7. The mean K concentration, 15.8 mg l⁻¹, is large and the reason is unknown. The concentration is certainly much in excess of that recorded for the Broadbalk plots (Table 2). The drain is shallow, 0.6 m, and it probably collects water from a small catchment of a few hectares. The maximum K concentration recorded, 40 mg l⁻¹, was matched by large Ca and NO₃-N concentrations (see Section 11).

The concentration of K in drainage at Brimstone Farm under well fertilized arable crops has only been measured throughout one drainage season, 1979/80 (Harris *et al*, 1984), largely because the concentrations of K in drainage were very small, range 0.5 to 3.5 mg l⁻¹. On drained plots, i.e. those with clay pipe drains with pebble back fill into which mole channels discharged, 1.18 kg ha⁻¹ K was lost in water draining from depth. There was much less K, 0.49 kg ha⁻¹, in the smaller volumes of water removed as surface run off and interflow. On undrained plots most of the excess water moved laterally through the soil as surface runoff and interflow and these removed 0.50 and 0.87 kg ha⁻¹ K respectively. Thus the total loss of K from both treatments was small and similar, 1.67 and 1.37 kg ha⁻¹ from drained and undrained soils. In practice all three types of drainage would discharge to streams and rivers. However, the method or speed at which the drainage reached the stream had little effect on the amount of K lost.

9. K in boreholes on experimental farms

Boreholes into the underlying aquifers exist at Rothamsted, Broom's Barn and Woburn. It is assumed that the local hydrology causes a continuous flow of water out of and into the borehole. Certainly the water level varies appreciably throughout a 12 month period. They have been sampled as dipwells regularly each month for some years. The exception is the Rothamsted Farm borehole where the sample is taken by pumping out about 20 l of water on each sampling occasion.

The Rothamsted Farm borehole is deep (99 m); it goes into the chalk at 13 m and the depth to the water is 35 m. It is used to extract water for irrigating experimental crops. The mean K concentration and range has changed little between two periods 1968-74 and 1986-91 (Table 8). As part of a study of the movement of nitrate into aquifers, two shallower boreholes were drilled into the chalk in the late 1970s. That at Knott Wood goes into chalk at 1 m and the water is at 15 m. It is situated under deciduous woodland on sloping ground. Water from this shallow borehole had K concentrations remarkably similar to those in the much deeper Farm borehole about 500 m away.

Table 8. Concentration of K in borehole water at three experimental stations in South Eastern England.

Site	Period	Depth to water, m	Concentration mg K l ⁻¹	
			mean	range
Rothamsted Farm	1968 - 74	99	0.9	0.8 - 1.6
	1986 - 91		1.2	1.0 - 1.4
Knott Wood Highfield	1986 - 91	15	1.2	1.1 - 1.2
	1986 - 91	45	2.7	2.3 - 3.9
Broom's Barn	1970 - 74	29	4.4	3.8 - 7.6
	1986 - 91		4.2	4.0 - 4.3
Woburn	1988 - 91	7	2.1	1.9 - 2.2

The borehole on Highfield reaches chalk at 15 m and the water at 45 m. It is on flat ground on the edge of a large experiment on ley arable farming systems with other arable cropping adjacent. Over a six-year period the water contained only 2.7 mg l⁻¹ K. The borehole at Woburn was drilled in 1978 to sample water from a sandstone aquifer underlying intensive arable cropping for nitrate studies. The nitrate analyses suggest that the water quality responds rapidly to treatment at the surface and there was some indication that K concentrations increased briefly following large applications of KCl. This rapid response is perhaps not surprising because the depth to the water is only 7 m. However, the average K concentration over four years was only 2.1 mg l⁻¹, very similar to that at Rothamsted. The Broom's Barn borehole is sunk into chalk overlain by mainly coarse texture soils heavily fertilized with K for sugar beet in particular. The depth to the chalk is 11 m and the water is at 29 m. Of the five boreholes sampled this water had the largest K concentration, just over 4 mg l⁻¹, but the K concentration changed little over a 20 year period and was still well below the EEC guide level of 10 mg l⁻¹.

10. K in water, the regional picture in England and Wales

During the period 1968-74, Williams (1976) analysed the water supplied to the laboratories at Rothamsted and Woburn by their respective water supply companies. At Rothamsted the water was blended from three deep boreholes in the chalk and 98 samples averaged 1.3 mg l⁻¹ K (range 0.9 to 4.8). At Woburn the 70 m deep borehole is in a sandstone aquifer and 67 samples averaged 3.4 mg l⁻¹ K (range 2.4 to 6.4).

By 1987 the Polish Development Association in Britain was concerned about the Maximum Admissible Concentration (MAC) for K in water supplied for human consumption under the EC Drinking Water Directive. At that time water supply was the responsibility of Regional Water Authorities. Each Authority was asked to supply what information it could on the concentration of K in potable water. All were able to supply data with varying degrees of detail and in different formats, usually for years around 1986, and the information is discussed briefly here by courtesy of J.D. Hollies (personal communication).

None of the Authorities saw a problem either then or in the foreseeable future to supply water below the MAC limit. One Authority pointed out that larger than normal levels of K can indicate pollution, for example by leachate from land-fill sites, which usually leads to more detailed investigation, especially for possible organic and inorganic pollutants and microbial contamination.

There were some interesting similarities and differences within the data which relate not only to the agriculture of the region but also to estimates of the mean excess winter rainfall which can result in either surface run off or through drainage. Excess winter rainfall can be put into three bands, less than 150 mm, 150 to 250 mm, and more than 250 mm, and the Water Authorities grouped by having most of their catchments in one of the three bands.

Regions with predominantly more than 250 mm excess winter rainfall include Wales, the North West, South West and Wessex. Welsh Water get their supply from 260 sources which can be grouped as: upland surface water mainly derived from streams and reservoirs draining peaty or afforested catchments with K concentrations which ranged from 0.2 to 2.5 mg l⁻¹; lowland surface water mainly taken from the middle and lower reaches of rivers contained 2.0 to 7.5 mg l⁻¹ K, and similar concentrations, 2.5 to 9.5 mg l⁻¹, were found in groundwaters derived mainly from aquifers in limestone or stony gravel at shallow depths. Like Welsh Water, North

West Water also derives its supplies from upland reservoirs, lowland rivers and boreholes. It also noted that upland reservoirs directly fed by streams had the lowest K levels. Averaged over all supplies, concentrations ranged from 0.5 to 6.0 mg l⁻¹ K. In both regions water which could be draining from agricultural land into lowland rivers and shallow aquifers had a larger K concentration than that from upland areas. Welsh Water noted that K concentrations showed seasonal variation but this may relate to the volume of water flowing into the reservoirs or streams at any one time. Similarly, South West Water supplying Devon and Cornwall, which are mainly livestock areas, recorded an average of 1.5 mg l⁻¹ K (range 0.4 to 5.0) over two years and 52 sources.

Northumbrian Water in the North East of England has about half the area with 150 - 250 mm excess winter rainfall and the rest over 250 mm. It covers an area with mainly low input agriculture and forestry. Data for 23 water supply sources gave a mean of 1.6 mg l⁻¹ K (range 0.6 to 3.7). There was one value of 15 mg l⁻¹ K out of 12 observations at one site (see Section 11). On the other hand Southern Water with more than half the area with more than 250 mm but mainly arable agriculture, reported K concentrations usually below 3 mg l⁻¹ and with maximum values of 6 mg l⁻¹.

Yorkshire Water, Anglia and Thames have about two thirds of their areas with 150 - 250 mm excess winter rainfall. Yorkshire with the remaining third over 250 mm covers an area of variable geology and farming and includes some large industrial conurbations. It divides its region into zones. The Pennine area with low input stock rearing had K concentrations ranging from 0.5 to 2.0 mg l⁻¹ and this range was very similar to that (1 to 2 mg l⁻¹) in the East of the region where water is taken from chalk boreholes but where the agriculture includes the intensively farmed Vales of York and Pickering. Water supplied from sandstone boreholes in the south east of the region, in an area of arable cropping, and that in the north of the region, the Northern Springs, with more mixed farming, both had K concentrations in the range 1 to 3 mg l⁻¹. By contrast, Anglian Water has the other third of its area with less than 150 mm excess winter rainfall and it covers the eastern counties of England with the largest concentration of arable agriculture. Recorded K concentrations were normally between 1 and 6 mg l⁻¹; thus the largest values in the range are greater than those in the Yorkshire region. Anglia also has one or two geologically old underground waters with up to 14 mg l⁻¹ K. They consider that these levels are naturally occurring and the Authority has been granted derogations under the EEC Drinking Water Directive. It is interesting that

some other spring waters derived from underground sources also have larger K concentrations than those found in surface waters. It should also be noted that Welsh Water reported that groundwaters derived from limestone aquifers had the largest concentrations of K in their region although these were still below the MAC.

Severn Trent Water in the central midlands and Wessex Water in the Bristol region together with Somerset and Dorset are both in areas of mixed arable and animal husbandry. Wessex Water, with the majority of its region with more than 250 mm excess winter rainfall, has 130 different sources of supply and K concentrations range from < 1 to 10.6 mg l^{-1} . Severn Trent, with most of its region with 150 to 250 mm, has 259 sources which supplied 1704 million litres a day with K concentrations ranging from < 1 to 5 mg l^{-1} and a further 20 sources which supplied 315 M l day^{-1} with 5 to 10 mg l^{-1} K. Thus the range of K concentrations appears to be little affected by the quantity of excess winter rainfall.

It is interesting to compare the range of K concentrations in UK drinking waters with those in bottled mineral waters. Nine bottled waters, available widely in the UK, declared the K concentration on the label. These values ranged from 0.3 to 5.7 mg l^{-1} K (mean 2.2 mg l^{-1}).

11. Large concentrations of K in drainage

Attention has been drawn to the large concentration of K in one of the Rothamsted drains, most probably due to pollution, and in one source of supply on one occasion in data from Northumbrian Water (Section 10).

Van Schreven (1970) also reported very large losses of K in drainage during 1962-66 from the Eastern Flevoland polder which emerged from the water in 1957. Rainfall averaged 854 mm each year and added about 7 kg ha^{-1} K. On average 162 kg ha^{-1} K (range 105 to 226) was lost each year in drainage from the polder; the concentration of K was not given. These losses are very much larger than others given in this paper. The large annual rainfall, the shallow depth of soil above the water table and the very recent commencement of drainage probably all contributed to the large loss of K. Smaller losses, 54 kg ha^{-1} K, were reported in 1963-64 for the North eastern polder (emerged from the water in 1942), so the age of the polder was probably important. Unfortunately the amounts of Na lost were not given, neither was the ratio of Na to K in the drainage or in nearby sea water, which might have allowed the K losses to be related to the drainage of water which previously saturated the soil. The soil was described as very heavy

with the clay fraction containing about 80% illite and initially much exchangeable K. It is difficult to see why the true exchangeable K content should have fallen on drainage but as pointed out previously "exchangeable K" as measured analytically will include water soluble K held in the soil matrix. This water soluble K may have been a large proportion of the initial exchangeable K and would have been lost on drainage. It is also possible that the oxidation of organic matter decreased the CEC which would have released K, and that the disintegration of clay minerals on drying after many years of immersion in water released fixed K.

It is almost certain that these exceptionally large losses of K were not related to the use of fertilizers or manures because the amounts of N lost were very much smaller, about 15 kg ha^{-1} N each year, from both polders. This was only about 10% of the K lost from the Eastern Flevoland polder.

It would be helpful in future if authors reporting larger than anticipated K losses from soils, or water supplies or drainage with large concentrations of K, could attempt to offer an explanation. If this is not done then those responsible for framing legislation do not know whether to ignore the values as aberrant or take them into serious consideration when deciding on limiting values.

12. Conclusions

The reason for setting a maximum admissible concentration of 12 mg l^{-1} K in the EEC Drinking Water Directive is not known to the authors of this paper. If organisations supplying water for human consumption can use K concentrations as an easily measured indicator of possible contamination of sources of water supply then this is good but within a Directive the choice of any MAC should be soundly based.

At present water supply organisations in England and Wales foresee little difficulty in supplying water with less than 12 mg l^{-1} K. Across a wide range of rainfalls, farming systems, surface soils and underlying geological strata in the UK there is little dramatic change in the range of K concentrations in drainage from either agricultural soils or soils under other land use systems. In upland areas with less intensive farming and often greater rainfalls, the upper value for the range of K concentrations rarely exceeded 3 mg l^{-1} K. Even in areas of intensive arable production, usually associated with lower rainfalls and smaller quantities of through drainage, water taken from the middle or lower reaches of rivers and from boreholes

only occasionally had K concentrations approaching 10 mg l⁻¹. It is unlikely that this situation will change appreciably in the foreseeable future. One possible cause for increased losses of K in drainage could be that sites capable of holding exchangeable and non-exchangeable K in both topsoils and subsoils become saturated. This seems very unlikely except on the very highest textured soils. On such soils good farm practice applies K annually in amounts sufficient to match crop requirement.

Current awareness of increasing levels of chloride in water must not be linked to the use of KCl fertilizers which has changed little in recent years. Goulding *et al* (1986) showed that chloride deposited in rain increased through the 1970s and 1980s in some areas and has continued to increase in recent years.

The use of K fertilizers is increasing only very slowly and, with present rates of use, the national K balance is very small. Church and Skinner (1986) calculated K balances for England and Wales in 1982 for winter wheat, spring barley, oilseed rape and potatoes. For all four crops the K balance was positive based on average national yields and % K in dry matter and data from the Survey of Fertilizer Practice on the average amounts of K applied to each crop. However the balance was small; for winter wheat, 4 kg ha⁻¹ K, for spring barley 21 kg ha⁻¹ and for oilseed rape 12 kg ha⁻¹. It was much larger for potatoes, 69 kg ha⁻¹, but because potatoes are not grown frequently and often only on the lighter textured soils then the effect on the overall national K balance for arable rotations is likely to be small. Incorporating straw into soil because of the ban on straw burning, will make little difference to the national K balance for cereals because much of the K in the straw was returned to the soil in the ash and this was allowed for in these calculations.

With only a very small positive K balance for agriculture in England and Wales and little change likely during the coming years, with many soils having a large capacity to retain both exchangeable and non-exchangeable K, there seems little prospect that the concentration of K in drainage from agricultural land will increase to levels which could cause problems for water supply organisations to meet the maximum admissible concentration of K, 12 mg l⁻¹, imposed by the EEC Drinking Water Directive.

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