THE EFFECTS OF DRAINAGE FROM SURFACE IRRIGATION WITH TREATED SEWAGE EFFLUENT ON GROUNDWATER QUALITY AT TEMPLETON

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ABSTRACT

Chemical analysis of percolating soil water has enabled the effects of sewage effluent irrigation on groundwater quality to be interpreted more effectively. Drainage from the effluent irrigation, which was higher in NO_3–N, Ca and Mg than the effluent, but lower in NH_4–N and K, has resulted in increased concentrations of NO_3–N, Cl, Na and Ca in the groundwater, the effect being most marked in the wetter winter months when drainage losses are greatest.

INTRODUCTION

The Templeton sewage effluent irrigation scheme, situated on the Canterbury Plains 10 km south-west of Christchurch, was commenced in 1958. The oxidation pond effluent from a population of 1600 is surface irrigated onto 25 ha of pasture which is used for grazing sheep. The depth of soil (Templeton silt loam), varies considerably over the irrigation area (Martin 1976), but probably averages less than 1 metre. The soil is underlain by several hundred metres of alluvial material of the Springston formation (N.Z. Geological Survey). The annual effluent application is 840 mm (Quin & Forsythe 1978), and the total annual drainage resulting from this and the annual rainfall of 760 mm was calculated to be 900 mm.

In 1975, due to the increased interest in the use and effects of wastewater irrigation in New Zealand, and the lack of available information (Stevenson 1976), the Water and Soil Division of the Ministry of Works and Development commenced investigations at both the Templeton and Burnham sewage effluent irrigation schemes (Fig. 1), to establish whether the groundwaters below and downstream of the schemes were being contaminated, and, if so, to determine the dispersal, dilution and 'die–off' characteristics of the contamination.

Seven investigation bores were drilled at each scheme, one upstream of the oxidation ponds, two at the lower end of the irrigation areas, and another four more or less in line along a groundwater 'flow line' downstream of the schemes. The layout of the Templeton bores is shown in Fig. 2. Each bore was lined with

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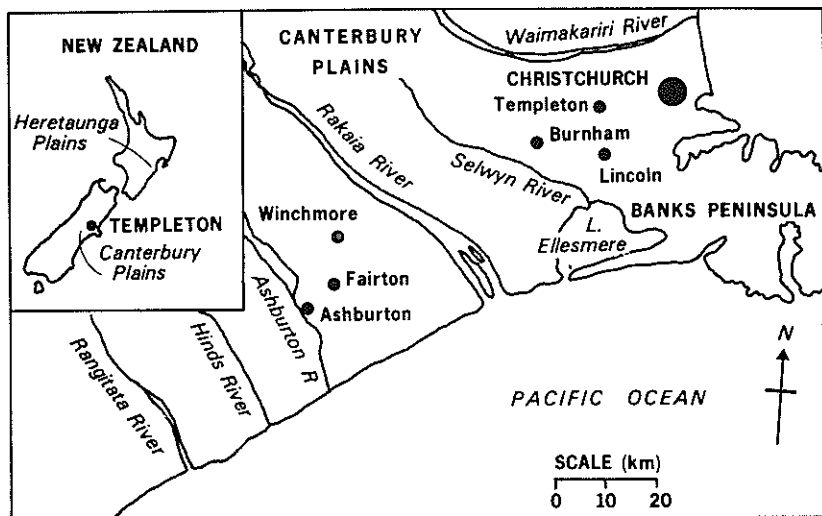
FIG.— 1 Canterbury Plains, New Zealand, showing location of Templeton and other study areas.

a PVC tube which was dotted over the lower 6 m, about 5 m of this being below the water table, which is approximately 13 m below ground level.

Intensive sampling of these bores was carried out during the period April 1975 to March 1976. Martin (1976) and Martin and Noonan (1977) reported that: "No direct evidence of chemical contamination of the aquifers downstream of the Templeton scheme was found. However, groundwater concentrations of several ions were substantially higher downstream of the scheme than was to be expected in comparison with the results of the baseline survey and in relation to the results from the upstream control bore." Subsequent to these reports, Quin & Forsythe (1978) reported data for 200 samples of percolating soil-water collected on the Templeton effluent irrigation scheme during the period June 1975 to May 1977. These data, together with more recent groundwater analysis, permit the effects of effluent irrigation on groundwater quality to be interpreted more clearly.

EXPERIMENTAL PROCEDURE

Samples of percolating soil–water were collected with PVC suction lysimeters (Quin & Forsythe 1976), most samples being taken from 20 sites within the boundaries of the three circles marked in Fig. 2. The groundwater was sampled with a weighted narrow slotted PVC cylinder, which was dropped rapidly to the desired sampling depth. The sampler filling time was sufficently long (>30 sec) to ensure that the amount of water entering the sampler during the drop was insignificant. The sudden change in chemical composition with increasing depth found in one of the bores (see text) demonstrated that this sampling technique is sufficiently depth distinctive for chemical analysis.
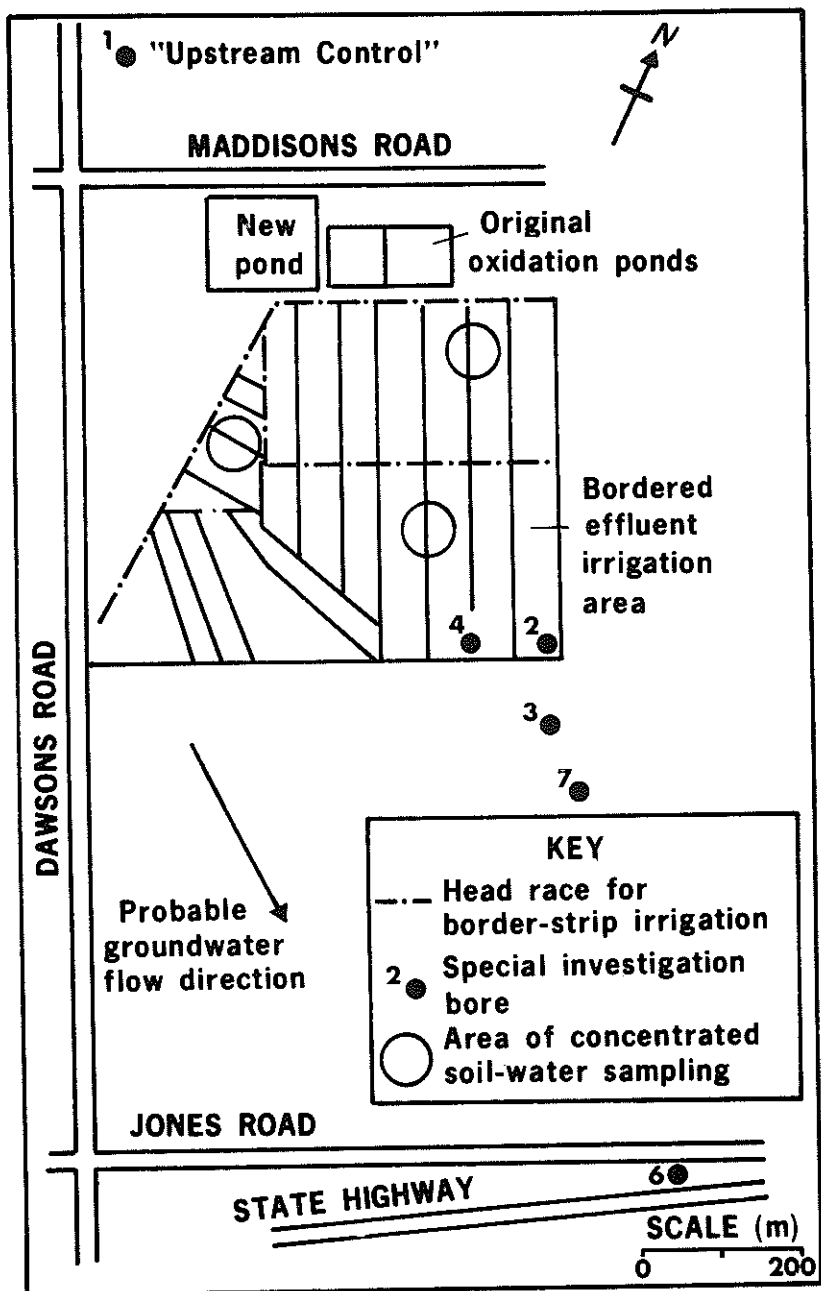
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FIG.— 2 The Templeton sewage effluent irrigation scheme, showing layout of ponds,
border-strips for surface irrigation, and location of percolating soil water
sampling sites and special investigation bores.

RESULTS AND DISCUSSION

Composition of Oxidation Pond Effluent and Percolating Soil–Water

The total annual effluent application of 840 mm is very similar to the total annual drainage (900 mm). Compared to the effluent, the percolating soil–water samples contained much higher levels of Ca, Mg and NO_3–N, and much lower levels of NH_4–N and K (Table 1). Ca and Mg are displaced from the soil exchange complex by K and Na contained in the effluent. The NH_4–N contained in the effluent is bound in the soil, but is rapidly converted to NO_3–N by soil bacteria. Some of this NO_3–N is leached directly from the soil during subsequent irrigations, while much of what is taken up by the pasture is returned to the soil as urea in sheep urine patches, and goes through the NH_4–N to NO_3–N conversion again (Quin & Forsythe 1978).

TABLE – 1 Chemical composition of effluent and percolating soil–water (mg. l.)

	Effluent[a]		Soil–water[b]	
	range	mean	range	mean
pH	7·1–7·4	7·2	6·1–7·3	6·5
NH_4–N	10·4–15·0	12·3	0·1–2·6	0·9
NO_3–N	<0·1–0.5	0·1	0·1–29[c]	7·3[c]
SO_4–S	3–10	5·5	1–13	5·5
Cl	29–48	38	25–62	37
Na	35–54	41	27–64	35
K	7–10	8·1	1–4	2·4
Ca	15–24	21	19–51	28
Mg	2–4	2·8	3–13	8

a – Samples taken at approximately 2 monthly intervals from May 1975 to February 1977.

b – Approximately 200 samples collected from 50–100 cm depth from August 1975 to July 1977.

c – Urine patches excluded. These were estimated to increase the mean NO_3–N content of the soil–water to over 15 mg. l. (Quin & Forsythe 1978).

In contrast, the species Cl, Na and SO_4–S have similar concentrations in both the effluent and drainage water. Chloride, and to a lesser extent Na, are little affected by soil processes, and the inputs of 319 and 344 kg.ha.yr. respectively in the effluent are balanced by the outputs of 330 and 315 kg.ha.yr. respectively in the drainage (Quin & Forsythe 1978). Inputs from rainfall and fertilizer amount to only a few kg.ha.yr., as do outputs in sheep products. Where pasture is harvested rather than grazed, however, as in the reed canarygrass study at Templeton (Quin, 1979), and the lucerne study by Stevenson & Wilcock (1978), in excess of 200 kg.ha.yr. of Cl may be removed in the harvested material.

Sulphate–S is more affected by soil processes, particularly by incorporation into soil organic matter, but this and the removal in sheep products is balanced in this case by the annual application of superphosphate fertilizer (Quin & Forsythe 1978).

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*Mixing and Vertical Velocity of Drainage Water in the Soil and Gravel
Substrata*
When discussing rates of vertical movement of drainage water, it is important
to consider the degree of mixing that takes place between the irrigation water and
the moisture that is already present in the soil and gravel substrata. The 'piston
effect', where irrigation water completely displaces without any mixing an
equivalent amount of water already present in the soil and substrata, almost
never occurs in practice (Kirkham & Powers 1972). It is probably most closely
approximated in fallow clay loams (Wetselaar 1962).

In coarser soils, textural non-homogeneity and the presence of plant roots,
cracks and holes greatly affect infiltration rates (Quin 1977). Furthermore,
because of the large gravitational influence on flow in a coarse material (whether
texturally homogeneous or not), surface irregularities can produce flow varia-
tions that will not be quickly smoothed out by lateral mixing and dispersion (Jury
et al., 1975).

Nevertheless, tracer irrigation studies with large concrete enclosed drainage
collection lysimeters at Winchmore (Fig. 1) have shown that, by the time the
drainage water has passed through 0.3 m of topsoil (Lismore stony silt loam) and
1 m of gravel substrata, it is a relatively homogeneous mixture of the irrigation
water, and the moisture initially present in the soil and gravel (B. F. Quin,
unpublished results). Initially, the drainage water is actually slightly closer in
composition to the irrigation water, then becomes a more complete mixture of
the two, and the last of the drainage is closer in composition to the moisture
initially present in the soil and gravel. This trend was also found in samples of
percolating soil–water collected (at soil depths down to 1 m) with PVC tube
suction lysimeters at Templeton (Templeton silt loam). These lysimeters were
especially designed to permit rapid sampling of percolating soil–water during
and after irrigation (Quin & Forsythe 1976). In both types of lysimeter expe-
riment, the trend was more exaggerated when the initial soil–moisture was low.

These findings can be explained by assuming that some of the irrigation water
passes rapidly through large pores and cracks without undergoing much mixing
(especially in the topsoil), and, at the same time, some of the moisture initially
present in the soil and gravel is forced into and trapped in crevices. As the wet soil
expands slightly, the pores and cracks decrease in size, the infiltration rate falls,
and more mixing and dispersion takes place. Finally, once all the water has
infiltrated below the soil surface, moisture which had been forced into crevices
can escape and the soil and gravel return to true field capacity. (The field capacity
of the gravel is defined here as the amount of water that is retained in the gravel
by surface tension after drainage has ceased.)

In both types of lysimeter study described above, drainage generally started
10–15 minutes after the commencement of surface irrigation, giving a vertical
velocity of the drainage water in excess of 5 m.hr., through the top metre.
However tracer studies at Fairton (Fig. 1) demonstrated that drainage induced
by continuous flooding of the surface took 18–22 hours to pass through the gravel
substrata and reach the water table, (25 m below ground surface), giving a
velocity only slightly greater than 1 m.hr. overall. This figure is· in good
agreement with the findings of a similar experiment by Thorpe (1977), who
measured vertical velocities of 0.6–1.0 m.hr. for drainage water through gravel
at Heretaunga (Fig. 1), where the water table is 10 m below ground surface.

The faster rate (5 m.hr.) found in both types of shallow lysimeter experiment

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is probably mainly due to the large contribution the soil cover makes to the total depth, as cracks, large pores and root holes would be more prevalent in the soil than in the less permeable gravel substrata. Furthermore, the layers of clay and compacted material frequently found in most deep gravels in New Zealand would further reduce the vertical velocity.

The gravel substrata at Fairton belongs to the Burnham formation, which is described as mainly fairly well sorted, little weathered, glacial outwash greywacke gravel (N.Z. Geological Survey), with a depth of several hundred metres (Mandel 1974). At Templeton, the gravel substrata belongs to the Springston formation, which comprises well sorted glacial outwash gravels which are described (N.Z. Geological Survey) as being finer but more permeable than the older Burnham formation gravels, although the results of Martin (1976) suggest that both have similar compositions with regards to the <10 mm fractions. In view of this, and taking into account the similar results of Thorpe (1977) at Heretaunga in the North Island, it is reasonable to assume that the excess water from a particular irrigation at Templeton will induce a movement of drainage travelling at a rate of approximately 1 m.hr. Assuming that the gravel is initially at field capacity this movement may continue until the water table is reached, but it must be emphasized that the drainage will, with increasing depth, become progressively more homogeneous due to mixing and dispersion.

The important implication of the 'smoothing' is that the chemical composition of the drainage reaching the water table will not vary greatly during the year, even though the amounts, and concentrations, of nitrate in particular being leached from the root zone will be much greater in winter than in summer (Quin & Forsythe 1978). The volume of drainage from each monthly irrigation of approximately 80 mm will vary from as little as 20 mm in summer to the full 80 mm in winter. Studies at both Winchmore and Templeton have shown that the gravel substrata holds, at the completion of drainage, an average of 4% moisture by weight or, using the measured bulk density of 2.2 g.cm^3., 9% by volume. At Templeton therefore, approximately 1200 mm of moisture (or 16 months drainage) is held in the gravel above the water table (13 m below ground surface).

Groundwater Velocity in the Saturated Zone

Groundwater velocity in the alluvial aquifers of the Canterbury Plains has traditionally been estimated at 5–10 m. day (D. D. Wilson, pers. comm.), and this is compatible with water balance calculations (Mandel 1974). However velocities as high as 250 m. day have recently been measured by tracer techniques at Burnham (McCabe and Rowse, 1976), and bacteriological studies at Templeton and Burnham (Martin 1976) gave good agreement with this measurement. Velocities in excess of 150 m. day have also been measured at Heretaunga by tracer and bacteriological methods (Thorpe 1977). The answer to this paradox may be that a small percentage of the total flow takes place along preferred channels of coarse material. As vertical velocities of drainage on a broad front through the unsaturated zone are only of the order of 20 m. day under heavy flooding, it is difficult to accept that the 'bulk' groundwater velocity is any higher than this, particularly as the gravitational influence would be much less.

Composition of Shallow Groundwater in Bores 1, 2 and 4

Table 2 gives the data for the chemical composition of the shallow ground-

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TABLE—2 Composition of groundwater in Bore 1 and Bores 2 and 4 (depth 1 m below water table), the soil–water, and bore/soil–water composition ratios

	Soil-water	Groundwater											
	Average all samples	Aug/Sept 1975[a]				Feb 1976[b]				Sept 1977[c]			
		Bore 1		Bores 2 & 4		Bore 1		Bores 2 & 4		Bore 1		Bores 2 & 4	
	mg/l	mg/l	ratio	mg/l	ratio	mg/l	ratio	mg/l	ratio	mg/l	ratio	mg/l	ratio
$NO_3–N$	15	10·8	0·72	13·0	0·86	7·30	0·48	9·8	0·65	11·0	0·73	12·2	0·81
$SO_4–S$	5·5	8·9	1·61	7·0	1·29	4·5	0·81	5·7	1·03	5·1	0·92	5·4	0·98
Cl	37	27	0·72	31	0·83	17·4	0·47	25·2	0·68	20	0·54	26	0·70
Na	35	19	0·54	28	0·80	14·4	0·41	21·9	0·62	22	0·62	33	0·94
K	2·4	2·7	1·12	2·4	1·00	1·9	0·79	2·4	1·00	2·1	0·87	2·5	1·04
Ca	28	19	0·67	27	0·96	21·3	0·76	25·4	0·90	35	1·25	33	1·17
Mg	8	–	–	–	–	4·7	0·58	6·4	0·80	6·5	0·81	7·3	0·91

– Not determined   [a]Martin (1975)   [b]Martin (1976)   [c]This work

water (1 m below water table) for the control bore (Bore 1) and the average for the two bores at the 'downstream' end of the irrigation scheme (Bores 2 and 4).

If the shallow groundwater at Bores 2 and 4 reflects the drainage from the effluent irrigation scheme, then the ratio of the chemical composition of Bores 2 and 4 to that of the drainage should be closer to unity than that of Bore 1 to the drainage. As shown in Table 2, this is invariably the case. The lower nutrient levels in Bores 2 and 4 in summer (February sampling) reflects the fact that in the drier months, the shallow groundwater is largely water from 'upstream', whereas in the winter the shallow groundwater may be composed to a large extent of drainage from the effluent irrigation scheme. Martin (1976) also found that highest levels of nitrate in groundwater occurred in winter. Furthermore, the data indicate that seepage from the original oxidation ponds is not responsible for the chemical composition of Bores 2 and 4, because even if the NH_4–N content of the oxidation pond effluent is completely converted to NO_3–N during seepage to the water table, it is unlikely that seepage could have caused the increased levels of Ca and Mg in the groundwater, because of the limited amount of these cations available for displacement by Na below the soil profile.

Depth of Groundwater Affected by Effluent Irrigation Drainage

In the original Ministry of Works and Development investigation, all groundwater samples were taken from 1 m below the water table. However, because the bores were slotted over the lower 6 m, it was possible to collect samples from a range of depths. This was done in August 1977, and the results for Bores 1, 2 and 3 are given in Table 3.

The results show that the composition of the groundwater in all 3 bores is constant throughout the depths sampled, which implies that there is normally a large degree of vertical mixing over short distances in these permeable gravels. The similarity between the data for Bores 2 and 3 reflects their close proximity to one another.

TABLE — 3 Composition of groundwater at various depths in Bores 1, 2 and 3, August 1977 (mg.l.)

	Bore 1				*Bore 2*				*Bore 3*		
	WT	*–1m*	*–2m*	*–4m*	*WT*	*–1m*	*–2m*	*–4m*	*WT*	*–1m*	*–2m*
NO_3–N	10·7	11·0	11·0	11·0	12·5	12·5	12·5	12·5	11·5	11·9	12·0
SO_4–S	4·9	5·1	5·3	5·3	5·3	5·4	5·4	5·4	5·1	5·1	5·3
Cl	24	25	26	22	28	28	27	27	26	26	27
Na	21	22	23	22	33	33	34	33	33	34	34
K	2·0	2·1	2·2	2·3	2·7	2·6	2·7	2·7	2·3	2·7	2·5
Ca	34	35	35	36	35	35	35	36	33	34	34
Mg	6·3	6·5	6·5	6·4	7·3	7·5	7·6	7·5	7·0	7·1	7·2

WT: at water table;   –xm: xm below water table

Effect of drainage from new pond on Bore 6

There was very little effluent irrigation during the period April to July 1977, as almost the entire content of the ponds was pumped continuously into a new pond (Fig. 2), which had been excavated in preparation for the Templeton township to be connected to the effluent treatment scheme. Because of poor sealing, the new pond was initially leaking 2000 m³ of water per day (500 m³ of effluent and 1500 m³ of irrigation race water were being pumped in daily to keep the pond full). By August 1977, leakage had dropped to 250 m³ day, as the base of the pond became coated with fine material.

In 1975 and 1976, the shallow groundwater (1 m below water table) in Bore 6 had a composition similar to the nearest upstream bore (Bore 7) (Table 4). However, the results for July 1977 showed a distinct decrease in the concentrations of most species. When samples were collected from a range of depths in August 1977, the results showed that this purer water occupied only the top 2 m of the water table, and a very abrupt change occurred below 2 m; these deeper samples had a composition very similar to that of Bore 7, (Table 4). Comparison of the shallow groundwater composition in Bore 6 with that of the new pond effluent in July 1977 (Table 4) indicates that drainage from the new pond was responsible, the clearest indications being the concentrations of NO_3–N, Cl and Na. Unlike irrigation, in which the soil processes alter the nitrogen content of the effluent drainage, the massive drainage loss from the unsealed new pond could not be expected to be significantly altered in chemical composition. By January 1978, Bore 6 had reverted to having a composition similar to Bore 7 throughout the sampling depths.

If the new pond did affect Bore 6 in this way, it is perhaps surprising that there was no higher NO_3–N groundwater overlying that from the new pond, as this drainage from the new pond must have passed under the western portion of the irrigation area once it reached the water table. This may be explained by the presence of a preferred channel of coarse material. If this channel passed under the new pond and intersected Bore 6, it might be expected that, because of the large amount of drainage from the pond, drainage from the effluent irrigation area would be displaced away from this channel. In fact, the existence of a preferred channel or boundary of some sort must be assumed in order to explain why the other downstream bores were not affected by drainage from the new pond.

Extrapolation to Burnham results

At the Burnham effluent irrigation scheme (Fig. 1), Martin and Noonan (1977) found that the downstream bores had a very similar composition to the upstream control bore. These results are in keeping with the composition of the Burnham effluent, in which the concentrations of the species relatively unaffected by soil processes, namely Na, Cl and SO_4–S, were similar to those in the upstream control bore.

CONCLUSIONS

The results presented in this paper demonstrate the advantages of carrying out detailed analysis of percolating soil–water for the interpretation of the effects of wastewater irrigation on groundwater quality. At Templeton, due to conversion

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TABLE – 4 Composition of Bores 6 and 7 (mg.l.)

| | Aug 1975 | | Feb 1976 | | July 1977 | | August 1977 | | | | | | | | | | New Pond |
| | −1m | | −1m | | −1m | | WT | | −1m | | −2m | | −3m | | −4m. | | July 1977 |
	7	6	7	6	7	6	7	6	7	6	7	6	7	6	7	6	
NO$_3$–N	12·1	10·1	9·6	9·1	17·2	5·0	10·0	4·2	10·0	4·2	10·0	4·7	10·0	8·5	10·2	9·5	4
SO$_4$–S	7·1	9·2	5·7	6·3	8·7	8·3	4·3	6·4	4·4	6·5	4·5	6·8	4·4	6·5	4·6	6·4	6·7
Cl	32	27	25	22	33	22	27	22	27	21	28	23	26	27	26	28	22
Na	28	21	22	20	31	19	26	24	27	23	27	24	27	27	26	29	24
K	2·6	2·3	2·3	2·3	2·2	1·7	2·2	2·1	2·2	1·9	2·4	2·4	2·1	2·0	2·0	2·3	–
Ca	27	26	25	24	39	20	33	22	33	22	33	25	32	31	33	31	19
Mg	7·7	6·8	6·3	6·2	8·3	4·4	5·7	4·6	5·7	4·6	5·8	5·0	5·8	6·3	5·6	6·3	–

and displacement in the soil, the percolating soil–water contained higher concentrations of NO_3–N, Ca and Mg than the effluent, but lower concentrations of NH_4–N and K.

Mixing and dispersion ensures that the drainage would be relatively homogeneous by the time the water table was reached. Not unexpectedly, the chemical composition of the shallow groundwater was closest to that of the average composition of the drainage in the wetter winter months, when the much increased volume of drainage reached the water table would have a dominating effect on groundwater quality. Drainage from the effluent irrigation resulted in increased concentrations of NO_3–N, Cl, Na and Ca in the groundwater.

The level of NO_3–N in the bores immediately downstream of the irrigation area tended to range from 10 mg. l. in summer to 13 mg. l. in winter, compared with 7 mg. l. to 11 mg. l. for the upstream control bore, and in excess of 15 mg. l. for the drainage.

Although the concentration of NO_3–N in the drainage from efflent irrigation could be reduced by cropping rather than grazing the pasture (Quin 1979), it is doubtful whether this is warranted in view of the frequent incidence of levels in excess of 10 mg. l. in groundwater under conventionally farmed land. Fortunately however, high NO_3–N levels in Canterbury are restricted to the upper 20-30 m of the saturated zone, where the ratio of drainage to river seepage is high (Quin & Burden 1979). NO_3–N values at deeper depths are invariably lower than 10 mg. l.

ACKNOWLEDGEMENTS

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