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EFFECT OF RECHARGE VARIATIONS ON REGIONAL GROUNDWATER QUALITY IN MID-CANTERBURY, NEW ZEALAND.

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ABSTRACT

A network of 22 wells between the Ashburton and Rakaia Rivers was sampled monthly between September 1990 and September 1991 and analysed for nitrate and other major ions. Sixteen of the wells had been sampled 12 years earlier and the data were compared to determine changes in groundwater quality over that period. Oxygen isotopes were also measured to provide insight into the recharge processes.

Less rain fell during 1990/91 than in 1978/79, so much more irrigation water was applied in the 1990/91 period. The resulting recharge patterns influenced groundwater quality. The number of wells with significant increases in parameter concentrations approximately equalled the number with significant decreases between the two study periods. Nitrate levels generally decreased or differed little between 1978/79 and 1990/91. The changes in land use between the two study periods were much less than the differences in recharge and, apart from two wells, there was no evident effect of land use changes on groundwater quality.

INTRODUCTION

New Zealand makes extensive use of groundwater, with about 37% of its population either totally or partially dependent on groundwater for drinking purposes; in addition large volumes are used for industry and agriculture (Groundwater Working Party, 1981). A number of wells in Mid-Canterbury were sampled in the late 1970's (Burden, 1982) to establish groundwater quality patterns. Since then, private irrigation development has taken place, with consequent intensification and diversification of agriculture.

Variations in recharge influence groundwater quality through: 1) leaching of soluble substances by infiltration or rising water tables, causing increases in chemical constituent levels; 2) dilution of groundwater by infiltration of water with lower constituent concentrations; and 3) the movement of groundwaters of different quality in response to changes in hydraulic head (Whittemore et al., 1989). Some recharge variations which affect groundwater quality are natural (e.g., Hackbarth, 1981) while others are affected or caused by man's activities (e.g., Close, 1987). Recharge often varies seasonally (Montgomery et al., 1987) but there are longer term variations as well (Close, 1987; Whittemore et al., 1989).

Burden (1982) showed that groundwater quality in the area between the Rakaia and Ashburton rivers was influenced by both the relative amounts of seepage from local rivers and recharge from irrigated and non-irrigated pastureland. Groundwater sources were inferred from the chemical composition and the degree of seasonal variability of concentrations of nitrate and chloride in each well. In this study wells from the earlier survey were resampled to examine changes in groundwater quality with changing land use and recharge patterns. The source of water in each well was determined using oxygen-18 isotopes.

STUDY AREA

The study area (1350 km^2) lies between the Rakaia and Ashburton Rivers on the Canterbury Plains (Fig. 1), and slopes steadily coastwards from an elevation of 500 m at the foot of Mt Hutt. The Plains consist of coalesced glacial outwash, and inter-glacial and post-glacial alluvium, with a discontinuous loess cover on older surfaces (Scott, 1980). Wilson (1973) noted that the gravels are up to 600 m thick in the central plains area, but this thickness decreases rapidly towards the Alps. The soils of the area are stony silt loams, and are typically shallow and free-draining. There are no groundwater bores deeper than 150 m and very few deeper than 80 m (Scott and Thorpe, 1986). Depth to water table generally ranges from 10 to 30 m but increases to more than 100 m in areas not adjacent to rivers in the northern part of the study area (Scott and Thorpe, 1986). Groundwater moves in a south-easterly direction towards the coast. Further information about the study area is given by Burden (1982) and Scott and Thorpe (1986).

The area is used predominantly for livestock grazing, with some cereal and crop farming. Land-use data were obtained from agricultural statistics published by the Department of Statistics for the Ashburton County/District Council which covers the area between the Rakaia and Rangitata rivers and from the coast to the main divide. The study area is slightly less than half of the county on the Canterbury Plains, and should show general trends similar to those for Ashburton County. Land use in Ashburton County has diversified and intensified between 1979 and 1990, with the land in horticulture and other crops increasing by 17%. Sheep numbers decreased and dairy, beef, pigs, deer, and goats increased. Total ewe equivalents, (which permit comparison of feed requirements for different animals), calculated using livestock conversion factors (Ministry of Agriculture and Fisheries, pers. comm.) indicate a minor intensification of 0.5%, which increases to 3.5% when the decrease in grassland area is taken into consideration. Most of this intensification would have taken place on the Plains, so the percentage change for the study area is more than that calculated for Ashburton County, which includes high country.

METHODS

The previous survey involved a network of 26 wells which were sampled at approximately monthly intervals from July 1978 to May 1979 (Burden, 1982). Wells from the earlier survey were identified and located where possible. Sixteen of the original wells could be sampled; five others (AR2, AR5, AR6, AR8 and AR14) had been replaced by new, generally deeper, wells in approximately the same location. Well AR10 could not be located so a new well (AR27) in the same area was sampled. Data from the 1978/79 survey were checked for accuracy and used for comparison. Well locations and depths are given in Table 1. Total well depths were measured where possible, or taken from well logs or well owner's information. There were a few, generally small, differences in well depths from those recorded in Burden (1982).

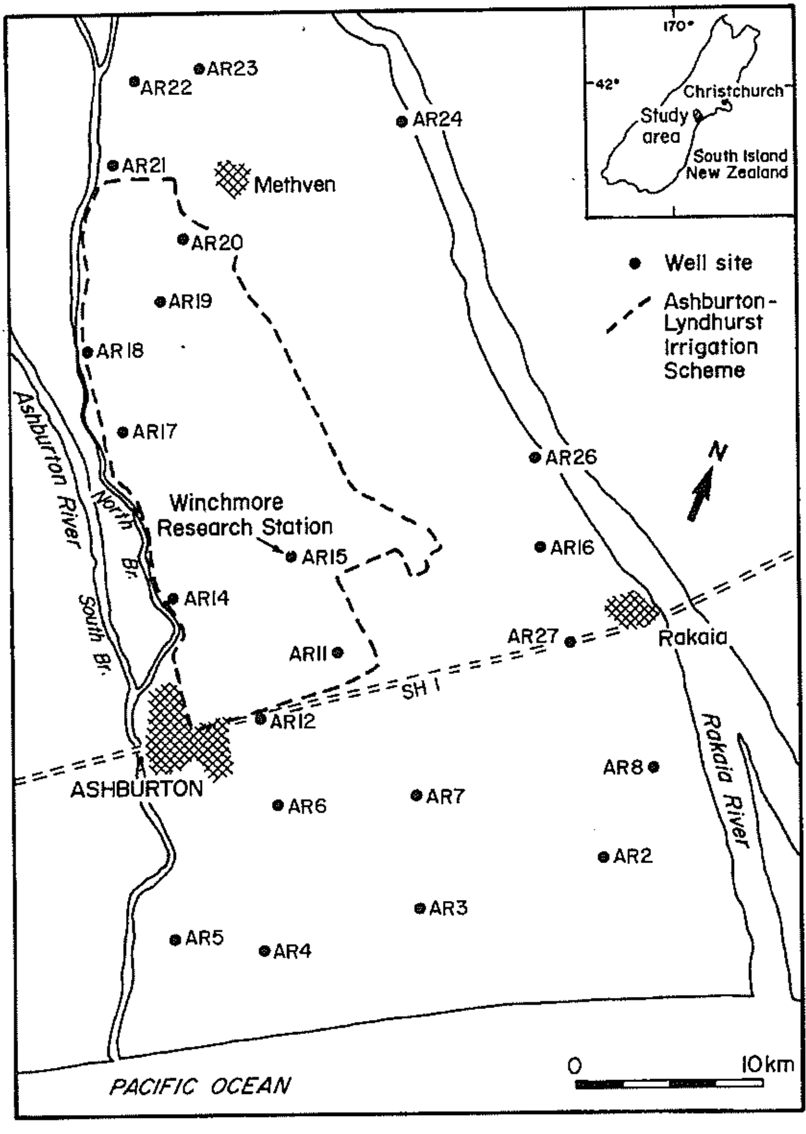

FIG. 1 — Location of the study area and well sites.

Samples were collected from the 22 wells at monthly intervals between September 1990 and September 1991. The water level was measured where possible, and the well was pumped before sampling to ensure that fresh groundwater was being sampled. The samples were taken in acid-washed plastic bottles and transported to the laboratory on the same day. The samples were analysed for pH, alkalinity, conductivity, chloride, sodium, potassium, calcium, magnesium, and iron using standard methods (APHA, 1985; methods 403, 205, 407D, & 303A). Nitrate was analysed using automated hydrazine reduction (Downes, 1978), and sulphate was measured using an automated methyl thymol blue method (McSwain et al., 1974). On 24 April 1991 samples were collected from each well and sent to the Nuclear Sciences Group, DSIR Physical Sciences, for oxygen-18 analysis.

TABLE 1 — Well locations and depths.

Well No.	Map reference	Total well depth (m)	Water level (m) (1990/1)	Screen depth below water table (m)
AR2	L37:343033	93	20	71
AR3	L37:261971	67.7	31	28
AR4	L37: 194917	18.3	8.4	9
AR5	L37: 145902	34.2	3.6	27
AR6	L37: 168987	41.3	20*	17
AR7	L37:231028	63.7	47*	15
AR8	L37:351096	44.4	22.5	21
AR11	L37: 165079	-	-	-
AR12	L37: 139032	109	33	74
AR14	K37:072073	7.7	4	3
AR15	L36:123115	66	50*	14
AR16	L36:240189	66	54	11
AR17	K36:011144	18	5	12
AR18	K36:972182	4.9	1.2	3
AR19	K36:004220	23.8	15*	7
AR20	K36:003257	18.3	10.4	7
AR21	K36:944275	8.7	6.3	2
AR22	K36:939324	18.3	9.6	8
AR23	K36:966345	6.0	-	
AR24	K36:079364	8.7	2.4	5
AR26	L36:218226	30.0	18*	11
AR27	L36:275134	-	-	

Note: Map reference is from NZMS 260 series.
* indicates water levels estimated from logs or surrounding wells.

The extent of seasonal variability was estimated by fitting a sine curve to the data of the form:

Concentration = constant + Amp * sine(days/365 + phase)

where Amp = amplitude of seasonal variability, and the constant is approximately equal to the mean of the series.

Standard deviations of the residuals from this sine fit were compared with the standard deviation of the original series. A large amplitude together with a lower standard deviation of the residuals indicates a high degree of seasonality in the data (results for chloride data are reproduced in Table 2).

The stable isotope ^{18}O can be used to indicate the sources of groundwater (Stewart and Taylor, 1981; Taylor and Stewart, 1979). ^{18}O concentrations are expressed as $\delta^{18}O$ values which represent the differences, in parts per thousand, between the $^{18}O/^{16}O$ ratios of water samples and that of the standard water V-SMOW (Vienna Standard Mean Ocean Water). An example of their use to indicate groundwater sources is given by Taylor et al.(1989). Fractionation of isotopes takes place during evaporation and precipitation, with the lighter isotopes tending to go into or remain in the vapour phase. The extent of fractionation is dependent on temperature and may vary with latitude, season and altitude at which precipitation occurs. Altitude is the dominant factor in the present study. Groundwater derived from precipitation on the Canterbury Plains has an average $\delta^{18}O$ value of -7.0 (Taylor et al., 1989). The rivers in the study area receive the bulk of their flow at much higher altitudes, and have more negative values. The following $\delta^{18}O$ values were taken as average values for the rivers: Rakaia River, -9.3 (Taylor et al., 1989); North branch Ashburton River, -11.0 (Taylor and Stewart, 1979); Ashburton River, -10.5 (Taylor and Stewart, 1979, assuming that the flow contribution from both branches is equal); Rangitata River (source of border strip irrigation water), -10.9 (C.B. Taylor, pers. comm.). These differences may allow the sources of the groundwater to be distinguished.

RECHARGE ESTIMATION

Recharge to groundwater from precipitation and irrigation was estimated for both survey periods using daily water balances. Soil moisture was taken as the sum of the initial soil moisture, rain and irrigation, minus evapotranspiration and recharge to groundwater. Recharge was calculated as the excess above a specified field capacity, and assuming soil moisture did not fall below permanent wilting point. Rainfall and pan evaporation data were obtained from the Winchmore Research Station climate station situated in the middle of the study area.

Two methods of irrigation are common in the study area; border strip irrigation within the Ashburton-Lyndhurst scheme and spray irrigation mainly southeast of State Highway 1 (Fig. 1). Water is obtained from the Rangitata Diversion Race (RDR) for border strip irrigation. Water-use data were available between the 1979/80 and 1988/89 irrigation seasons (P Mason, NIWA, unpublished data). There was a very good negative correlation between irrigation water use and rainfall for the October - March period (R2 = 0.94). This was used to estimate water use for the study period. The simulation was carried out for a "typical" farm applying irrigation every 3-4 weeks. An average border strip

TABLE 2—Mean concentrations (standard deviations in brackets) of chemical parameters in each well sampled Sept 1990 - Sept 1991. The number of data points for each well is 12 or 13 except AR2 (n=10) and AR24 (n=11). All units = g m^{-3} except conductivity (mS m^{-1}) and pH.

Well	pH	Alk	Cond	Cl	SO_4	NO_3	Na	K	Ca	Mg	Fe	Amp_{Cl}	σ_R
AR2	7.7	56.4	21.2	16.0	3.7	6.6	12.3	1.4	20.3	4.4	1.4	2.4	3.4
	(0.2)	(8.1)	(3.3)	(3.9)	(1.1)	(2.3)	(1.9)	(0.1)	(3.1)	(1.1)	(1.9)		
AR3	7.8	55.0	17.7	11.2	1.9	5.5	8.1	1.3	19.5	3.5	<0.1	0.1	0.2
	(0.1)	(1.0)	(0.4)	(0.2)	(0.5)	(0.3)	(0.2)	(0.1)	(0.3)	(0.1)	(0.1)		
AR4	6.7	47.8	22.6	13.7	9.8	10.0	15.4	1.3	18.0	5.7	<0.5	2.9	2.3
	(0.2)	(7.6)	(3.2)	(3.1)	(1.6)	(2.4)	(2.2)	(0.1)	(2.7)	(0.9)	(0.7)		
AR5	7.4	56.2	12.2	3.7	4.7	0.9	5.8	0.7	13.0	3.0	0.7	0.9	0.7
	(0.1)	(1.3)	(0.4)	(1.0)	(0.6)	(0.3)	(0.6)	(0.0)	(0.3)	(0.4)	(0.8)		
AR6	7.1	62.5	28.1	19.5	16.2	9.0	15.2	1.2	25.3	8.0	<0.2	0.6	0.5
	(0.0)	(1.2)	(0.4)	(0.7)	(0.8)	(0.6)	(0.4)	(0.1)	(0.5)	(0.3)	(0.2)		
AR7	7.2	46.6	19.7	16.1	4.5	7.0	11.9	1.2	16.1	5.5	<0.4	1.4	0.8
	(0.2)	(6.4)	(2.6)	(1.3)	(1.9)	(1.2)	(2.7)	(0.1)	(1.7)	(0.8)	(0.5)		
AR8	7.1	63.2	16.8	6.1	9.1	3.0	12.0	1.1	16.0	3.3	<0.4	0.2	0.3
	(0.1)	(3.0)	(0.3)	(0.4)	(0.5)	(0.2)	(0.4)	(0.1)	(0.4)	(0.1)	(0.6)		
AR11	7.8	79.2	19.5	4.6	7.6	4.6	12.3	1.1	16.8	6.2	<0.2	0.1	0.3
	(0.2)	(2.3)	(0.2)	(0.3)	(0.5)	(0.4)	(0.3)	(0.1)	(0.5)	(0.1)	(0.2)		
AR12	7.6	75.6	16.6	4.7	1.5	3.0	7.8	0.9	17.7	4.7	<0.1	0.1	0.2
	(0.1)	(1.0)	(0.2)	(0.2)	(0.5)	(0.2)	(0.1)	(0.1)	(0.3)	(0.1)	(0.1)		
AR14	6.6	34.2	9.5	2.6	5.6	1.7	4.2	1.0	10.1	2.0	<0.1	0.2	0.8
	(0.1)	(0.9)	(0.9)	(0.8)	(0.9)	(0.5)	(0.4)	(0.7)	(0.7)	(0.2)	(0.1)		
AR15	7.6	74.1	19.6	7.1	6.1	5.3	10.8	1.0	17.7	6.8	<0.1	0.1	0.3
	(0.0)	(3.8)	(0.4)	(0.3)	(0.5)	(0.5)	(0.3)	(0.1)	(0.4)	(0.3)	(0.1)		
AR16	7.7	77.8	26.6	17.7	1.4	9.8	14.9	1.7	24.2	7.5	<0.1	0.3	0.4
	(0.1)	(0.8)	(0.3)	(0.5)	(0.4)	(0.5)	(0.3)	(0.1)	(0.5)	(0.1)	(0.1)		
AR17	6.5	43.0	18.6	5.0	12.1	8.9	10.5	0.9	17.2	4.7	<0.1	0.2	0.1
	(0.1)	(1.4)	(0.4)	(0.2)	(0.8)	(0.8)	(0.3)	(0.1)	(0.5)	(0.1)	(0.1)		
AR18	6.7	38.7	9.2	1.7	5.6	1.1	2.9	0.9	11.1	2.0	<0.3	0.6	0.6
	(0.1)	(1.8)	(1.3)	(0.7)	(1.2)	(0.9)	(0.4)	(0.1)	(1.5)	(0.3)	(0.3)		
AR19	6.6	39.5	14.0	3.2	8.3	5.4	6.9	0.8	14.3	2.8	2.3	0.1	0.2
	(0.1)	(1.1)	(0.3)	(0.2)	(0.7)	(0.7)	(0.2)	(0.1)	(0.4)	(0.1)	(1.2)		
AR20	6.6	36.9	16.3	4.7	10.8	7.9	7.1	1.2	16.6	3.6	2.1	1.8	1.2
	(0.3)	(6.2)	(2.7)	(1.8)	(3.2)	(1.9)	(1.0)	(0.2)	(3.1)	(0.7)	(1.2)		
AR21	6.3	33.2	11.7	3.5	5.9	4.1	3.8	0.8	13.7	2.1	<0.1	1.7	0.9
	(0.1)	(7.5)	(1.7)	(1.6)	(1.4)	(2.2)	(0.5)	(0.1)	(1.7)	(0.4)	(0.1)		
AR22	6.4	42.7	11.7	2.8	3.9	3.2	3.9	0.6	14.9	1.8	<0.1	0.9	0.7
	(0.1)	(1.5)	(1.8)	(0.9)	(0.6)	(1.7)	(0.5)	(0.1)	(2.3)	(0.5)	(0.1)		
AR23	6.2	25.3	8.9	2.8	3.6	3.3	3.3	0.5	9.8	1.6	<0.1	1.0	0.6
	(0.1)	(2.6)	(1.4)	(0.9)	(0.6)	(1.7)	(0.3)	(0.0)	(1.6)	(0.3)	(0.1)		

AR24	7.0	29.1	5.9	0.7	3.3	0.1	1.9	0.6	7.7	1.0	<0.1	0.5	0.2
	(0.2)	(2.4)	(0.5)	(0.4)	(0.6)	(0.0)	(0.2)	(0.1)	(0.8)	(0.1)	(0.1)		
AR26	6.7	36.4	7.8	2.0	3.4	0.4	2.4	0.7	10.5	1.1	1.2	1.2	0.3
	(0.1)	(1.7)	(0.6)	(1.0)	(0.7)	(0.2)	(0.1)	(0.2)	(0.8)	(0.1)	(1.1)		
AR27	7.6	65.0	22.6	15.5	3.4	7.8	13.3	1.3	19.3	6.8	<0. 1	0.5	0.7
	(0.0)	(1.3)	(0.4)	(0.8)	(0.5)	(0.8)	(0.2)	(0.2)	(0.5)	(0.1)	(0.1)		

Note: Alk = alkalinity as HCO_3; Cond = conductivity at 25°C;
< for iron indicates that some values were below the detection limit ($0.1\ g\ m^{-3}$) for that well. These values were set to zero for the calculation of summary statistics. Amp_{Cl} = Amplitude of seasonal variation of Cl as fitted by sine curve; σ_R = standard deviation of residuals.

application of 130 mm was assumed (R. Stoker, RDR Management, pers. comm.) with the number of applications depending on the total water use for that irrigation season. For example, in the 1977/78 irrigation season there were eight applications (total application = 1040 mm) and in 1978/79 there were five border strip applications (total application = 650 mm).

The Ashburton-Lyndhurst scheme covers an area of 25,000 ha, and it was estimated that 80% and 90% of this area was developed for irrigation by 1979 and 1990, respectively (R. Stoker, RDR Management, pers. comm.). Recharge for the irrigation scheme area was estimated by combining recharge simulated with rainfall only, and recharge simulated with rainfall and irrigation, in proportion to the percent development of the area: for example, in 1979 recharge = 0.2 * recharge (rainfall only) + 0.8 * recharge (rainfall + irrigation).

Water use for spray irrigation was estimated from irrigation pump power usage, and spray applications of 55-60 mm were assumed (A. Taylor, IrriCon, pers. comm.). These applications were simulated for the late spring and summer. For example, in the 1977/78 irrigation season there were two applications of 60 mm and in 1990/91 there were three applications of 55 mm. The area coastwards of State Highway 1 consists of 58,000 ha, with 7,360 ha and 29,470 ha developed for irrigation in 1978/79 and 1990/91, respectively (A. Taylor, IrriCon, pers. comm.); recharge in this area was calculated in a similar way to that in the border strip irrigation area.

Potential evapotranspiration (PET) was calculated from pan evaporation (E_{pan}) using the procedure detailed in Scott and Thorpe (1986).

$$PET_i = 0.85\ N_i\ E_{pan}\ \text{mm/day} \qquad \text{for } E_{pan} < 5\ \text{mm/day}$$
$$PET_i = 0.85\ N_i\ 1.904\ (E_{pan})^{0.6}\ \text{mm/day} \qquad \text{for } E_{pan} > 5\ \text{mm/day}$$

where N_i is a day-length factor allowing for seasonal variation in plant growth. The exponential reduction for E_{pan} greater than 5 mm/day corrects for the greater influence of advected energy on an evaporation pan than on irrigated pasture.

Actual evapotranspiration (AET) is a function of the PET rate, soil moisture content and plant development. When PET is low, AET may equal PET, even at relatively low soil moisture levels. At high PET, AET may be limited by the plant transpiration. AET decreases as soil moisture levels decrease. A linear approximation has been developed to describe this relationship (Scott and Thorpe, 1986):

$$\begin{array}{ll} AET/PET = 1 & \text{for } SM > WHC(1 - 0.67/PET) \\ AET/PET = (0.2+SM/WHC)/(1.2-0.67/PET) & \text{for lower SM levels.} \end{array}$$

where SM = soil moisture (mm) and WHC = water holding capacity (mm).

A water holding capacity (WHC) of 90 mm was assumed for the area (R Stoker, RDR Management, pers. comm.). Simulations for each day were

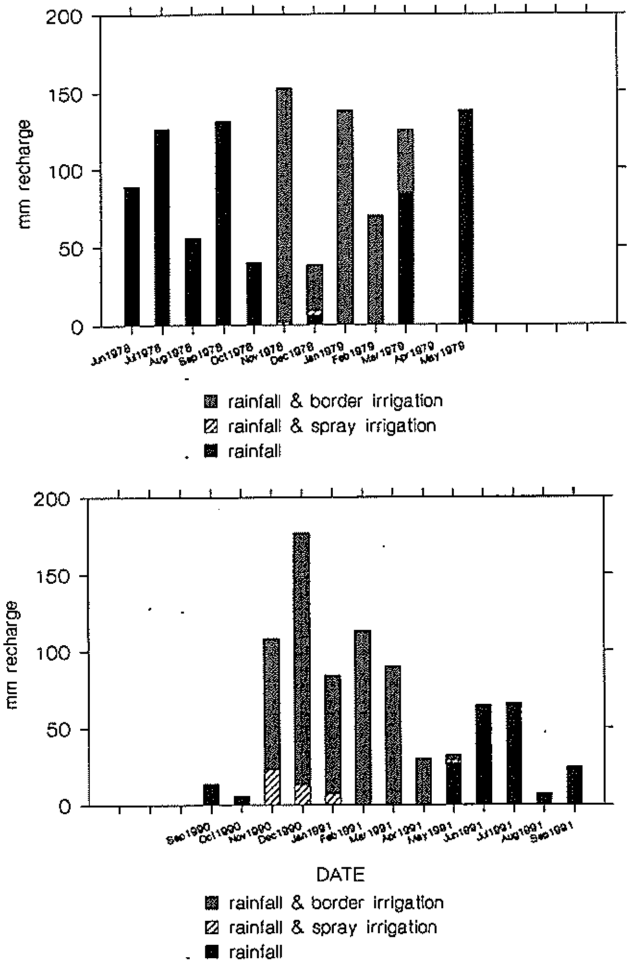

FIG 2—Recharge estimates for the two study periods for each type of recharge.

summed to give monthly totals (Fig. 2). Rainfall increases from the coast to the foothills; recharge estimates will be most accurate around the centre of the study area where the climate station is situated (Fig. 1), but the temporal patterns should be applicable to the whole study area. The recharge estimates for rainfall plus border strip irrigation apply to wells within the Ashburton-Lyndhurst scheme, those for rainfall plus spray irrigation apply to wells south-east of State Highway 1, and the rainfall-only estimates apply to the remainder of the wells.

There was much less rainfall during the 1990/91 study period (665 mm, Sept 90 - Aug 91 inclusive) than during the 1978/79 period (1141 mm, Jun 78 - May 79 inclusive). The long term average annual rainfall at Winchmore is 760 mm. Much more irrigation water was thus applied in 1990/91. Water-use data indicates that about 60 mm and 650 mm were applied in 1978/79 for spray and border strip irrigation, respectively, and 165 mm and 780 mm in 1990/91.

Figure 2 shows variations in estimated recharge for the two study periods for three irrigation practices - no irrigation (rainfall alone), rainfall plus spray and rainfall plus border strip irrigation. There were 12-month recharge totals of 672 mm, 677 mm, and 1105 mm for the 1978/79 period for rainfall, rainfall plus spray and rainfall plus border strip irrigation, respectively. Twelve-month recharge totals for the 1990/91 period (Sept 90 - Aug 91 inclusive) were 184 mm, 229 mm, and 792 mm for rainfall, rainfall plus spray, and rainfall plus border strip irrigation, respectively. Recharge was reasonably uniform throughout the year for border strip areas in 1978/79 but in 1990/91 there was far more summer recharge for these areas. In areas with no irrigation or spray irrigation the bulk of recharge occurred in winter, with no recharge occurring for six months over summer/autumn for non-irrigated areas in 1990/91.

Data from lysimeters at the Winchmore Irrigation Research Station were available for the period December 1977 to November 1978. The recharge amounts in mm for 2-monthly intervals for the lysimeters and model simulations,

TABLE 3—Summary of t-test results for wells common to both surveys. ($\alpha = 0.05$)

Well	1990/91 > 1978/79	1990/91 < 1978/79
AR3	pH, SO_4	Cl, K
AR4		Cl, Na, K
AR7	pH, Alk	Cond, Cl, Na, K
AR11	pH, Alk, Cond, SO_4, Na, Ca, Mg	Cl, No_3, K
AR12	Cond, SO_4, Ca, Mg	Cl, K
AR15	Alk	Cl, No_3, K
AR16	Alk, Cond, Cl, No_3, Na, K, Ca, Mg	SO_4
AR17	Alk, SO_4	Cond, Cl, Na, K, Ca, Mg
AR18		NO_3
AR19	Alk, Cond, SO_4, Mg	Cl
AR20	pH, Alk	NO_3, Na
AR21	pH, Alk, Cond, Cl, K, Ca, Mg	
AR22	pH, Cond	
AR23	pH, Alk, Cond, NO_3, SO_4, Na, Ca, Mg	
AR24		Cond, Cl, NO_3, Na, K, Mg
AR26		Cond, Cl, NO_3

respectively, were : 3, (0); 0, (0); 132, (203); 235, (216); 197, (187); 38, (40). The annual recharge from lysimeter data was 605 mm, compared with 646 mm from the model simulation, a difference of 6.5%. The recharge indicated by the lysimeter data was much less than the simulated value for the third pair of values but greater for the fourth and fifth pairs, indicating that the simulated recharge appears faster than that determined from lysimeter data. This is because the model does not consider the time taken for water movement. Recharge was found to be relatively insensitive to changes in water-holding capacity (WHC). A WHC of 120 mm (+33%) gave a simulated recharge for the same period of 623 mm (-3.6%) and a WHC capacity of 60 mm (-33%) gave a simulated recharge of 673 mm (4.2%).

RESULTS

Chemical data for the 1990/91 study period are summarised in Table 2. The mean nitrate-N value for wells AR4 and AR16 were equal or very close to the drinking water standard of 10 g m^{-3} (NZ Board of Health, 1984). Thirteen values from five different wells were greater or equal to the drinking water standard for nitrate. Iron results were sometimes above the guideline value (1.0 g m^{-3}) for aesthetic quality of drinking water (NZ Board of Health, 1984). The guideline values for pH specify a range of 7.0 to 8.5 to avoid problems with corrosion and scale. About half of the pH values were less than 7.0, with a minimum value of 6.1. All other parameters were within guideline values for drinking waters.

The results from the 1990/91 survey were compared with those from 1978/79 using the Student's t-test for wells common to both surveys (Table 3). If there was significant seasonal variation, paired comparisons were made by comparing values collected in the same month. There was wide variation in the t-test results. The number of wells with significant increases in parameter concentrations roughly equalled the number with significant decreases. Nitrate, chloride, and potassium levels generally decreased or showed no significant difference from 1978/79 to 1990/91, and pH, alkalinity, conductivity, sulphate, calcium, and magnesium levels generally increased or showed no significant difference.

Results of the isotope analyses are given in Table 4. The composition of the recharge was calculated by assuming that only two sources contributed to any one well, and selecting the most likely river recharge source based on regional groundwater flows. This is a simplification for some wells, such as AR17, which could receive recharge from both the North Ashburton River and the Rangitata Diversion Race via the border strip irrigation scheme (Table 4). However, even these wells should give a reasonable estimate of the rainfall percentage, as differences among the ^{18}O values for the rivers in the south of the area, where there may be overlap, is small. The remaining percentage recharge would be divided between the diversion race and the river. Wells AR3, AR6, AR7, and AR4 were assumed to have input from the diversion race as they were downstream from the irrigation scheme. Rainfall as percentage of recharge was estimated as:

$$\text{Rainfall \%} = (\text{Sample } \delta^{18}\text{O} - \text{River } \delta^{18}\text{O})/(\text{Rain } \delta^{18}\text{O} - \text{River } \delta^{18}\text{O})$$

The statistical error in measurement of $\delta^{18}O$ values results in a variation of ± 5-10% in calculated rainfall composition (Table 4). The values assumed for the various river sources are estimates and may vary. For example, Taylor et al. (1989) show that a range in catchment mean temperature of about 1°C (using a

TABLE 4 — Oxygen-18 values for each well and calculated recharge from rainfall and other sources. $\delta^{18}O$ values for the sources are as follows: rainfall -7.0; Rakaia R -9.3; RDR -10.9; Nth Ashburton R -11.0; Ashburton R -10.5

WELL	$\delta^{18}O$	± SE	% RAIN	% OTHER SOURCE	
AR2	-8.41	0.11	39 ± 9*	61 ± 9	Rakaia R.
AR3	-8.70	0.11	56 ± 6	44 ± 6	RDR
AR4	-9.42	0.13	31 ± 7	69 ± 7	Ashburton R. (or RDR)
AR5	-10.26	0.12	7 ± 6	93 ± 6	Ashburton R.
AR6	-9.04	0.11	48 ± 5	52 ± 5	RDR
AR7	-8.34	0.1 1	66 ± 5	34 ± 5	RDR
AR8	-8.78	0.12	23 ± 10	77 ± 10	Rakaia R.
AR11	-9.03	0.12	48 ± 6	52 ± 6	RDR
AR12	-9.21	0.10	43 ± 5	57 ± 5	RDR
AR14	-10.02	0.10	25 ± 5	75 ± 5	Nth Ashburton R. (or RDR)
AR1S	-9.0 2	0.10	48 ± 5	52 ± 5	RDR
AR16	-8.70	0.10	26 ± 9	74 ± 9	Rakaia R.
AR17	-9. 10	0. 10	48 ± 5	52 ± 5	Nth Ashburton R. (or RDR)
AR18	-10.52	0.10	12 ± 5	88 ± 5	Nth Ashburton R. (or RDR)
AR19	-9.42	0.10	38 ± 5	62 ± 5	RDR
AR20	-8.96	0.12	50 ± 6	50 ± 6	RDR
AR21	-9.68	0.10	33 ± 5	67 ± 5	Nth Ashburton R.
AR22	-9.31	0. 10	42 ± 5	58 ± S	Nth Ashburton R.
AR23	-6.42	0.10	100 ± ?	0	
AR24	-8.96	0.10	15 ± 9	85 ± 9	Rakaia R.
AR26	-8.78	0. 10	23 ± 9	77 ± 9	Rakaia R.
AR27	-8.611	0.10	30 ± 9	70 ± 9	Rakaia R.

Note: RDR is the Rangitata Diversion Race
SE is the standard error; = 0.1 for rainfall and river sources
* variation due to measurement error of ^{18}O

3 year running mean temperature at Craigieburn) can result in a range in mean $\delta^{18}O$ of about 0.6 for the Waimakariri River. Variation of ± 0.3 in the values assumed for the river $\delta^{18}O$ values would result in an additional variation of ± 3-11% in estimated rainfall composition, with larger variations for lower percentage rainfall.

Seasonal variation of $\delta^{18}O$ in precipitation is damped by mixing during the residence in the river catchments. A similar process should occur in percolation of water through the soil profile and in the groundwater system. Quin and Burden (1979) showed that mixing and dispersion in the unsaturated alluvial gravels of Mid-Canterbury resulted in relatively constant chemical concentrations (coefficient of variation = 20%) below a depth of 3 m. Seasonal variation in ^{18}O values from precipitation should also be damped by the time recharge reaches the water table.

The estimated percentage of rainfall for the wells ranges from 7% for AR5 to 100% for AR23. Percentages are lower close to the rivers as would be expected.

Only in the centre of the study area does rainfall make up more than 50% of the groundwater. The $\delta^{18}O$ value for AR23 (-6.42) is less negative than the rainfall. Evaporation from the relatively shallow water table at this site, which could affect the isotope value, would be most likely at the end of summer when the sample was taken, and variability in the precipitation may not be fully damped out at the shallow well depth (about 5 m).

DISCUSSION

Some geographical variations in the well responses were indicated by the t-test comparisons (Table 3). For two wells changes in land use may have caused the observed changes in water quality. Irrigation began in the early 1980's on the farm upstream of well AR16. This would have increased production and leaching, and probably caused the observed increases in parameter concentrations. In the first survey, well AR24 had been affected by disposal of septic tank effluent upstream. This practice had stopped before 1990 and this was a factor in the significantly lower concentrations in 1990/91.

For wells adjacent to rivers which were common to both study periods (AR4, AR18, AR24, AR26), all the significant t-test results showed decreases in concentrations between 1978/79 and 1990/91. These wells were least influenced by rainfall, with percentages ranging from 12 to 31% (Table 4). In wells near the rivers the percentage of river water in 1990/91 is probably higher than it would have been in 1978/79, because the recharge from rainfall was much lower (Fig. 2) whereas recharge from the rivers would be more constant. River water generally has lower concentrations of ions than water which has percolated through the soil profile, resulting in a general decrease in chemical concentrations between 1978/79 and 1990/91.

The wells nearest the foothills (AR21, AR22 and AR23) had significant increases in chemical concentrations. These wells were not influenced by irrigation, and the lower volumes of recharge would have meant that the percolating water carried higher chemical concentrations. These wells were shallow (Table 1) and would respond to changes in recharge concentration more rapidly than the deeper wells downstream. Wells in the border strip irrigation area showed no clear trend, with both significant increases and decreases in parameter concentrations between the two study periods.

Apart from wells AR16 and AR23, which showed increased nitrate, the other six wells with significant changes in nitrate all showed decreases in concentration (Table 3). Three of the six wells (AR18, AR24, AR26) were adjacent to rivers and the other three were in the middle of the border strip irrigation area with recharge during the summer, although overall recharge was lower than in 1978/79. This would result in less nitrate-rich water reaching the groundwater. The mean nitrate-N concentrations for the 16 wells common to both studies were 5.3 g m^{-3} for 1978/79 and 5.0 g m^{-3} for 1990/91, a slight decrease which was not statistically significant.

Groundwater chemical concentrations seem mainly to be influenced by variability in recharge. There is no evidence that intensification in land use has resulted in nitrate concentration increases apart from that noted for well AR16. Increases in land use have been relatively minor (3-17%) compared to the much lower recharge, with 1990/91 amounts being 27%, 34% and 72% of 1978/79

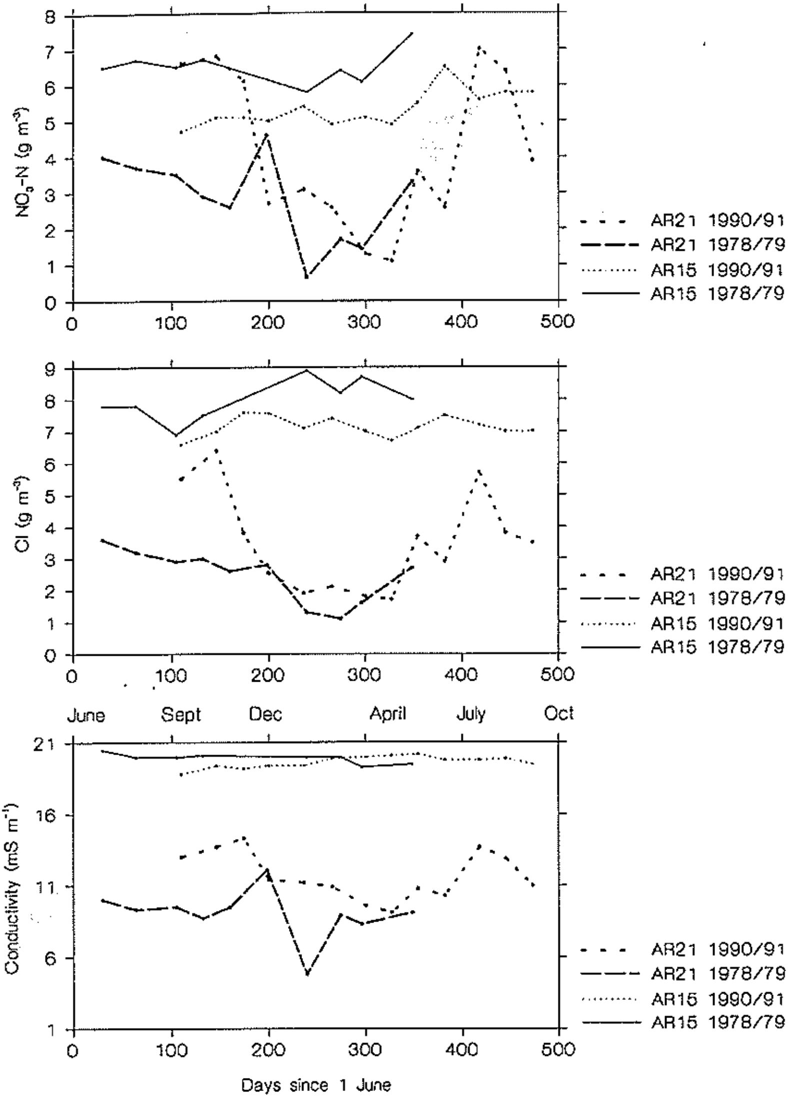

FIG. 3 — Seasonal variation in nitrate, chloride, and conductivity for AR15 (66 m deep) and AR21 (9 m deep) in the 1978/79 and 1990/91 study periods.

values for rainfall, rainfall plus spray irrigation and rainfall plus border strip irrigation, respectively.

There was a wide range in temporal variability of chemical parameters in both study periods (e.g., wells AR15 and AR21 for nitrate, chloride, and conductivity - Fig. 3). AR15 is in the middle of the border strip irrigation scheme and is moderately deep (66 m), whereas AR21 is just upstream of the scheme and is shallow (9 m). Both seasonal and random variations are indicated by the amplitude of seasonality for chloride and the standard deviations in Table 2. The variations reflect the depth below water table (Table 1) and the location of the well. Variability generally decreased with increasing depth below water table. An exception to this was well AR2 where both temporal variability and parameter concentrations were high even though the depth below water table was apparently about 70 m. The reason for this anomaly is unclear. Well location determined recharge patterns, and hence seasonal influences, i.e. wells within the Ashburton-Lyndhurst irrigation scheme were affected by recharge from rainfall plus border irrigation, whereas wells south of State Highway 1 were affected by recharge from rainfall plus spray irrigation.

The effect of recharge pattern on temporal variability in groundwater chemical concentrations can be seen for well AR21 (Figs. 2 and 3). Groundwater concentrations of ions rose in December 1978 and also in March and May 1979, particularly for nitrate, reflecting recharge from rainfall. In 1990/91, groundwater chemical concentrations generally decreased until May 1991 when concentrations rose with increasing recharge. Well AR15 varies much less with time because it is deeper and is recharged by rainfall plus border strip irrigation in every month for both study periods.

The oxygen isotope data (Table 4) indicate recharge sources for the groundwater that are consistent with likely flow paths and provide an estimate of the relative contribution of rainfall, irrigation and river recharge. There are some limitations in applying this technique to the study area. In areas with both rainfall and recharge from possibly two other sources (e.g., North Ashburton River and irrigation from the Rangitata Diversion Race), there is additional uncertainty (wells AR14, AR17 and AR18; Fig. 1). Because $\delta^{18}O$ values for the North Ashburton River and the diversion race are similar (Table 4), either could be a source of the non-rainfall portion of the groundwater. The estimate of the rainfall contribution should be much more precise because of the greater difference in $\delta^{18}O$ values between rainfall and surface water sources (Table 4). The amount of recharge from spray irrigation is difficult to estimate from the isotope data because groundwater is used for spray irrigation. The only opportunity for fractionation would be the brief period for evaporation while the water is being sprayed.

The southern part of the study area is recharged by rainfall, irrigation and river seepage. To refine estimates of the contribution from each of these sources, the relative contribution of rainfall and Rangitata Diversion Race were examined for two wells (AR11 and AR15) at the western edge of the irrigation scheme which should have inputs only from these two sources (Fig. 1). The oxygen isotope data indicate rainfall percentages in these two wells of 48%. Calculations were also made based on inputs from each of these sources, assuming that water from each source was transpired in approximately the same ratio as it was applied. Quin and Burden (1979), assuming simple displacement and a moisture content of 10% in the unsaturated zone, estimated that recharge from the surface should take about 7 years to reach the water table in the area around well AR15. Recent recharge has been slightly greater; making the same assumptions, it could take 5-7 years to reach the water table. Rainfall and irrigation data for 1983 to 1989 (2-8 years before isotope sampling) indicate rainfall was 49% of the total. This agrees with the oxygen isotope data and indicates that the assumptions are reasonable for these two wells. This suggests that, for wells within the Ashburton-Rakaia irrigation scheme (Fig. 1), there is about an equal contribution from rainfall and the diversion race. This will vary slightly because of the rainfall gradient in the area. Additional amounts indicated in Table 4 as "other source" would come from the North Ashburton River (wells AR12, AR14, AR18 and AR19). For example, for well AR14, Table 4 indicates that 25% comes from rainfall. The above suggests that another 25% comes from the diversion race and the remaining 50% from the North Ashburton River. Downstream from the irrigation scheme (e.g., AR3, AR7), the contribution of rainfall increases as there is no further input from the diversion race.

There is a general presumption that increasing intensity of land use will cause a steady decrease in groundwater quality. This study shows that consideration of recharge sources and patterns is vital to understanding changes in groundwater quality and that studies looking at the effects of land use on groundwater quality also need to consider recharge variability.

CONCLUSIONS

There were significant differences between the two study periods, with much more rainfall recharge during the 1978/79 period. The percentage changes were much greater for recharge amounts than for land use changes between the two periods. Groundwater quality was affected more by differences in recharge than changes in land use.

Wells with significant increases in groundwater chemical concentrations approximately equalled those with significant decreases; most changes reflected well location e.g., proximity to a river, and the differences in the recharge between the study periods. There were two examples (AR16 and AR24) of localised land-use changes which correlated with groundwater quality changes.

^{18}O isotope was used to indicate sources of groundwater recharge. The percentage contributed by rainfall ranged from 7% for well AR5 (near a river) to 100% for well AR23 (remote from rivers and upstream of any irrigation inputs). The percentage of rainfall-derived recharge increased with distance from the rivers as would be expected.

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