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Hydrological investigation at Howard East, N.T.

2. Eucalypt savanna site: soil physics and groundwater geochemistry

P.G. Cook, A.L. Herczeg, D. Pidsley, and R. Farrow

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HYDROLOGICAL INVESTIGATION AT HOWARD EAST, N.T.

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ABSTRACT

The work described in this report forms part of a larger project which aims to describe the water balance of the Howard River basin, Northern Territory, and to determine what effects groundwater extraction may have on the ecosystem. This report presents unsaturated zone soil water content and matric potential data from sites beneath the Eucalypt savanna, and concentrations of chlorofluorocarbons and carbon-14 measured in the groundwater. Stable isotopes of water (^{2}H and ^{18}O) were measured both on water samples extracted from unsaturated soils, and on groundwater samples. Most of the groundwater within the top 10 - 20 m of the aquifer is less than 40 years old, as evidenced by measurable concentrations of chlorofluorocarbons CFC-11 and CFC-12, and near modern ^{14}C. This data was used to estimate a net groundwater recharge rate of approximately 200 mm yr^{-1}. Stable isotopes suggest that the recharge is derived from large rainfall events, and undergoes little evaporation during transport through the unsaturated zone. Measurements of soil matric potential suggest that the vegetation is not dependent on groundwater for transpiration during the dry season.

1. INTRODUCTION

The Howard East basin has been identified as a future water supply for Darwin and its surrounds, to augment the current, predominantly surface water resource. A borefield on the western side of the Howard River is currently operational, and pumping from the Howard East basin is scheduled to begin within the next few years. Despite this, very little is known about recharge to the basin. Groundwater levels vary seasonally by up to 10 m, but much of the wet season recharge appears to be used by the vegetation during the dry season. In 1996, a collaborative project between Power and Water Authority (now Lands, Planning and Environment), Northern Territory University and CSIRO Division of Water Resources (now CSIRO Land and Water) was put together, and funded for a two-year period by LWRRDC (July 1996 - June 1998), although investigations by CSIRO had begun in 1994. The project aimed to quantify the effect of groundwater pumping on vegetation health, focussing on the Eucalypt savanna and paperbark swamp ecosystems. This report is the second in a series describing CSIRO’s contribution to the project. It describes the soil and groundwater components of the investigation into the hydrology of the Eucalypt savanna ecosystem.

2. SITE DESCRIPTION

The study area comprises the catchment of the Howard River, approximately 30 km southeast of Darwin (Fig. 1). A general description of the field area can be found in the first report in this series (Hatton et al., 1997). The hydrogeology of the basin on the western side of the Howard River is described in Jolly (1983).

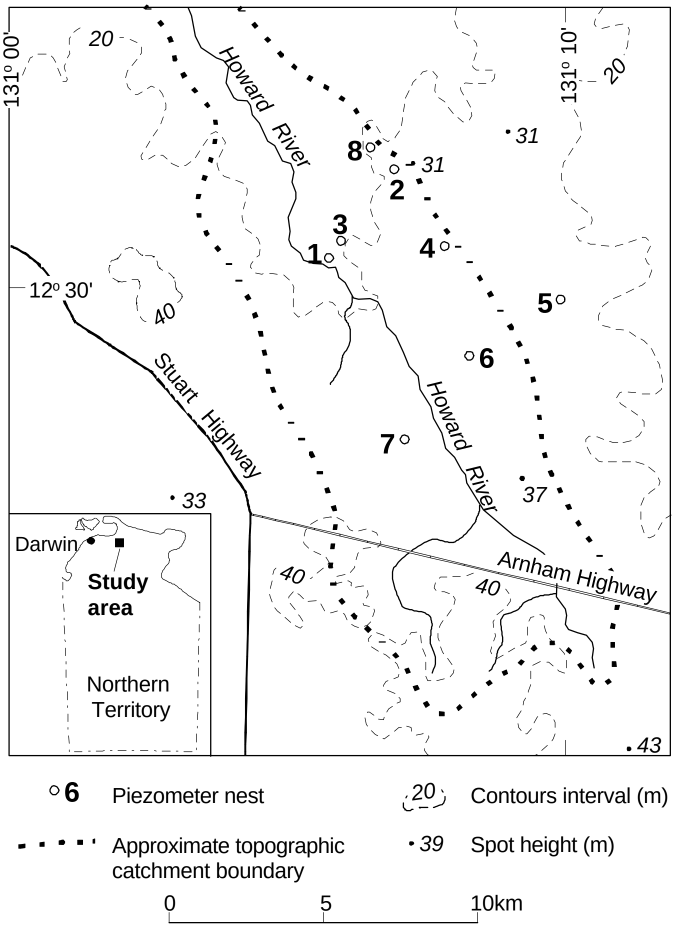

Figure 1. Location map.

3. SOIL PHYSICS

3.1 Introduction

This component of the project was designed to:

(i) determine the amount of soil water available to plants and used by plants, by measurement of the soil moisture characteristic, and by comparing in situ soil water contents and matric potentials at different times of the year;

(ii) estimate the specific yield of the aquifer material, to aid interpretation of bore hydrographs; and

(iii) if possible, determine the sources of water used by the vegetation, by comparing stable isotope ratios (^{2}H, ^{18}O) in groundwater, soil water and plant material.

3.2 Methods

Soil cores were obtained beneath Eucalypt savanna, near Piezometer Nest 4 (Fig. 1), using hollow-stemmed augers with wireline core recovery equipment. This was the same site as that used for the evapotranspiration investigation (Hatton et al., 1997). Soil coring to a depth of 6.35 m took place on 12 August 1996. After a mechanical breakdown on the following day, the hole was continued to 9.5 m on 15 August. At the time of drilling, the water table was at approximately 6.5 m depth. (The water level in bore 22069 was at 4.82 m below ground level (BGL) on 21.8.96

and 6.70 m BGL on 21.10.96.) Follow-up coring took place between 16-19 December 1996, less than 20 m from the first core site. The water table had fallen to approximately 8 m BGL at this time.

Drilling was accomplished without the addition of drilling fluids, and soil samples were immediately stored in airtight glass jars to minimise evaporation. Gravimetric water contents were determined by oven-drying at 105°C for 24 hours, and matric suctions were estimated using the filter paper method (Greacen et al., 1989). Deuterium concentrations were measured on soil water which had been extracted by azeotropic distillation. Moisture characteristics were measured on selected soil samples by equilibrating on pressure plates held at 15, 300 and 1300 kPa.

3.3 Results

3.3.1 Water Content and Matric Suction

Soil water contents and matric suctions are given in Table 1 and Fig. 2. Assuming a constant dry bulk density of 1.4 g cm^{-3}, and interpolating between sampled intervals, we estimate a total of 1655 mm of water stored in the profile to a depth of 9.10 m (an average of 182 mm per metre) in August 1996. In December, the quantity is estimated to be 1228 mm to 7.3 m (average of 168 mm per metre).

Matric suction profiles show a zone of drying between 4 and 6 m depth at both sampling times. A second zone of drying above 1.5 m depth in August was not apparent in December, presumably

Table 1. Results of soil coring near Nest 4.

Date Drilled	Sample No.	Depth (cm)	Water Content (g/g)	Matric Suction (kPa)	^{2}H (per mille)
12.8.96	101	60-70	0.056	2084	-62.9
	102	120-140	0.06	250	-56.3
	103	190-200	0.126	490	-42.5
	104	260-270	0.191	887	-29.9
	105	385	0.131	2743	-40.6
	106	530	0.129	4013	-42.2
	107	635	0.146	520	
15.8.96	108	635	0.157	338	
	109	670-680	0.083	94	-39.8
	111	790	0.164	85	
	112	850	0.12	293	
	113	920	0.106	54	
	114	950	0.122	15	-37.1

16.12.96	101	0-70	0.103	8
	102	70-140	0.109	61
	103	140-220	0.169	554
	104	220-300	0.118	671
	105	300-370	0.12	1590
	106	370-420	0.17	1275
	107	420-430	0.082	4203
	109	490-560	0.117	12597
	111	560-630	0.103	2218
	112	630-680	0.131	1127
	113	680-730	0.13	661

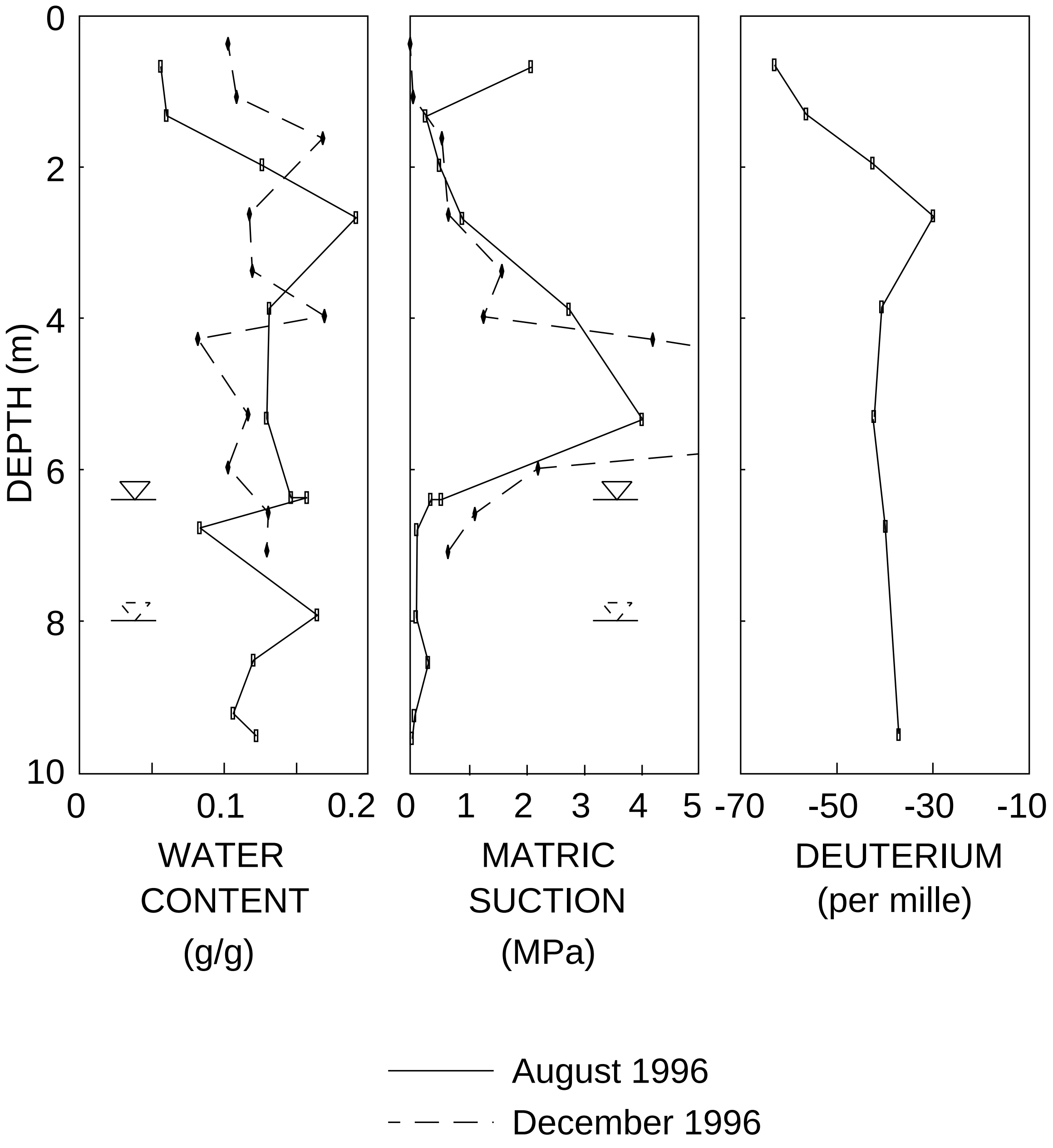

Figure 2. Soil profiles of gravimetric water content, matric suction and soil water deuterium, measured near Nest 4. Solid and broken triangles indicate approximate position of the water table in August and December, respectively.

as a result of early wet season rains. Matric suctions between 1.5 m and 2.5 m are less thanwilting point at both times of year, indicating availability of moisture to plants.

3.3.2 Deuterium

Deuterium (^{2}H) concentrations measured on water extracted from the soil core obtained in August 1996 are given in Table 1 and Fig. 2. Below 2 m, concentrations range between -29 and -43‰ (per mille), which is similar to concentrations measured in the groundwater (see Section 4.3.2). Above 2 m, concentrations are lower, probably reflecting the isotopic composition of the most recent rainfall.

3.3.3 Moisture Characteristic

Water contents at saturation, 30 kPa and 1500 kPa were measured by PAWA in December 1987 on samples from bores 25340, 25342 and 25341 in McMinns Borefield, west of the Howard River (Table 2). In the present study, moisture contents at 15 kPa, 300 kPa and 1300 kPa were measured on samples obtained in August 1996 (Table 3). From this data, it would appear that most of the soil water (0.2 - 0.25 g g^{-1}) is released between saturation (0 kPa) and field capacity (15 kPa). A further 0.04 - 0.05 g g^{-1} (on average) is released between 15 kPa and 300 kPa. Little additional water is released as the soil suction is increased to 1300 kPa.

Table 2. Pressure plate measurements of gravimetric water content on cores obtained from McMinns borefield.

Bore No.	Depth	Matric Potential (kPa)		
		0	30	1500
25340	2.7-5	0.339	0.13	0.099
	7.5-8	0.396	0.175	0.151
	8-10	0.382	0.225	0.191
	13-8	0.404	0.182	0.141
	20-23	0.328	0.139	0.114
	22-23	0.305	0.122	0.098
	25.5	0.315	0.066	0.05
	27.5	0.456	0.206	0.151
	32	0.476	0.228	0.211
25342	2	0.496	0.207	0.171
	4	0.456	0.207	0.157
	9.8	0.383	0.161	0.121
	13.5	0.37	0.153	0.142
	21	0.542	0.23	0.194
	30	0.295	0.092	0.075
	34	0.282	0.067	0.048
25341	0-0.1	0.385	0.071	0.049
	4	0.533	0.225	0.191
	8	0.456	0.184	0.153
	14	0.451	0.179	0.151
	20.5	0.507	0.239	0.199
	23.3	0.603	0.244	0.202
	31	0.287	0.063	0.046
	35	0.357	0.149	0.117
	37	0.453	0.249	0.218

Table 3. Pressure plate measurements of gravimetric water content on cores obtained from near Nest 4.

Site	Depth	Matric Potential (kPa)		
		15	300	1300
Hole1	1.2-1.4	0.082	0.057	0.058
	3.85	0.218	0.142	0.141
	6.35	0.191	0.148	0.148
	9.5	0.164	0.115	0.136

3.4 Discussion

The large difference between gravimetric water contents measured at saturation and field capacity cannot be easily reconciled with the magnitude of the seasonal water level variation (see Section 4.3.1), unless the soils are swelling clays. Thus the moisture characteristic measured in the laboratory is not representative of in situ conditions, because the overburden pressure has been removed.

The hydraulic potential (ϕ) of a swelling clay soil can be written

$$\phi = \psi_u + \Omega$$

where ϕ is the matric potential of the loaded soil, ψ_u is the matric potential of the unloaded soil, and Ω is the overburden potential occuring a depth z. In a uniform soil,

$$\Omega = \beta g \rho_{wb} z$$

where β is the compressibility factor, ρ_{wb} is the wet bulk density, g is the acceleration due to gravity, and z is depth below the soil surface (Marshall and Holmes, 1988:141). Thus a swelling clay soil under an overburden pressure of Ω = 35 kPa (z = 5 m, ρ_{wb} = 1.4 g cm^{-3}, β = 0.5), will be saturated (ϕ = 0) at an unburdened matric potential of - 35 kPa. (The water content of the saturated, loaded soil will be the same as an unloaded soil at a matric potential of -35 kPa.)

Figure 3 depicts the in situ moisture profiles of a uniform swelling clay soil, having the unloaded moisture characteristic shown in the inset of this figure. The in situ water contents at saturation, field capacity and wilting point will decrease with depth, and only at the surface will they be equal to the values measured on the pressure plate. Also shown on this figure is the equilibrium water content for a water table depth of 9 m. The equilibrium water content is defined by ψ_u = -h, where h is the height above the water table. It is the water content profile which will occur in a soil at equilibrium, i.e. no flow.

If, at the end of the dry season, the soil has a unburdened matric potential of close to wilting point (1500 kPa), then the specific yield will be the difference between wilting point and saturation. In our soils the matric potential at the end of the dry season is variable, but an average value of 1500 kPa is used for the purposes of these calculations. Thus the specific yield at the soil surface would be 0.2 - 0.3, but a depths of 2 - 10 m, it would be approximately 0.05 - 0.08. Using an average water level fluctuation of 7 metres (from 2 m to 9 m below the surface), this translates into a water deficit of 400 - 500 mm at the end of the dry season. However, most of this water goes into wetting the soil to the equilibrium water content (250 - 400 mm), and once this has occurred, only a further 100 - 150 mm is required to raise the water table.

Little discrimination in deuterium concentrations below 2 m depth in the soil profile limits the possibilities for using stable isotopes of water for determining the sources of water used for transpiration.

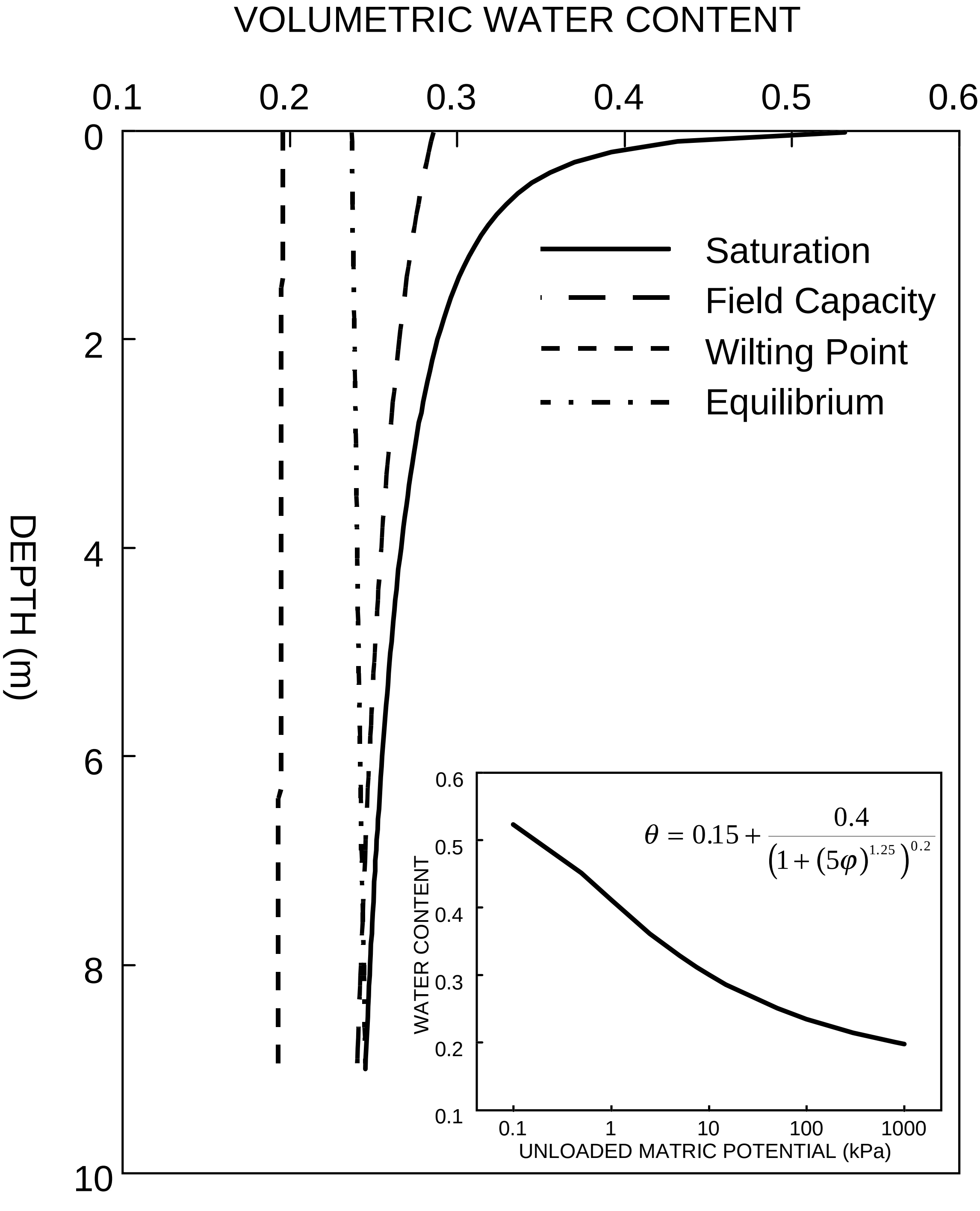

Figure 3. In situ moisture profiles for a uniform, swelling clay soil (ρ_{wb}=1.4 g cm^{-3}, β=0.5), with moisture characteristic given in the inset. The equilibrium water content profile is calculated for a water table at 9 m depth.

4. GROUNDWATER CHEMISTRY

4.1 Introduction

This component of the project aimed to:

(i) estimate net rates of groundwater recharge to the unconfined aquifer by groundwater dating in existing piezometer nests; and

(ii) identify recharge mechanisms using stable isotopes of water.

Groundwater dating was carried out using chlorofluorocarbons (CFCs) and ^{14}C. Chlorofluorocarbons are man-made organic compounds which are produced for a range of industrial and domestic purposes. Chlorofluorocarbons CFC-11 and CFC-12 have relatively long atmospheric lifetimes, and are the most abundant. Their atmospheric concentrations have been steadily increasing since the 1950s and are well documented (Fig. 4). Concentrations of CFC-11 and CFC-12 in groundwater have been used to estimate groundwater age, and hence to infer rates of vertical groundwater recharge (Busenberg and Plummer, 1992; Dunkle et al., 1993). Because of their short time-frame (up to 50 years), they are particularly well-suited to investigations of young groundwaters, with high recharge rates. Groundwater dating using ^{14}C has been described elsewhere (Mazor, 1991), and the reader is refered there for more information.

Stable isotopes of water (^{18}O and ^{2}H) are affected by evaporation and condensation processes, either during vapour or rain formation, or during residence within the top 1m or so of the soil

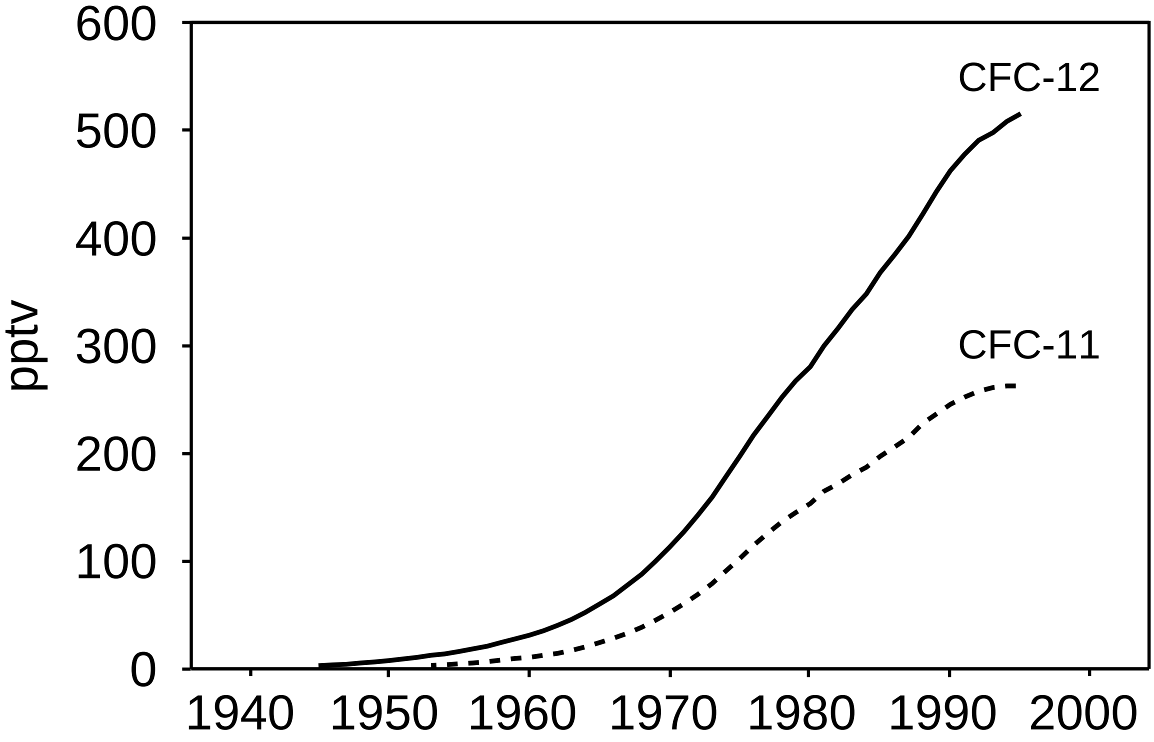

Figure 4. Atmospheric concentrations of CFC-11 and CFC-12, from 1940 to the present. Units are parts per trillion, by volume.

profile. Once they are at greater depth than that, and eventually in the groundwater, they behave conservatively and permanently record conditions at, or just prior to recharge.

4.2 Methods

A total of 25 piezometers were sampled. These were arranged in eight nests, each containing three or four piezometers. Piezometers were constructed of PVC or steel, with screen lengths ranging from 0.6 to 11 m. Chlorofluorocarbon samples were collected on three sampling trips, designed to coincide with the end of consecutive wet, dry and wet seasons. The first sampling trip was between 23 and 25 May 1995, the second between 25 and 27 October 1995, and the third between 15 and 17 April 1996. Piezometers from Nest 5 were not accessible in March 1995 or April 1996 because of inundation of the surrounding areas. They were sampled on 27 October 1995, and also on 6 June 1996. Further samples were obtained from selected piezometers between February 1997 and January 1998, to investigate seasonal variations in CFC concentrations. Samples for ^{18}O and ^{2}H were collected on 21-24 March 1995 and 25-27 October 1995. (Selected wells were also sampled in May and December 1996.) Samples for ^{13}C analyses were collected from selected piezometers in October 1995 and May 1996. ^{14}C samples were collected from four piezometers in May 1996. Full results of all chlorofluorocarbon analyses are presented in Appendix 1-4, and isotopic analyses in Appendix 5.

At least one well volume was pumped from each of the shallow wells prior to sampling. (For the deeper, larger diameter wells, it was considered that excessive well purging would disturb the hydrologic system. For these, the pump was positioned close to the water table, and the well was pumped for sufficient time to purge the screened interval.) Samples for ionic and isotopic analyses were obtained directly from the pump outlet. Samples for CFC analyses were collected from the screened interval using a sealed copper or stainless steel bailer, in a manner similar to that described by Cook et al. (1995).

Chlorofluorocarbon concentrations were measured by gas chromatography at CSIRO Land and Water, Adelaide, using a purge and trap system. The principles of the system are described by Bullister and Weiss (1988). Analytical precision for CFC-11 is approximately ± 2% at 500 pg kg^{-1}, ± 5% at 100 pg kg^{-1}, and ± 20% at 20 pg kg^{-1}. Analytical precision for CFC-12 is ± 2% at 500 pg kg^{-1}, ± 10% at 100 pg kg^{-1}, and ± 30% at 20 pg kg^{-1}. Corresponding errors in apparent CFC ages are approximately ± 2 years for ages less than 20 years, increasing to ± 4 years for ages of 40 years. The detection limit for both CFCs is approximately 5 pg kg^{-1}, which corresponds to a groundwater age of approximately 40 years (at a recharge temperature 28°C). The sampling blank is estimated to be < 5 pg kg^{-1} for CFC-12 and < 20 pg kg^{-1} for CFC-11.

^{18}O and ^{2}H were measured using the CO_2 equilibration technique. ^{14}C and ^{13}C were measured after first precipitating the dissolved inorganic carbon as $BaCO_3$. ^{14}C was analysed using a liquid scintillation counter and the direct absorption method (Leaney et al., 1994).

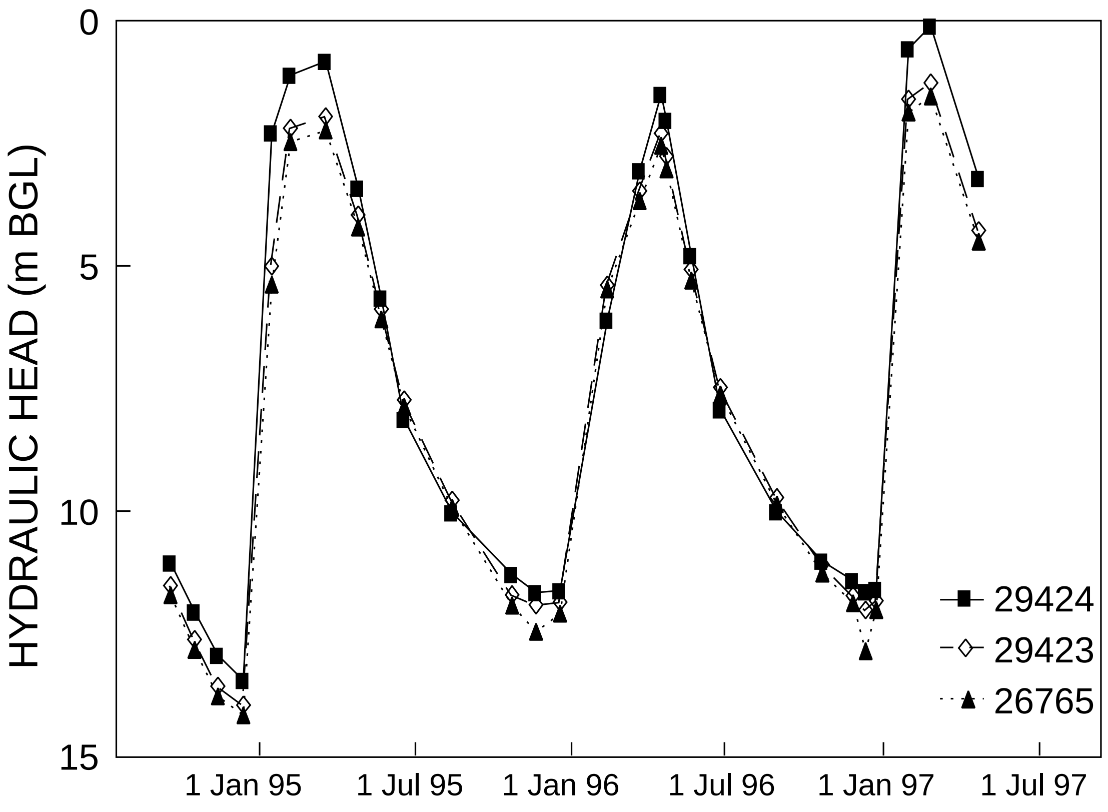

Figure 5. Groundwater hydrographs measured in Nest 2.

4.3 Results

4.3.1 Groundwater Levels

The annual water level variation averages approximately 7 m, and sampling times were designed to coincide with times of highest and lowest water table (at the end of the wet and dry seasons). In most nests, a downward head gradient exists throughout the the year, and averages between 0.01 and 0.03 m m^{-1}. The gradient is typically greatest towards the end of the wet season, when the water table is highest (March), and declines during the dry season (Fig. 5). In some nests, a small gradient reversal occurs towards the end of the dry season, which may indicate net groundwater discharge at this time. This may be due to groundwater use by vegetation, or by upwards water movement from the groundwater in response to evapotranspiration from the unsaturated soil.

Anomalies are apparent in Nests 3, 4 and Nest 7. In Nests 3 and 7, a downward head gradient is observed between the shallowest and intermediate piezometers at all times, but an upward gradient exists between the intermediate and the deepest piezometers. In Nest 4, a downward gradient exists between the upper piezometer and the other three, although the third piezometer displays a significantly higher head than the piezometers both above and below it at all times (see Table 4).

Table 4. Groundwater chemistry.

				March - April 1995					October 1995						April - May 1996						
Nest	Well	Screen (m BGL) Top	Bottom	SWL (m BGL)	EC (uS cm^{-1})	CFC-11 (pg kg^{-1})	CFC-12 (pg kg^{-1})	DO (mg l^{-1})	SWL (m BGL)	EC (uS cm^{-1})	CFC-11 (pg kg^{-1})	CFC-12 (pg kg^{-1})	DO (mg l^{-1})	^{13}C (per mille)	SWL (m BGL)	EC (uS cm^{-1})	CFC-11 (pg kg^{-1})	CFC-12 (pg kg^{-1})	DO (mg l^{-1})	^{13}C (per mille)	^{14}C (pmc)
1	29390	4.0	7.0	2.19	74	38	106	0.0	5.19	114	92	84		-19.76	1.2	67	17	-			
	29389	11.0	15.0	2.32	53	111	61	0.0	5.2	125	44	35	0.0	-19.99	1.65	18	144	113	0.1		
	29388	22.0	28.0	2.44	330	0	23	0.0	5.3	308	19	5	0.0	-12.81	1.76	293	2	38	0.0		
2	29424	15.0	20.0	5.63	22	278	161		11.27	22	203	119	2.9		-0.93		252	157			
	29423	30.0	35.0	5.86	217	30	32		11.69	209	-	35	0.8	-19.00	-0.82		13	30			
	26765	56.0	62.0	6.06	423	37	26		11.9	434	43	30	0.0		-0.86		12	12			
3	29422	12.0	16.0	3.72	35	21	-	0.4	7.69	48	65	115	0.4	-20.36	2.65	35	97	109	1.0		
	21760	31.0	33.0	4	362	-	5		7.98	376	0	0	0.0	-10.22	3	353	5	-	0.1		
	29421	34.0	37.0	3.69	382	3	2	0.0	7.65	378	0	0	0.0	-12.16	2.7	295	8	20	0.0		
4	22069	12.7	17.0	1.07	22	84	74		6.96	23	57	79	4.3		0.19	18	263	177	7.7		
	22068	34.0	36.0	3.35	148	22	60		8.67	52	95	79			2.39	92	66	67	0.0		
	21767	40.0	45.8	1.35	65	-	30		7.3	24	8	3	0.0		0.61	21	10	7	3.7		
	21765	48.0	56.0	4.42	137	96	74		9.37	143	77	72	2.4		3.4	132	94	79	3.7		
5	29427	5.0	10.0	-0.47					3.38	160	170	128			0.79	149	91	208	3.2		
	29426	18.0	21.0	-0.7					3.39	113	6	44	0.0		0.47	125	34	44	0.0		
	29425	30.0	35.0	6.92					12.52	318	14	10	1.4		7.68	335	17	15	1.3		
	21046	60.0	70.8	9.87					16.06	220	0	0	0.0		10.69	223	25	9	0.0		
6	22170	6.9	7.5	5.26	48	217	146		Dry						3.38	21	50	58	2.6	-23.8	112.3+/-2.0
	22171	26.0	28.0	6.31	42	85	21		10.23	36	10	11	0.9		5.19	27	20	26	1.1	-22.4	94.8+/-1.9
	20497	51.0	57.5	6.79	325	44	6		10.75	277	9	0	0.0		6.1	240	6	14	0.0	-12.8	52.6+/-1.4
7	22175	11.6	14.6	7.62	92	101	80		8.56	130	29	76	1.3		5.25	97	92	109	0.3	-19.2	118.8+/-3.2
	22176	22.0	24.0	7.84	170	0	32		10.86	257	0	0	0.0		11.64	144	0	8	0.0		
	22177	23.0	26.0	7.455	26	153	105		8.385	26	26	25	2.6		5.015	26	18	18	2.2		
8	22066	7.2	13.0	7.13	22	142	142		12.3						1.8	22	183	163	3.7		
	22067	14.0	20.0	8.14	22	206	145		13.45	22	197	118	0.8		3.25	22	195	135	1.3		

4.3.2 Stable Isotopes of Water (^{18}O, ^{2}H)

Most groundwater samples fall close to the global meteoric water line, with ^{18}O concentrations between -4.6 and -6.6 ‰, and ^{2}H concentrations between -29.9 and -44.7 ‰ (Fig. 6, Appendix 5). This is indicative of recent rainfall with little evaporation. The long-term weighted mean for Darwin rainfall is ^{2}H = -29.7 ‰, ^{18}O = -5.04 ‰. Most groundwater data are significantly depleted in heavy isotopes of water relative to the mean rainfall, and this reflects the importance of large rainfall events in contributing to recharge. (Rainfall derived from large events is depleted in heavy isotopes, a phenonema which is know as the 'amount effect'.) The relatively small spread in isotope composition for most groundwater samples (15 ‰ in deuterium compared with over 80 ‰ for monthly rainfall) suggests that there is sufficient storage in the soil zone to even out month to month variations.

Stable isotopic compositions from three wells, occur significantly to the right of the meteoric water line, and fall on a line with a slope of approximately 6.5. These are the two shallowest and the deepest wells at Nest 5, which is adjacent to a permanent waterhole. The slope of the line is indicative of evaporation from an open water body. However, the stable isotopic composition of water from well 29425, which is screened between 30 and 35 m below ground, shows no significant evaporation. Hence, the upper two wells (29427, 29426) are believed to represent recharge derived from the waterhole, whereas the third (29425) appears to represent regional groundwater, derived from recharge areas upgradient. The deepest piezometer also has a signal suggesting open water evaporation, and may represent recent recharge from adjacent waterholes.

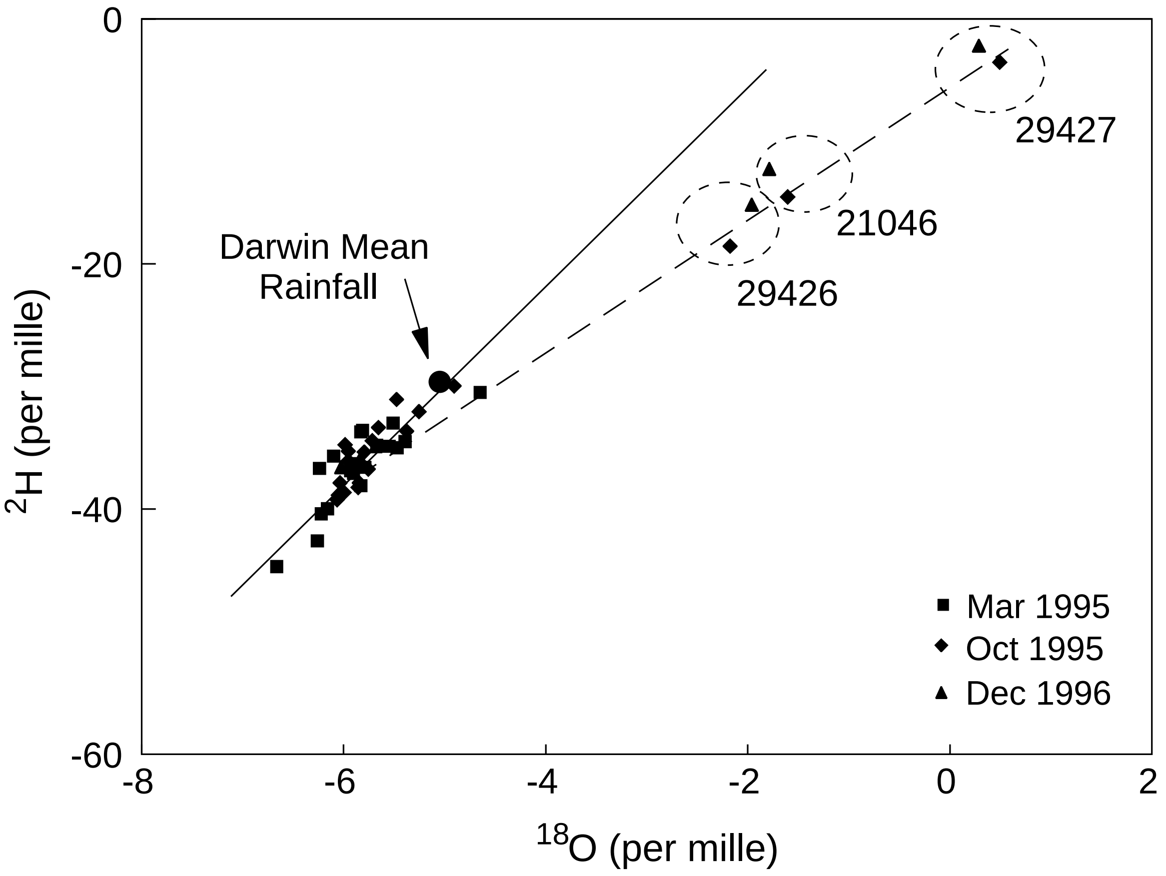

Figure 6. ^{18}O and ^{2}H concentrations on groundwater samples. The solid line depicts the global meteoric water line.

4.3.3 Chlorofluorocarbons

CFC- 11 and CFC- 12 concentrations measured between March 1995 and May 1996 are presented in Table 4. In Fig. 7, measured CFC-11 and CFC-12 concentrations from all piezometers are plotted against each other. Also shown is the trend which would be expected from water in equilibrium with the atmosphere at a temperature of 28°C. Water in equilibrium with the modern atmosphere would be expected to have CFC-11 and CFC-12 concentrations of 336 and 165 pg kg-’ respectively, and recharge in earlier years should have lower concentrations. (The mean annual air temperature at Darwin is 28°C and so the temperature at the base of the unsaturated zone, where partitioning of dissolved gases into groundwater recharge occurs, should be close to this value.) All of the data fall well below this equilibrium line, except at very low concentrations where measurement error and sampling blanks become significant. Degradation of CFC-11 has been widely reported in anaerobic environments (Dunkle et al., 1993; Cook et al., 1995; Katz et al., 1995) and is the most likely explanation for this. Even though several samples which appear depleted in CFC-11 contain high oxygen concentrations, it is possible that some part of the soil profile becomes anaerobic seasonally, and that degradation occurs at this time. Because CFC-11 is not behaving conservatively, only CFC-12 concentrations will be used to infer groundwater ages and flow velocities.

In two cases, measured CFC-12 concentrations were significantly in excess of water in equilibrium with the modern atmosphere at 28°C (wells 22069 and 29427 sampled in April 1996). It is possible that these are due to groundwater recharge which occured rapidly following large rainfall events, during which the temperature was somewhat less than 28°C. If the water temperature did not equilibrate with the soil temperature before recharge occured, then higher CFC concentrations

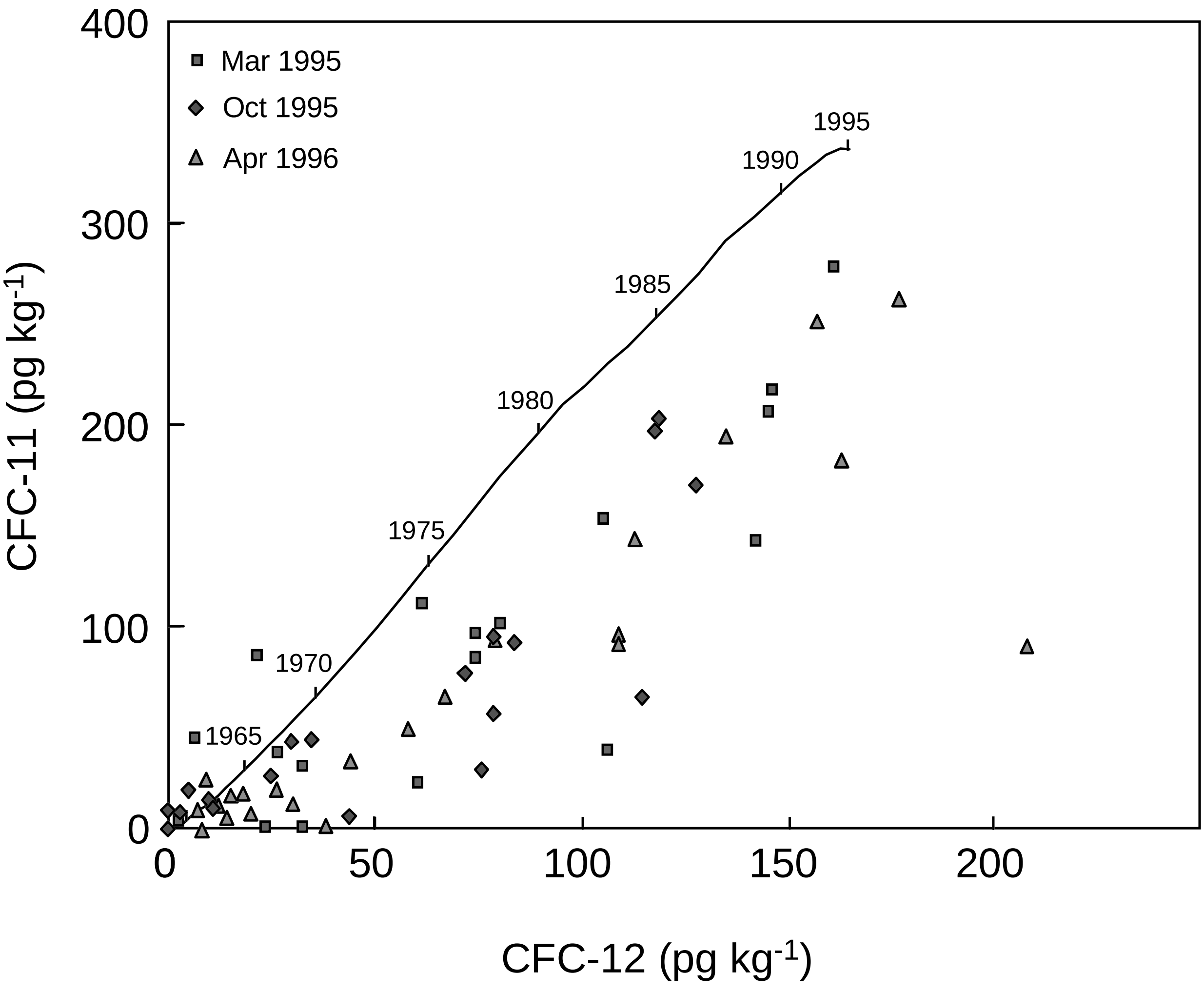

Figure 7. CFC-11 and CFC-12 concentrations measured in piezometers. The curve indicates concentrations which would be expected from water in equilibrium with the atmosphere at a temperature of 28°C. Measured data fall mostly to the right of this line, suggesting anaerobic degradation of CFC-11.

would be possible. (Water in equilibrium with the modern atmosphere at a temperature of 22 °C, would have a CFC-12 concentration of 204 pg kg^{-1}.)

Apparent CFC-12 ages are presented in Table 5. The latter are calculated by converting the measured CFC concentrations (pg kg^{-1}) to equivalent atmospheric concentrations (pptv) using the known solubility (Warner and Weiss, 1985) and assuming a recharge temperature of 28 °C. In most piezometer nests, concentrations of CFC-12 decrease with depth, with is consistent with increasing groundwater ages. Figure 8 depicts CFC-12 concentrations at all sites, plotted against depth below the water table at the end of the dry season (as measured in October 1995). The vertical bars on this figure indicate the vertical extents of the well screens. The horizontal bars do not indicate measurement uncertainty (which is relatively small), but rather the seasonal variation in concentration which was observed in each piezometer. Most of the data from the shallow piezometers (screens within 5 - 10 m of the dry season water table) have concentrations between 100 and 150 pg kg^{-1}, although there is considerable variability in concentrations measured at different times throughout the year. In most cases, CFC-12 concentrations in piezometers with screens below 20 m depth are less than 50 pg kg^{-1}.

Two piezometers lie significantly away from the trend apparent from most of the data, with concentrations greater than 50 pg kg^{-1} at depths below 25 m. Both of these piezometers are from Nest 4 (22068 and 21765) and suggest some preferential flow of young water to these depths. It is not clear whether this represents preferential flow through the soil, or poor piezometer completion. At Nest 7, the deepest piezometer (22177) has a higher hydraulic head than the intermediate piezometer (22176) and also higher CFC and dissolved oxygen concentrations and

Table 5. Apparent CFC-12 ages.

		Screen (m BGL)		Age (yrs)		
Nest	Well	Top	Bottom	03/95	10/95	04/96
1	29390	4.0	7.0	13	18	-
	29389	11.0	15.0	22	27	13
	29388	22.0	28.0	31	>40	27
2	29424	15.0	20.0	3	11	5
	29423	30.0	35.0	28	27	29
	26765	56.0	62.0	30	28	38
3	29422	12.0	16.0	-	11	13
	21760	31.0	33.0	>40	>40	>40
	29421	34.0	37.0	>40	>40	33
4	22069	12.7	17.0	19	19	1
	22068	34.0	36.0	22	19	22
	21767	40.0	45.8	28	>40	>40
	21765	48.0	56.0	20	20	20
5	29427	5.0	10.0		9	1
	29426	18.0	21.0		25	26
	29425	30.0	35.0		39	36
	21046	60.0	70.8		>40	>40
6	22170	6.9	7.5	6		23
	22171	26.0	28.0	32	39	31
	20497	51.0	57.5	>40	>40	>40
7	22175	11.6	14.6	19	19	13
	22176	22.0	24.0	28	>40	>40
	22177	23.0	26.0	13	30	34
8	22066	7.2	13.0	7		4
	22067	14.0	20.0	7	11	9

Note : An estimated blank of 5 pg/kg has been subtracted from the measured values before ages have been calculated.

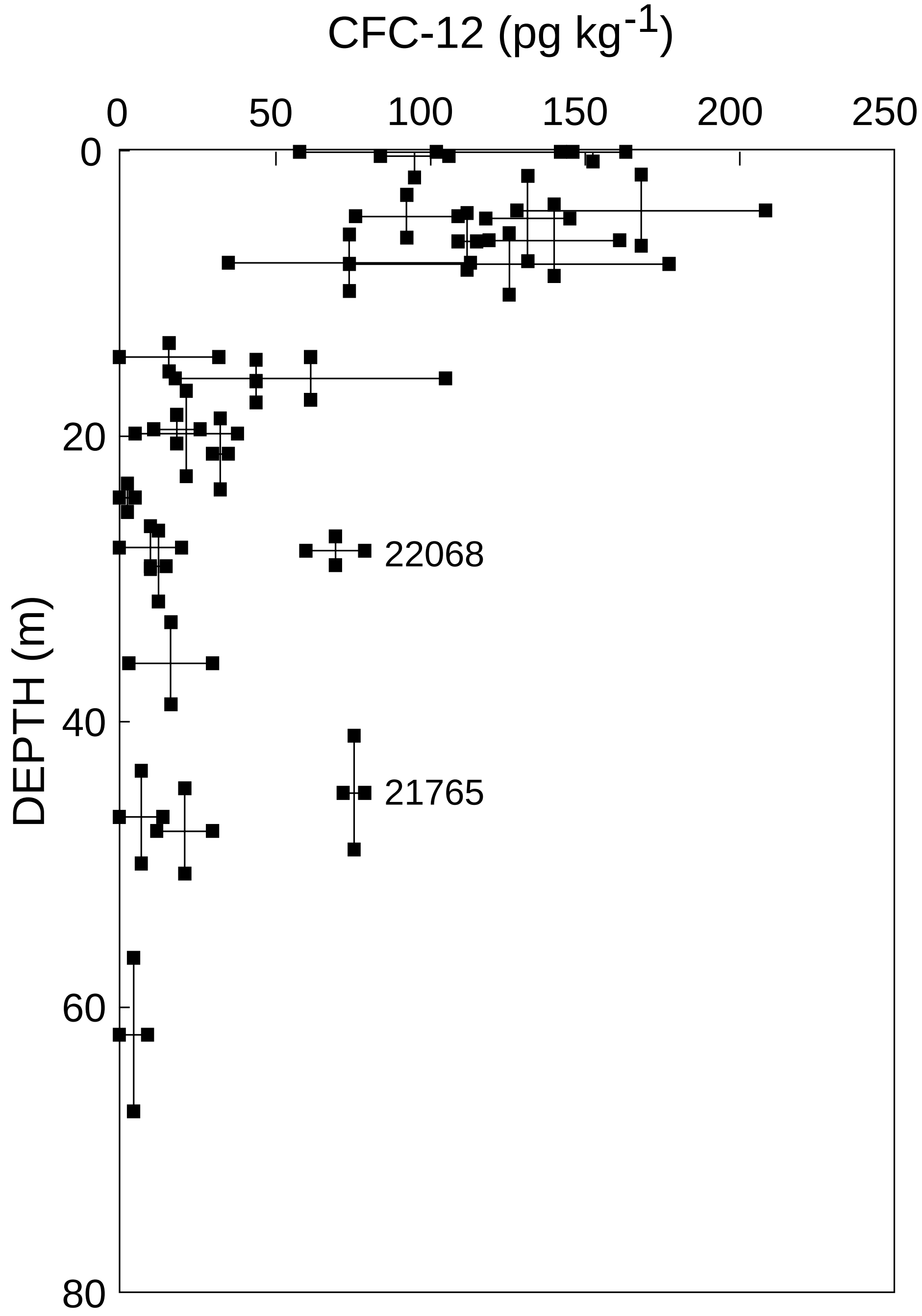

Figure 8. CFC-12 concentration versus depth below the permanent water table. Horizontal bars indicate the range of values measured at different sampling times. Vertical bars indicate the vertical extent of the well screen.

a lower electrical conductivity. These parameters are all similar to those measured in the upper piezometer (22175).

Figure 9 plots CFC-12 concentrations measured in May 1996, against those measured in the same wells in October 1995. Much of the data falls close to the Y=X line, although many wells plot to the right of this line, indicating that CFC-12 concentrations measured in May 1996 were significantly higher than those measured on the same wells in October 1995. This temporal variation in concentration, which may have a seasonal pattern to it, is most apparent for the shallower piezometers. Fig. 10 shows CFC-12 concentrations measured between May 1995 and January 1998. In well 29424 (Nest 2), measured CFC-12 concentrations were 161 pg kg^{-1} in March 1995, 119 pg kg^{-1} in October 1995, 157 pg kg^{-1} in April 1996, 109 pg kg^{-1} in December 1996, and 43 pg kg^{-1} in January 1998. Concentrations in the intermediate piezometer in the same nest (well 29423) were relatively stable. The concentrations in the shallow piezometer correspond to ages of 3, 11, 5, 14 and 27 years respectively. Similarly, the shallow piezometer in Nest 5 (well 29427) had apparent ages of 9 years in October 1995, and <1 year in April 1996.

4.3.4 Carbon Isotopes (^{14}C and ^{13}C)

^{14}C activities were measured on samples from Nest 6 (wells 22170, 22171 and 20497) and from the shallowest piezometer in Nest 7 (22175). Both shallow piezometers (22170 and 22175) had ^{14}C activities in excess of 100 pmc, indicating groundwater which recharged the aquifer since 1960. Well 22171 has a ^{14}C activity of 94.8 ± 1.9 pmc, suggesting a groundwater age between 35 and 500 years. (^{14}C is relatively insensitive over this timescale.) This is consistent with an

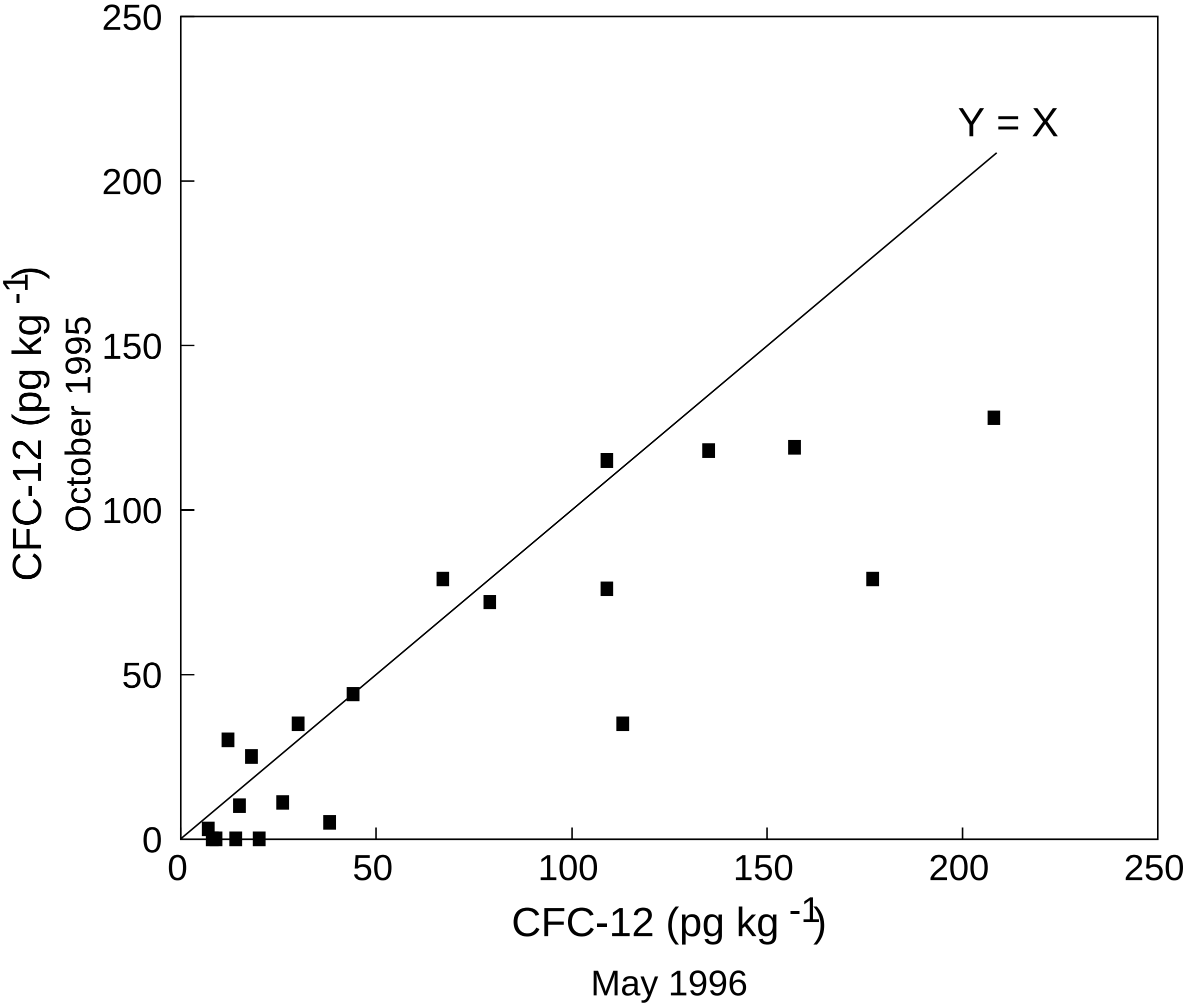

Figure 9. Comparison of CFC-12 concentrations measured in October 1995 and May 1996.

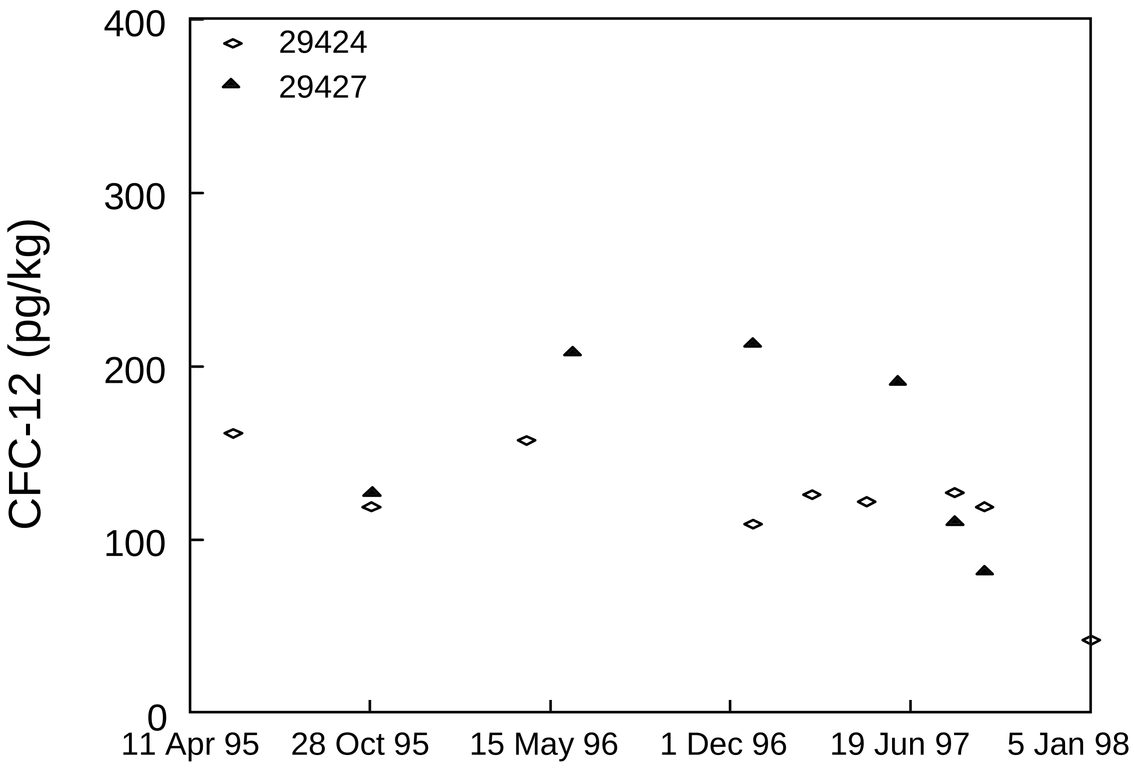

Figure 10. Seasonal variations in CFC-12 concentrations measured in selected shallow piezometers.

apparent CFC-12 age of between 30 and 40 years (Table 5). ^{13}C concentrations in these wells were between -19.2 and -23.8‰. Well 20497 has a ^{14}C activity of 52.6 ± 1.4 pmc, but its ^{13}C concentration is significantly more enriched than in the other samples (-12.8 ‰). This indicates that exchange with aquifer carbonates has occured, which has lowered the ^{14}C concentration. (This piezometer is screened in the dolomite aquifer.)

4.4. Discussion

Groundwater ages determined with CFC-12 and ^{14}C are in good agreement, although the latter has poor resolution over the relevant timescales. CFC-12 concentrations usually decrease with depth within the aquifer, which is consistent with increasing groundwater ages. However, in a few cases, anomalously high concentrations, or reversed gradients (increasing concentrations with depth) were observed. Often, these same wells displayed reversed (upward) hydraulic gradients. This is probably due to preferential flow within the aquifer, which is highly heterogeneous.

The seasonal variation in groundwater age which is apparent from the CFC data may also be explained by preferential flow through soil macropores during the wet season. If most of the recharge occurs as macropore flow, then groundwater ages during the wet season would be youngest in piezometers which sampled these macropores. Over the dry season, mixing of recent recharge, with recharge from previous years (in the aquifer matrix), would result in apparent increases in groundwater age.

Using this model, the groundwater age measured at the end of the dry season would provide a better indication of the mean age of the water in the aquifer. Figure 11 is a plot of the lowest concentration measured in each of the piezometers (usually that measured in October 1995) versus depth (midpoint of the well screen) below the dry season water table. Also shown are results of a model simulation depicting concentration depth profiles under vertical, one-dimensional flow at recharge rates between 50 and 200 mm yr^{-1} (porosity = 0.25, dispersivity = 0.02 m). Although there is considerable scatter, largely reflecting site to site variability, most of the data points fall between these curves.

The model depicted in Fig. 11 however, assumes that soil gas concentrations immediately above the water table are in equilibrium with the atmosphere. This may not be the case if the unsaturated zone is deep or of heavy texture (Cook and Solomon, 1994). In this case, there will be a finite time lag associated with diffusion of atmospheric gases through the unsaturated zone. Consequently, soil gas concentrations immediately above the water table will be lower than atmospheric concentrations. This problem is compounded where there is a large seasonal variation in the water table. It appears to be an important process at this site because concentrations in the shallowest wells are significantly below equilibrium values. In particular the water table was within the well screen at 29390 (Nest 1) in October 1995, and so the water table sampled from this well would have been expected to be in equilibrium with the atmosphere (165 pg kg^{-1}). However, a much lower concentration (84 pg kg^{-1}) was measured (apparent age of 18 years). Also, well 22170 (Nest 6) was dry in October 95, and yet water sampled from the piezometer in April 1996, which must have recharged during the preceeding wet season, had an apparent groundwater age of 23 years.

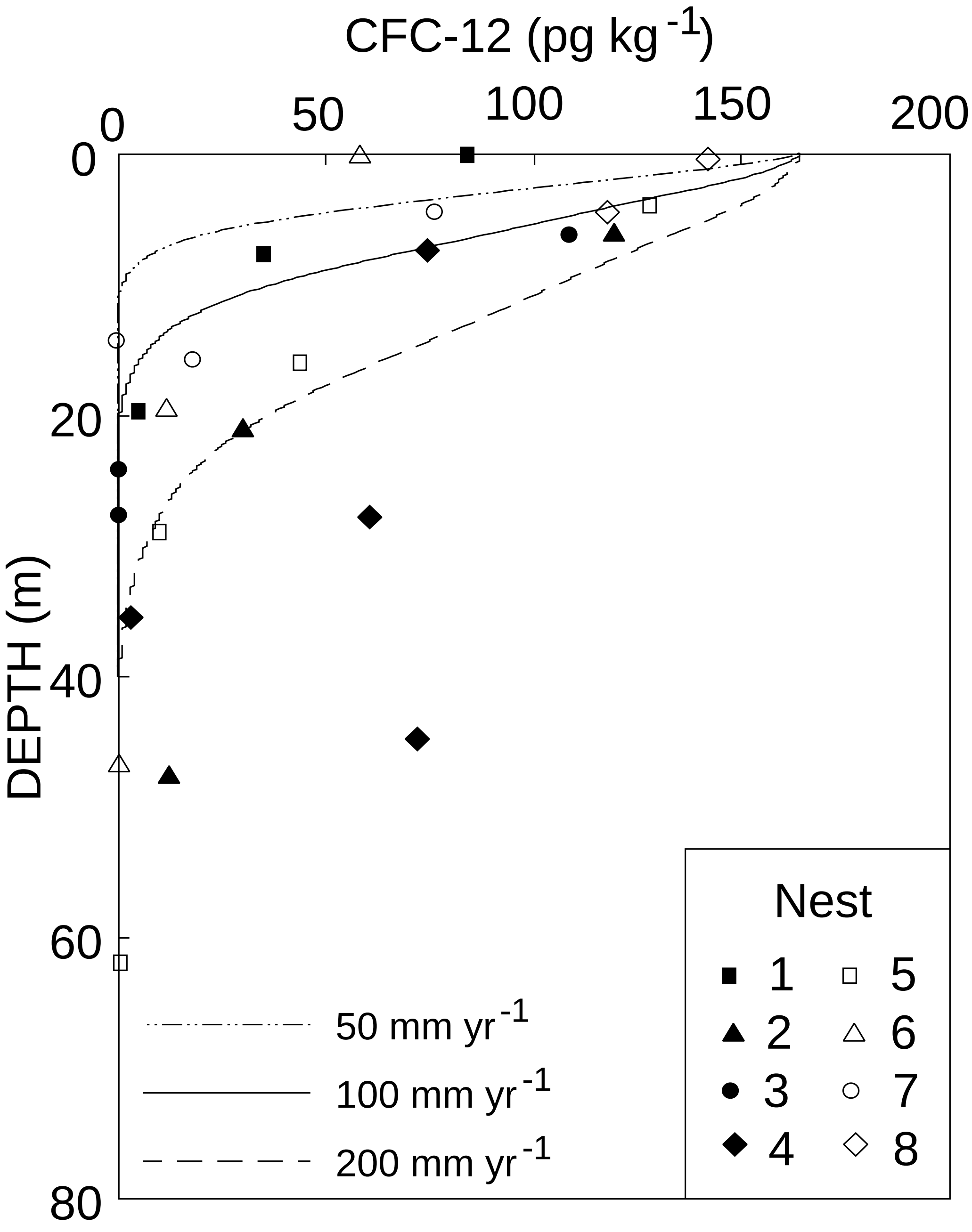

Figure 11. Lowest measured CFC-12 concentration versus depth below the dry season water table (October 1995). Curves indicate results of a one dimensional solute transport model at recharge rates between 30 and 200 mm yr^{-1}, and assuming a porosity of 0.25.

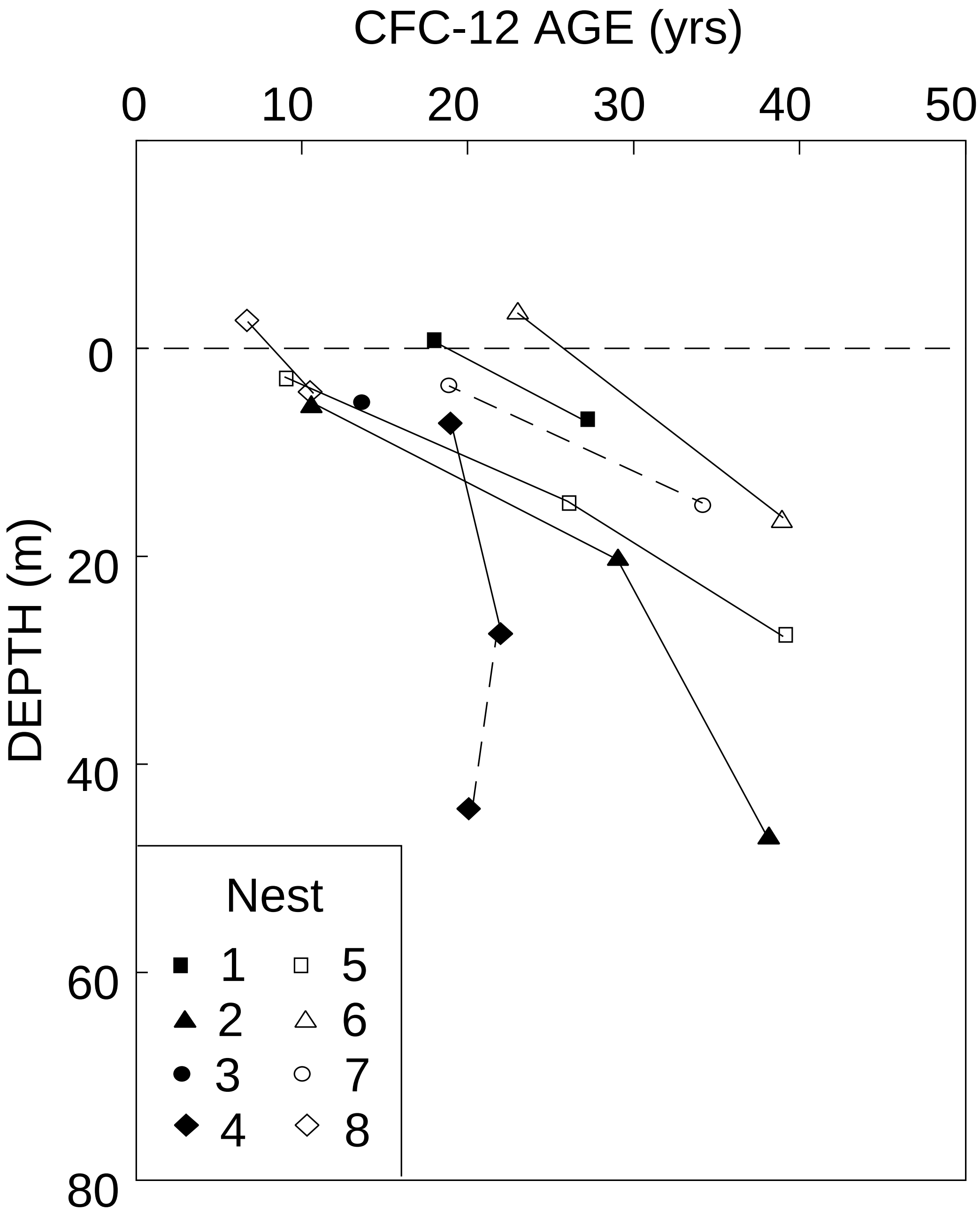

Figure 12. Maximum measured CFC-12 age versus depth below the dry season water table (October 1995).

Figure 12 depicts maximum CFC-12 ages mesured in each of the piezometers, versus depth below the dry season water table. Slow diffusion of CFCs through the unsaturated zone will result in non-zero CFC ages at the water table, but the age gradient below the water table should not be affected. Lines have been drawn on this plot to connect ages obtained on piezometers within the same nest. Groundwater age gradients observed in Nests 1, 5, 6, 7, 8 and between the upper two piezometers in Nest 2 are all between 0.6 and 1.3 years per metre, with the average gradient being approximately 1.2 years per metre. This is equivalent to a vertical groundwater velocity of 0.8 m yr^{-1}. Assuming predominantly one-dimensional flow, and a porosity of 0.25, this gives a recharge rate of approximately 200 mm yr^{-1}.

Shallower age gradients (more vertical lines on Fig. 6) are apparent in Nest 4 and between the deeper two piezometers in Nest 2, and may be the result of preferential flow.

5. CONCLUSIONS

Chlorofluorocarbon profiles were interpreted using a piston flow model, to estimate a net recharge rate of approximately 200 mm yr^{-1}. However, significant variations in groundwater age occur throughout the year, with younger ages apparent at the end of the wet season. This is believed to reflect rapid preferential flow of water through soil macropores. Several wells appear to intersect young water at great depth, which cannot be explained in terms of piston flow. It is also possible that purging the wells has induced some of this preferential flow. Nevertheless, we believe that the CFC-12 ages obtained at the end of the dry season (after mixing of recent recharge with older water in the aquifer matrix) provide a reasonable estimate of the mean groundwater age. Where they were measured, ^{14}C ages are consistent with CFC-12 ages.

The soil moisture defecit at the end of the dry season is estimated at 400 - 500 mm, although because of the swelling nature of the soils, considerable uncertainty should be attached to this figure. Measurements of soil matric suction in August and December 1996 suggest that plants are not dependent on groundwater for transpiration during the dry season.

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APPENDIX 1 : HOWARD EAST CFC ANALYSES : MAY 1995

Recharge Temp. (K) : 301

Well	Replicate	Date Collected	Date Analysed	Salinity (ppt)	Concentration (pg/kg) CFC-11	CFC-12	Concentration (pptv) CFC-11	CFC-12	Age CFC-11	CFC-12	Comments
29390	2	24.5.95	23.8.95		38	94					
	3	24.5.95	21.8.95		-	118					
	Mean			0.035	38	106	30	330	1966	1983	
29389	1	24.5.95	23.8.95		120	61					
	2	24.5.95	23.8.95		108	52					
	3	24.5.95	23.8.95		106	70					
	Mean			0.019	111	61	87	190	1973	1974	
29388	1	24.5.95	27.7.95		-	13					H_2S interference
	3	24.5.95	21.8.95		0	33					
	Mean			0.181	0	23	0	72	< 1950	1966	
29424	1	25.5.95	28.7.95		277	170					
	2	25.5.95	28.7.95		304	163					
	3	25.5.95	8.8.95		253	149					
	Mean			0.016	278	161	216	501	1987	1993	
29423	1	25.5.95	28.7.95		40	42					
	2	25.5.95	8.8.95		25	28					
	3	25.5.95	10.8.95		25	27					
	Mean			0.137	30	32	23	101	1965	1969	
26765	1	25.5.95	28.7.95		39	31					
	2	25.5.95	28.7.95		31	29					
	3	25.5.95	8.8.95		42	17					
	Mean			0.044	37	26	29	80	1966	1967	
29422	2	24.5.95	25.8.95		18	-					
	3	24.5.95	24.8.95		23	129					CFC-12 may be double peak
	Mean			0.036	21	-	16	0	1963	< 1940	
21760	1	24.5.95	25.8.95		-	7					
	2	24.5.95	25.8.95		-	3					
	Mean			0.1752	-	5	0	16	< 1950	1955	
29421	1	24.5.95	28.7.95		-	6					H_2S interference
	2	24.5.95	25.8.95		4	0					
	3	24.5.95	25.8.95		2	0					
	Mean			0.166	3	2	2	6	1954	1950	
22069	1	23.5.95	20.7.95		105	88					
	2	23.5.95	19.7.95		63	60					
	Mean			0.011	84	74	65	231	1971	1976	
22068	1	23.5.95	26.7.95		-	51					H_2S interference
	2	23.5.95	5.7.95		-	61					H_2S interference
	3	23.5.95	19.7.95		22	69					
	Mean			0.024	22	60	17	188	1963	1974	
21767	1	23.5.95	19.7.95		86	35					
	2	23.5.95	19.7.95		-	25					interference from previous sample
	3	23.5.95	26.7.95		-	-					interference from previous sample
	Mean			0.000	86	30	67	94	1971	1968	
21765	1	23.5.95	5.7.95		97	82					
	2	23.5.95	5.7.95		97	66					
	3	23.5.95	27.7.95		94	73					
	Mean			0.000	96	74	75	230	1972	1976	
22170	1	23.5.95	5.7.95		225	154					
	2	23.5.95	5.7.95		216	147					
	3	23.5.95	19.7.95		211	138					
	Mean			0.010	217	146	169	456	1982	1990	
22171	1	23.5.95	19.7.95		83	17					
	2	23.5.95	5.7.95		87	25					
	Mean			0.016	85	21	66	65	1971	1965	
20497	1	23.5.95	5.7.95		47	9					
	2	23.5.95	26.7.95		45	9					
	3	23.5.95	19.7.95		41	0					
	Mean			0.185	44	6	35	19	1967	1956	
22175	1	23.5.95	27.7.95		95	76					
	2	23.5.95	27.7.95		96	74					
	3	23.5.95	28.7.95		112	89					
	Mean			0.025	101	80	79	248	1973	1977	
22176	1	23.5.95	27.7.95		-	30					H_2S interference
	2	23.5.95	27.7.95		-	39					H_2S interference
	3	23.5.95	25.8.95		0	26					
	Mean			0.055	-	32		99	< 1950	1969	
22177	1	23.5.95	28.7.95		156	112					
	2	23.5.95	28.7.95		161	101					
	3	23.5.95	28.7.95		143	102					
	Mean			0.014	153	105	119	327	1976	1983	
22066	1	25.5.95	27.7.95		136	135					
	2	25.5.95	27.7.95		146	142					
	3	25.5.95	27.7.95		144	148					
	Mean			0.010	142	142	110	442	1975	1989	
22067	1	25.5.95	27.7.95		205	130					
	2	25.5.95	27.7.95		207	159					
	Mean			0.013	206	145	160	450	1981	1989	

APPENDIX 2 : HOWARD EAST CFC ANALYSES : OCTOBER 1995

Recharge Temp. (K) : 301

Well	Replicate	Date Collected	Date Analysed	Salinity (ppt)	Concentration (pg/kg)		Concentration (pptv)		Age		Comments
					CFC-11	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12	
29390	1	27.10.95	16.11.95		109	86					
	2	27.10.95	15.11.95		94	91					
	3	27.10.95	29.11.95		74	76					
	Mean			0.068	92	84	72	263	1972	1979	
29389	1	27.10.95	15.11.95		45	36					
	2	27.10.95	16.11.95		45	34					
	3	27.10.95	28.11.95		43	36					
	Mean			0.075	44	35	35	110	1967	1969	
29388	1	27.10.95	15.11.95		24	4					
	2	27.10.95	15.11.95		21	10					
	3	27.10.95	28.11.95		12	0					
	Mean			0.185	19	5	15	15	1962	1955	
29424	1	26.10.95	29.11.95		214	124					
	2	26.10.95	29.11.95		205	117					
	3	26.10.95	28.11.95		191	115					
	Mean			0.013	203	119	158	370	1980	1985	
29423	1	26.10.95	29.11.95		112	32					
	2	26.10.95	29.11.95		168	43					
	3	26.10.95	29.11.95		64	30					
	Mean			0.125	-	35	0	109	< 1950	1969	
26765	1	26.10.95	17.11.95		45	31					
	2	26.10.95	29.11.95		48	30					
	3	26.10.95	28.11.95		35	29					
	Mean			0.260	43	30	33	94	1967	1968	
29422	1	26.10.95	16.11.95		75	119					
	2	26.10.95	16.11.95		62	114					
	3	26.10.95	28.11.95		57	111					
	Mean			0.029	65	115	50	357	1969	1984	
21760	1	26.10.95	16.11.95		0	0					
	2	26.10.95	17.11.95		0	-					
	3	26.10.95	28.11.95		0	0					
	Mean			0.226	0	0	0	0	< 1950	< 1940	
29421	1	26.10.95	28.11.95		0	0					
	2	26.10.95	29.11.95		0	0					
	3	26.10.95	28.11.95		0	0					
	Mean			0.227	0	0	0	0	< 1950	< 1940	
22069	1	26.10.95	17.11.95		61	80					
	2	26.10.95	17.11.95		59	81					
	3	26.10.95	29.11.95		52	77					
	Mean			0.014	57	79	45	247	1969	1977	
22068	1	26.10.95	16.11.95		87	70					
	2	26.10.95	16.11.95		107	89					
	3	26.10.95	28.11.95		90	78					
	Mean			0.031	95	79	74	246	1972	1977	
21767	1	26.10.95	17.11.95		9	6					
	2	26.10.95	17.11.95		7	0					
	3	26.10.95	29.11.95		29	22					
	Mean			0.014	8	3	6	9	1957	1952	
21765	1	26.10.95	16.11.95		75	64					
	2	26.10.95	16.11.95		80	84					
	3	26.10.95	28.11.95		76	68					
	Mean			0.086	77	72	60	225	1971	1976	
29427	1	27.10.95	16.11.95		179	125					
	2	27.10.95	16.11.95		177	129					
	3	27.10.95	28.11.95		155	130					
	Mean			0.096	170	128	133	399	1977	1987	
29426	1	27.10.95	15.11.95		9	42					
	2	27.10.95	15.11.95		0	44					
	3	27.10.95	28.11.95		8	47					
	Mean			0.007	6	44	4	138	1956	1971	
29425	1	27.10.95	29.11.95		11	12					
	2	27.10.95	16.11.95		17	19					
	3	27.10.95	29.11.95		13	0					
	Mean			0.191	14	10	11	32	1961	1960	
21046	1	27.10.95	15.11.95		0	0					
	2	27.10.95	15.11.95		0	0					
	3	27.10.95	28.11.95		0	0					
	Mean			0.132	0	0	0	0	< 1950	< 1940	
22171	1	25.10.95	16.11.95		11	10					
	2	25.10.95	16.11.95		9	11					
	3	25.10.95	29.11.95		10	12					
	Mean			0.022	10	11	8	34	1959	1961	
20497	1	25.10.95	16.11.95		7	0					
	2	25.10.95	17.11.95		14	0					
	3	25.10.95	28.11.95		7	0					
	Mean			0.166	9	0	7	0	1958	< 1940	
22175	1	25.10.95	16.11.95		26	76					
	2	25.10.95	29.11.95		31	77					
	3	25.10.95	29.11.95		31	75					
	Mean			0.078	29	76	23	237	1965	1977	
22176	1	25.10.95	30.11.95		0	0					
	2	25.10.95	30.11.95		-	0					
	3	25.10.95	29.11.95		0	0					
	Mean			0.154	0	0		0	< 1950	< 1940	
22177	1	25.10.95	17.11.95		24	21					
	2	25.10.95	17.11.95		26	27					
	3	25.10.95	29.11.95		27	26					
	Mean			0.016	26	25	20	77	1964	1967	
22067	1	27.10.95	16.11.95		188	118					
	2	27.10.95	16.11.95		205	123					
	3	27.10.95	28.11.95		-	113					
	Mean			0.013	197	118	153	368	1980	1985	

APPENDIX 3 : HOWARD EAST CFC ANALYSES : APRIL 1996

Recharge Temp. (K) : 301

Well	Replicate	Date Collected	Date Analysed	Salinity	Concentration (pg/kg)		Concentration (pptv)		Age		Comments
				(ppt)	CFC-11	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12	
29390	1	15.4.96	5.7.96		21	89					
	2	15.4.96	8.7.96		14	-					
	3	15.4.96	8.7.96		15	-					
	Mean			0.040	17	-	13	0	1962	< 1940	
29389	1	15.4.96	2.7.96		143	91					
	2	15.4.96	4.7.96		153	140					
	3	15.4.96	5.7.96		135	107					
	Mean			0.011	144	113	112	351	1975	1984	
29388	1	15.4.96	8.7.96		5	-					
	2	15.4.96	2.7.96		0	29					
	3	15.4.96	4.7.96		0	46					
	Mean			0.176	2	38	1	117	1952	1970	
29424	1	16.4.96	2.7.96		245	159					
	2	16.4.96	5.7.96		257	155					
	3	16.4.96	4.7.96		254	158					
	Mean			0.016	252	157	196	490	1985	1992	
29423	1	16.4.96	4.7.96		14	25					
	2	16.4.96	3.7.96		16	37					
	3	16.4.96	4.7.96		10	29					
	Mean			0.137	13	30	10	95	1960	1968	
26765	1	16.4.96	2.7.96		13	25					
	2	16.4.96	3.7.96		11	0					
	3	16.4.96	5.7.96		11	12					
	Mean			0.240	12	12	9	39	1960	1962	
29422	1		8.7.96		88	-					
	2		3.7.96		101	107					
	3		2.7.96		101	111					
	Mean			0.021	97	109	75	340	1972	1983	
21760	1	15.4.96	2.7.96		0	0					
	2		5.7.96		11	157					
	3										
	Mean			0.212	5	-	4	0	1956	< 1940	
29421	1		4.7.96		2	16					
	2		5.7.96		68	475					
	3		2.7.96		14	24					
	Mean			0.177	8	20	6	62	1957	1965	
22069	1	17.4.96	2.7.96		256	176					
	2	17.4.96	4.7.96		272	190					
	3	17.4.96	3.7.96		260	165					
	Mean			0.011	263	177	204	552	1986	cont.	
22068	1	17.4.96	2.7.96		65	66					
	2	17.4.96	3.7.96		74	99					
	3	17.4.96	4.7.96		58	67					
	Mean			0.055	66	67	51	209	1970	1975	
21767	1	17.4.96	3.7.96		7	0					
	2	17.4.96	3.7.96		15	21					
	3	17.4.96	2.7.96		7	0					
	Mean			0.013	10	7	8	22	1959	1957	
21765	1	17.4.96	2.7.96		89	69					
	2	17.4.96	2.7.96		103	87					
	3	17.4.96	3.7.96		89	82					
	Mean			0.079	94	79	73	247	1972	1977	
29427	1	6.6.96	27.6.96		80	216					
	2	6.6.96	2.7.96		92	229					
	3	6.6.96	27.6.96		99	194					
	4	6.6.96	27.6.96		92	194					
	Mean			0.089	91	208	71	650	ERR	cont.	
29426	1	6.6.96	27.6.96		67	55					
	2	6.6.96	27.6.96		34	42					
	3	6.6.96	27.6.96		33	36					
	Mean			0.075	34	44	26	138	1965	1971	
29425	1	6.6.96	27.6.96		22	22					
	2	6.6.96	27.6.96		19	11					
	3	6.6.96	27.6.96		10	12					
	Mean			0.201	17	15	13	47	1962	1963	
21046	1	6.6.96	27.6.96		30	0					
	2	6.6.96	27.6.96		12	10					
	3	6.6.96	27.6.96		34	17					
	Mean			0.134	25	9	20	28	1964	1959	
22170	1	16.4.96	3.7.96		54	48					
	2	16.4.96	4.7.96		44	65					
	3	16.4.96	4.7.96		119	115					
	4	16.4.96	4.7.96		53	60					
				0.013	50	58	39	180	1968	1974	
22171	1	16.4.96	5.7.96		28	39					
	2	16.4.96	2.7.96		14	13					
	3	16.4.96	8.7.96		17	-					
	Mean			0.016	20	26	15	81	1963	1967	
20497	1	16.4.96	3.7.97		0	0					
	2	16.4.96	5.7.96		14	32					
	3	16.4.96	4.7.96		4	7					
	4	16.5.96	3.7.97		27	51					
	5	16.5.96	3.7.97		102	126					
	6	16.5.96	3.7.97		48	59					
	Mean			0.144	6	4	5	11	1956	1953	
22175	1	17.4.96	2.7.96		92	117					
	2	17.4.96	2.7.96		98	97					
	3	17.4.96	2.7.96		87	114					
	Mean			0.058	92	109	72	341	1972	1983	
22176	1	17.4.96	4.7.96		0	9					
	2	17.4.96	4.7.96		0	15					
	3	17.4.96	5.7.96		0	0					
	Mean			0.086	0	8		25	< 1950	1958	
22177	1	17.4.96	5.7.96		19	-					
	2	17.4.96	3.7.96		23	22					
	3	17.4.96	4.7.96		12	14					
	Mean			0.016	18	18	14	56	1962	1964	
22066	1	15.4.96	3.7.96		174	150					
	2	15.4.96	2.7.96		191	178					
	3	15.4.96	3.7.96		189	166					
	4	15.4.96	3.7.96		178	157					
	Mean			0.013	183	163	142	507	1979	1994	
22067	1	15.4.96	2.7.96		194	134					
	2	15.4.96	3.7.97		200	135					
	3	15.4.96	2.7.96		191	0					
	Mean			0.013	195	135	152	419	1980	1988	

APPENDIX 4 : HOWARD EAST CFC ANALYSES : DEC 96 - JAN 98

Recharge Temp. (K) : 301

Well	Replicate	Date Collected	Date Analysed	Salinity	Exc Air	Conc. (pg/kg)		Equiv. Conc. (pptv)		Age (yrs)		Comments
						CFC-11	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12	
20497	1	27.02.97	3.07.97			0	0					
	2	27.02.97	9.09.97			3	4					
	Mean				0	0	0	0	0	< 1950	< 1940	
20497	1	1.05.97	9.09.97			0	0					
	2	1.05.97	9.09.97			8	8					
	Mean				0	0	0	0	0	< 1950	< 1940	
21046	1	24.12.96	9.09.97			0	0					
	2	24.12.96	9.09.97			0	0					
	3	24.12.96	9.09.97			0	0					
	Mean				0	0	0	0	0	< 1950	< 1940	
21046	1	4.06.97	2.07.97			58	6					
	2	4.06.97	2.07.97			12	16					
	3	4.06.97	11.09.97			0	0					
	Mean				0	-	0	-	0	-	< 1940	
22170	1	27.02.97	3.07.97			252	129					
	3	27.02.97	11.09.97			125	89					
	Mean				0	-	109	-	340	-	1983	
22170	1	29.04.97	9.09.97			111	122					
	2	29.04.97	3.07.97			135	101					
	3	29.04.97	11.09.97			113	76					
	Mean				0	120	100	93	312	1974	1982	
22170	1	9.01.98	13.02.98			176	146					
	2	9.01.98	13.02.98			198	145					
	Mean				0	187	146	145	455	1979	1990	
22171	1	24.12.96	2.07.97			5	30					
	2	24.12.96	2.07.97			12	18					
	3	24.12.96	11.11.97			14	25					
	Mean				0	10	24	8	75	1959	1966	
22171	1	27.02.97	3.07.97			20	23					
	2	27.02.97	9.09.97			32	26					
	3	27.02.97	11.11.97			19	11					
	Mean				0	18	15	14	47	1962	1963	
22171	1	29.04.97	3.07.97			28	18					
	2	29.04.97	9.09.97			22	18					
	3	29.04.97	9.09.97			16	23					
	Mean				0	22	20	17	62	1963	1965	
22171	1	10.09.97	11.02.98			17	10					
	2	10.09.97	11.02.98			17	16					
	Mean				0	17	13	13	41	1962	1962	
22171	1	9.01.98	12.02.98			14	23					
	2	9.01.98	12.02.98			13	22					
	Mean				0	14	23	11	72	1961	1966	
26765	1	28.02.97	30.06.97			26	-					
	2	28.02.97	3.07.97			23	20					
	3	28.02.97	11.11.97			22	17					
	Mean				0	23	19	18	59	1963	1965	
26765	1	1.05.97	9.09.97			13	-					
	2	1.05.97	9.09.97			21	16					
	3	1.05.97	11.11.97			15	23					
	Mean				0	16	20	12	62	1961	1965	
26765	1	9.09.97	11.02.98			14	13					
	2	9.09.97	11.02.98			14	17					
	Mean				0	14	15	11	47	1961	1963	
26765	1	9.01.98	11.02.98			13	21					
	2	9.01.98	12.02.98			18	32					
	Mean				0	16	27	12	84	1961	1967	
29388	1	28.04.97	9.09.97			2	7					
	2	28.04.97	9.09.97			0	9					
	3	28.04.97	11.11.97			1	5					
	Mean				0	0	0	0	0	< 1950	< 1940	
29389	1	28.04.97	3.07.97			12	44					
	2	28.04.97	30.06.97			13	48					
	3	28.04.97	9.09.97			12	37					
	Mean				0	12	43	9	134	1960	1971	
29390	1	28.04.97	2.07.97			14	78					
	2	28.04.97	9.09.97			10	100					
	3	28.04.97	11.11.97			7	83					
	Mean				0	10	87	8	271	1959	1979	
29423	1	24.12.96	2.07.97			0	13					
	2	24.12.96	2.07.97			0	21					
	Mean				0	0	17	0	53	< 1950	1964	
29423	1	28.02.97	2.07.97			0	0					
	2	28.02.97	2.07.97			0	0					
	Mean				0	0	0	0	0	< 1950	< 1940	
29423	1	1.05.97	2.07.97			0	0					
	2	1.05.97	2.07.97			22	24					
	3	1.05.97	11.11.97			1	7					
	Mean				0	0	0	0	0	< 1950	< 1940	
29423	1	7.08.97	22.01.98			0	20					
	2	7.08.97	22.01.98			13	21					
	3	7.08.97	22.01.98			42	29					
	Mean				0	-	23	-	72	-	1966	
29423	1	9.09.97	11.02.98			0	0					

	2	9.09.97	11.02.98			2	7					
	3	9.09.97	11.02.98			2	0					
	Mean				0	0	0	0	0	< 1950	< 1940	
29423	1	9.01.98	11.02.98			1	4					
	2	9.01.98	11.02.98			0	4					
	Mean				0	0	0	0	0	< 1950	< 1940	
29424	1	24.12.96	02.07.97			182	104					
	2	24.12.96	03.07.97			183	128					
	3	24.12.96	11.11.97			167	95					
	Mean				0	177	109	138	340	1979	1983	
29424	1	28.02.97	02.07.97			237	101					
	2	28.02.97	03.07.97			233	147					
	3	28.02.97	11.11.97			247	129					
	Mean				0	239	126	186	393	1984	1986	
29424	1	1.05.97	03.07.97			233	153					
	2	1.05.97	9.09.97			214	137					
	3	1.05.97	11.11.97			244	75					
	Mean				0	230	122	179	380	1983	1986	
29424	1	7.08.97	22.01.98			200	129					
	2	7.08.97	22.01.98			91	121					
	3	7.08.97	22.01.98			215	132					
	Mean				0	208	127	162	396	1981	1986	
29424	1	9.09.97	11.02.98			51	115					
	2	9.09.97	11.02.98			71	118					
	3	9.09.97	11.02.98			68	124					
	Mean				0	63	119	49	371	1969	1985	
29424	1	9.01.98	11.02.98			0	36					
	2	9.01.98	11.02.98			0	49					
	Mean				0	0	43	0	134	< 1950	1971	
29425	1	24.12.96	9.09.97			1	7					
	2	24.12.96	9.09.97			3	9					
	3	24.12.96	11.11.97			6	10					
	Mean				0	0	0	0	0	< 1950	< 1940	
29425	1	4.06.96	9.09.97			8	8					
	2	4.06.96	9.09.97			616	283					
	3	4.06.96	9.09.97			606	379					
	Mean				0	-	-	-	-	-	-	
29425	1	9.09.97	22.01.98			7	10					
	2	9.09.97	22.01.98			1	15					
	3	9.09.97	22.01.98			7	13					
	Mean				0	5	13	4	41	1956	1962	
29425	1	12.01.98	13.02.98			8	8					
	2	12.01.98	13.02.98			11	10					
	Mean				0	10	9	8	28	1959	1959	
29426	1	24.12.96	3.07.97			0	11					
	2	24.12.96	30.06.97			20	156					
	3	24.12.96	11.11.97			4	36					
	Mean				0	0	24	0	75	< 1950	1966	
29426	1	4.06.97	9.09.97			14	41					
	2	4.06.97	2.07.97			9	50					
	3	4.06.97	11.11.97			19	45					
	Mean				0	14	45	11	140	1961	1971	
29426	1	7.08.97	22.01.98			14	54					
	2	7.08.97	22.01.98			14	51					
	3	7.08.97	22.01.98			18	48					
	Mean				0	15	51	12	159	1961	1973	
29426	1	9.09.97	22.01.98			3	48					
	2	9.09.97	22.01.98			3	47					
	3	9.09.97	22.01.98			3	43					
	Mean				0	3	46	2	143	1954	1972	
29426	1	12.01.98	13.02.98			9	36					
	2	12.01.98	13.02.98			8	29					
	Mean				0	9	33	7	103	1958	1969	
29427	1	24.12.96	3.07.97			27	117					
	2	24.12.96	9.09.97			25	228					
	3	24.12.96	9.09.97			9	215					
	4	24.12.96	11.11.97			17	197					
	Mean				0	20	213	16	664	1963	cont.	
29427	1	4.06.97	2.07.97			740	338					
	2	4.06.97	9.09.97			0	184					
	3	4.06.97	11.11.97			4	198					
	Mean				0	0	191	0	595	< 1950	cont.	
29427	2	7.08.97	22.01.98			7	123					
	3	7.08.97	22.01.98			0	98					
	Mean				0	0	111	0	346	< 1950	1984	
29427	1	9.09.97	22.01.98			0	71					
	2	9.09.97	22.01.98			0	88					
	3	9.09.97	22.01.98			0	89					
	Mean				0	0	83	0	259	< 1950	1979	
29427	1	12.01.98	13.02.98			21	52					
	Mean				0	21	52	16	162	1963	1973	

APPENDIX 5 : GROUNDWATER ISOTOPE ANALYSES

Well	Date Sampled	^{18}O (per mille)	^{2}H (per mille)	^{13}C (per mille)	^{14}C (pmc)
29390	22.3.95	-4.65	-30.5		
	27.10.95	-4.91	-29.9	-19.76	
29389	22.3.95	-6.66	-44.7		
	27.10.95	-5.26	-32.0	-19.99	
29388	22.3.95	-5.51	-33.0		
	26.10.95	-5.38	-33.6		
	27.10.95			-12.81	
29424	22.3.95	-6.22	-40.4		
	25.10.95	-5.86	-38.2		
29423	22.3.95	-5.83	-38.1		
	25.10.95	-6.00	-38.6		
	26.10.95			-19.00	
26765	22.3.95	-5.90	-37.1		
	25.10.95	-6.06	-38.8		
	28.12.96	-5.70	-34.8		
29422	22.3.95	-5.67	-34.8		
	26.10.95	-5.85	-37.8	-20.36	
21760	22.3.95	-5.79	-36.6		
	26.10.95	-5.84	-36.2	-10.22	
29421	22.3.95	-5.55	-34.9		
	26.10.95	-5.76	-36.7	-12.16	
22069	22.3.95	-6.16	-40.0		
	26.10.95	-5.93	-36.3		
22068	22.3.95	-5.87	-36.3		
	26.10.95	-5.96	-35.2		
21765	26.10.95	-5.80	-35.3		
29427	27.10.95	0.49	-3.5		
	27.12.96	0.29	-2.1		
29426	27.10.95	-2.18	-18.5		
	27.12.96	-1.96	-15.1		
29425	27.10.95	-6.07	-39.2		
	27.12.96	-5.85	-35.8		
21046	27.10.95	-1.61	-14.5		
	27.12.96	-1.79	-12.2		
22170	22.3.95	-6.26	-42.6		
	16.5.96	-5.91		-23.80	112.3 +/- 2.0
22171	22.3.95	-5.93	-36.9		
	25.10.95	-5.96	-36.0		
	7.06.96			-22.40	94.8 +/- 1.9
20497	22.3.95	-6.10	-35.7		
	25.10.95	-5.99	-34.7		
	16.5.96	-6.03		-12.80	52.6 +/- 1.4
	28.12.96	-6.04	-36.5		
22175	22.3.95	-5.83	-33.7		
	25.10.95	-5.72	-34.4		
	7.06.96			-19.20	118.8 +/- 3.2
22176	22.3.95	-5.81	-33.6		
	25.10.95	-5.66	-33.3		
22177	22.3.95	-6.24	-36.7		
	25.10.95	-6.04	-37.8		
22066	22.3.95	-5.47	-35.0		
22067	22.3.95	-5.39	-34.5		
	27.10.95	-5.48	-31.0		