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An Investigation of Recharge to the Namoi Valley Aquifers Using Environmental Isotopes

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Abstract

Environmental tritium and radiocarbon were used to study aspects of groundwater origin, transport and mixing in the complex aquifer system underlying the Namoi Valley, N.S.W. A substantial proportion of the water in the upper aquifer (depth less than 25 m) percolated underground in the post-nuclear period (after 1955). The observed relationship between $\delta^{13}C$ value and distance is evidence for riverwater recharge in the upper aquifer. There is evidence that water in the middle aquifer system (depth 50–75 m) percolated underground about 600 years ago. Finally, it is suggested that water from the Great Artesian Basin leaks into the deeper water of the lower aquifer system.

Introduction

The contribution that nuclear techniques can make to the understanding of aspects of the water cycle is becoming more widely recognized. Environmental tritium (hydrogen-3) and radiocarbon (carbon-14) studies are most widely used in complementing the more basic hydraulic investigations of aquifer systems (International Atomic Energy Agency 1968). The Australian Atomic Energy Commission (AAEC) has systematically sampled and analysed the tritium content of rain and riverwater, and the tritium and radiocarbon levels of groundwater samples from the Namoi Valley, N.S.W., during the years 1971–1974.

The aims of the program have been

(*a*) to assess the relative importance of the various sources of recharge (river, rainwater, irrigation channel) to the groundwater system;

(*b*) to investigate the extent of groundwater mixing between various aquifers;

(*c*) where possible to estimate the mean residence time of water in the aquifer system.

Description of Area

The Water Resources Commission of New South Wales (WRC), previously named the Water Conservation and Irrigation Commission, has published an extensive survey of this region (WCIC 1970), and the following brief description is extracted from that report. The extent of the portion of the Namoi Valley under consideration is shown in Figs. 1 and 2.

The Namoi River is one of the major tributaries of the Barwon–Darling Rivers system and drains an area of about 43 000 km^2 extending from near Walcha westward to Walgett.

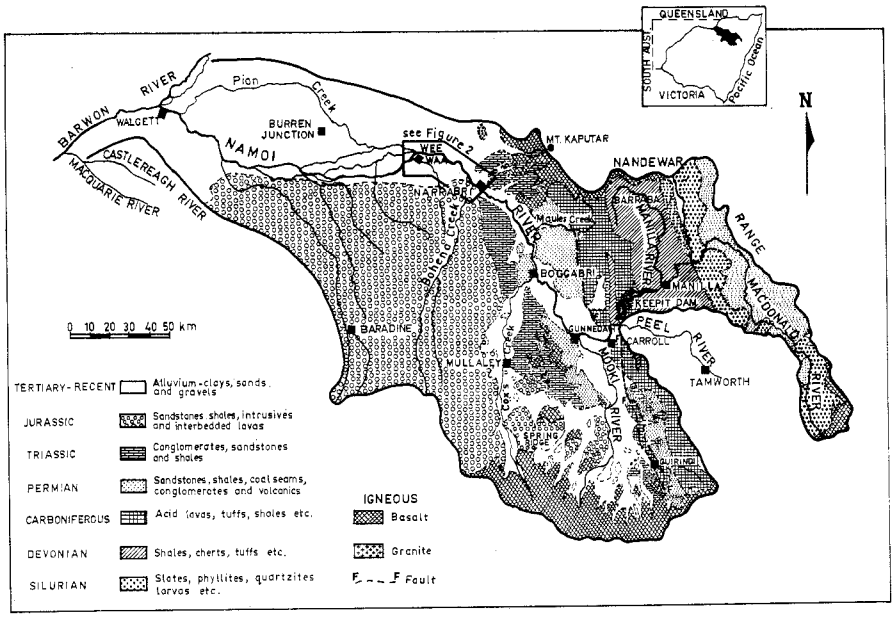

Fig. 1. Namoi River Valley—geological formations.

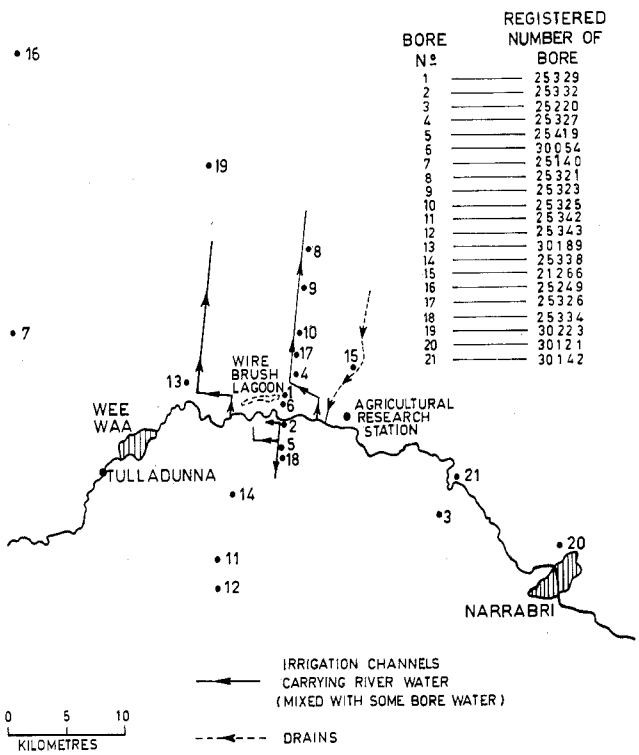

Fig. 2. Location of sampling points for tritium and carbon-14 investigation. Bores 1, 2, 4–6, 8–12, 14, 17 and 18 are sited on Gurleigh Section.

The dominant feature of the area is the alluvium which is associated with the Namoi River. From Boggabri to about 6 km downstream of Narrabri, the river flats vary in width from about 0·5 km to 13 km. Below Narrabri they become wider, and towards Wee Waa, become extensive riverine plains. The alluvium ranges up to about 120 m in thickness, is of recent and Tertiary origin, and has probably the greatest overall groundwater potential of any prospective source in New South Wales.

Near Boggabri, Permian rocks form the side slopes. These consist of acid volcanics on both sides of the river with sandstones, conglomerates and shales occurring further to the east and in the Maules Creek area.

Triassic sandstones and shales outcrop further downstream and extend as far as Narrabri, with Tertiary basalts forming the higher areas to the east around Mt Kaputar.

Jurassic rocks outcrop downstream of Narrabri mainly on the south side of the Namoi River and dip to the north-west under the plains. The Pilliga Sandstone is the main rock type and forms the intake beds for the Great Artesian Basin. These sandstones directly underlie the alluvium in the Narrabri area, but further west, Cretaceous shales and mudstones overlie the sandstones and appear to form an impervious layer between them and the alluvium.

As a result of the advent of cotton growing in the Wee Waa district and the recent prolonged drought from 1964 to 1966, large scale development of groundwater for irrigation use has occurred. Numerous irrigation bores have been constructed, the average depth being about 90 m, and supplies from these bores range up to 20 m^3 min^{-1}, all water supplies of significant flow being usually allowed to enter the bores by slotting the casing or screening opposite each aquifer.

The WRC has drilled over 200 observation bores throughout the valley. At some sites up to six bores, represented by the numbers /1 to /6, have been sunk to various depths into the aquifer system. The registered number of each bore is shown in Fig. 2. All borewater sampled in this investigation was obtained from such observation bores.

A vertical cross-section of the Gurleigh section of the aquifer supplied by the WRC is shown in Fig. 3. The system is so complex that to explain the carbon isotope and tritium data, the results were classified into five groups A, B, C, D and E, depending on the depth of the bore screens below the surface. Fig. 3 shows (dotted lines) that this grouping is not entirely arbitrary, and it correlates reasonably well with aquifers which can be identified on the cross-section shown.

Groundwater Dating

Tritium and radiocarbon are produced in the troposphere principally by the interaction of cosmic-ray produced neutrons and nitrogen gas. Since 1952, substantial quantities of both isotopes have also been released into the biosphere by atmospheric thermonuclear testing.

Environmental tritium is usually measured in tritium units (TU), which is the number of tritium atoms per 10^{18} hydrogen atoms in the sample. Facilities for the measurement of the natural levels of tritium in water have been developed by the AAEC (Calf *et al.* 1976*a*), and all results have an estimated standard deviation of 8·5% or 0·4 TU, whichever is the larger. The tritium content of Australian rainfall usually varies between 5 and 50 TU (Calf *et al.* 1976*b*), and activities of less than 5 TU are found in many groundwaters in Australia.

For radiocarbon analyses, the dissolved carbonates and bicarbonates in a groundwater sample were precipitated with an alkaline solution of barium chloride (IAEA 1975). This precipitate was converted to benzene in the laboratory (Polach *et al.* 1972), and the percentage modern carbon determined (Calf and Polach 1974).

In principle, groundwater ages can be determined using tritium (half-life $T_{\frac{1}{2}} = 12{\cdot}26$ years) and radiocarbon ($T_{\frac{1}{2}} = 5730$ years). Precipitation and river recharge transfers tritium directly to groundwater as the isotope water molecule HTO. Radiocarbon in groundwater originates from carbon dioxide in rainwater, from root respiration of plants, and from the decomposition of plant material in the upper layers of the soil. In addition, the solution of inorganic mineral carbonates (calcite, dolomite etc.) by soil water complicates the interpretation of the isotope hydrology of an aquifer.

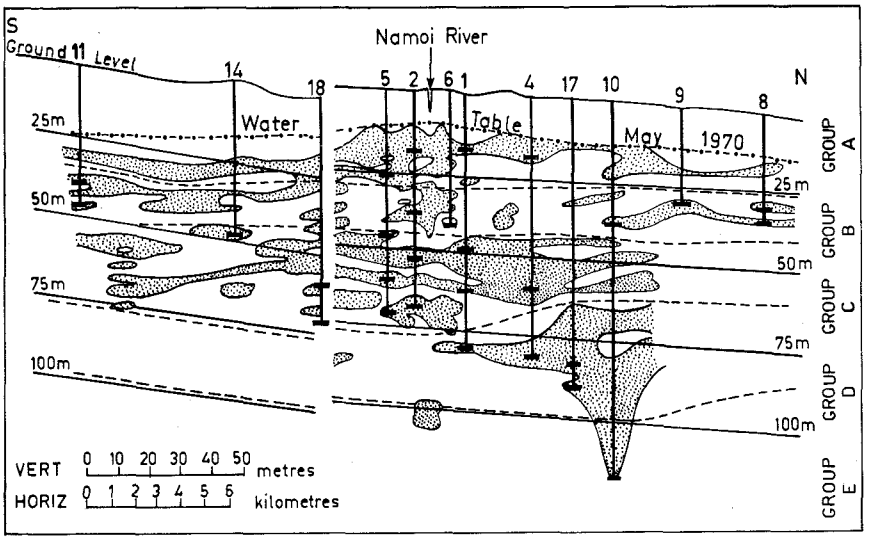

Fig. 3. Vertical cross-section of the Gurleigh section of the Namoi Valley aquifer showing the depths of samples taken for radiocarbon estimations.

If the initial isotope activity of the water entering the saturated zone is I_0 at the time of recharge $t = 0$, and the only change in radioisotope activity is caused by radioactive decay (closed system), then the age of groundwater at time t is given by

$$t = \lambda \ln(I_0/I) \tag{1}$$

where the mean life λ is given by $T_{\frac{1}{2}}/\ln 2$.

The limits of dating depend on the sensitivity of measurement and on the half-life of the radioisotope, and for tritium and radiocarbon dating, are about 50 and 35 000 years respectively.

Bomb-tritium in groundwater is proof of recharge since 1954. Radiocarbon dating is not usually influenced by carbon-14 of nuclear origin, except for very recent waters which also should contain bomb-tritium.

In absolute radiocarbon dating, it is necessary to know the initial carbon-14 content, I_0, and to understand the details of the complex geochemistry of the carbon

dioxide–bicarbonate system in both the unsaturated and saturated zones. These complex processes have been discussed by Wendt (1971). Information on the time scales involved in the transport of water can be obtained from a systematic study of the variation in the concentration and isotopic composition of bicarbonate in a large number of samples taken from the saturated zone.

The following approach has been applied by Pearson and Swarzenki (1974) in a study of the origin of arid region groundwater in the North-eastern Province of Kenya.

If the relationships between the total carbonate C_t in the groundwater derived from biogenic and mineral sources C_b and C_m with isotopic compositions I_t, I_b and I_m (either ^{14}C or $\delta^{13}C$)* are as follows:

$$C_t = C_b + C_m \tag{2}$$

and

$$C_t I_t = C_b I_b + C_m I_m, \tag{3}$$

then it follows that

$$I_t = \frac{C_b(I_b - I_m)}{C_t} + I_m. \tag{4}$$

The plot of the reciprocal of the total carbonate $(C_t)^{-1}$ against the isotopic composition (I_t) is predicted to be a straight line with an intercept $I_t = I_m$ at $(C_t)^{-1} = 0$ and slope $C_b(I_b - I_m)$. In the case of radiocarbon, I_t varies with time because of radioactive decay, and equation (4) will only predict a linear relationship between I_t and $(C_t)^{-1}$ if the decay can be neglected.

Table 1. Average $\delta^{13}C$ values found in nature

Sample	Average δ^{13} value/ ‰ PDB	Reference
Atmospheric carbon dioxide	−7·0±0·4	Schwarcz (1969)
Marine limestone and shells	−0·4±2·2	
Freshwater limestone	−6·5±0·5	
Oceanic bicarbonate	−2·2	
Sedimentary organic carbon, oil, coal	−28 ±4	
Plants, Calvin photosynthesis cycle	−27 ±4	Troughton (1972)
Plants, Hatch–Slack photosynthesis cycle	−12 ±2	

Under these conditions the straight line represents water of the same age.

Tritium and Radiocarbon Sampling Program

After an initial investigation of tritium levels in a number of samples of borewater, rainwater and riverwater collected in the Namoi Valley in 1968 and 1969, sites were selected in 1971 for a sampling program to observe temporal and spatial variations in tritium activity. Monthly samples were taken from nine bore and three river sites; results from two bores and one river site are shown in Fig. 4. Rainwater samples

* $\delta^{13}C$ is defined as $[\{C_{13}/C_{12}(\text{sample})\}/\{C_{13}/C_{12}(\text{standard})\}-1]\times 1000$. The standard used for $\delta^{13}C$ values is a sample of Belemnitilla Americana Cretaceous (PDB) found in the P–D Formation of South Carolina (Craig 1957). Some typical $\delta^{13}C$ values are listed in Table 1.

were collected at the Agricultural Research Station (New South Wales Department of Agriculture), these samples being monthly composites of rainfall. Locations of tritium sampling points are shown in Fig. 2.

Forty-five groundwater samples were collected in the Narrabri–Wee Waa area for radiocarbon and $\delta^{13}C$ analyses. The borehole sites are shown in Fig. 2.

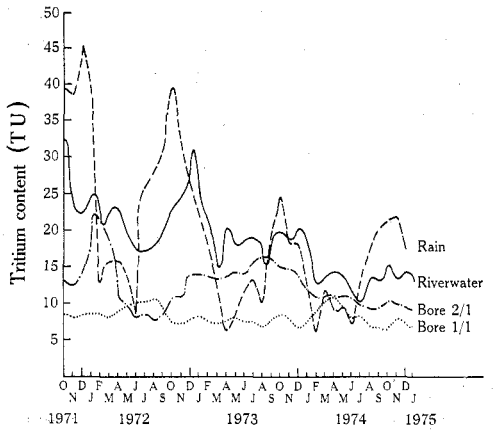

Fig. 4. Graph of the variation in the tritium content of the Namoi River at Tulladunna, of rainfall at the Agricultural Research Station and of bores 1/1 and 2/1 over the years 1971–1974.

Interpretation of Tritium and Radiocarbon Data

Tritium

The measured tritium levels in rainfall and the Namoi River over the period 1971 to 1974 are shown in Fig. 4. The time dependence of the tritium levels in bores 1/1 and 2/1 is also shown in Fig. 4. The detailed shape of these curves depends on a number of factors including:

(i) the tritium levels in rainfall and the rainfall intensity distribution;
(ii) the tritium levels in the river;
(iii) the relative importance of various contributions to the recharge process including:
  (*a*) precipitation recharge,
  (*b*) river recharge,
  (*c*) recharge of river water and bore water from irrigation channels, and
  (*d*) the hydraulic history of the aquifer in the past few decades.

Detailed interpretation is therefore not possible. However, the magnitude of the tritium levels shows that a substantial proportion of the water sampled in bores 1/1 and 2/1 percolated underground in post-nuclear times (say after 1955). Before the advent of atmospheric testing the mean level of tritium in rainfall is estimated to have been about 6 TU, equivalent to a 1975 level of about 2 TU.

Carbon-13

Fig. 5 shows the relationship between $\delta^{13}C$ and reciprocal total carbonate for bores on the Gurleigh section. A linear relationship is observed for water in groups A, B, C and D, which confirms equation (4). Since $\delta^{13}C$ values are linearly related to

the $^{13}C/^{12}C$ ratio (I_t), it is valid to substitute $\delta^{13}C$ values in the equation. The intercept in the lines in Fig. 5 at zero reciprocal carbonate content for groups B, C and D are $-8{\cdot}4‰$, $-8{\cdot}5‰$ and $-3{\cdot}1‰$ respectively, which represents the $\delta^{13}C$ value of soil mineral and aquifer carbonate dissolved by the infiltrating groundwater (Pearson and Swarzenki 1974). These $\delta^{13}C$ values for groups B and C indicate that the carbonate is of fresh water origin, while that in group D is of marine origin (Table 1).

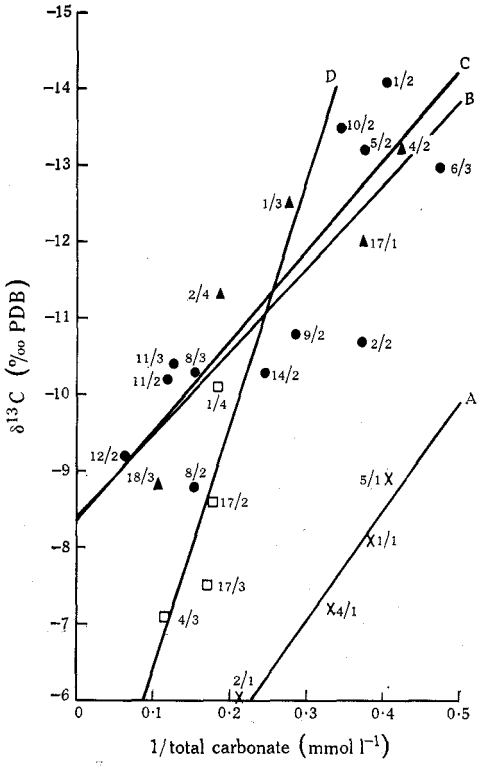

Fig. 5. Graph of $\delta^{13}C$ versus reciprocal total dissolved carbonate content for bores sited on Gurleigh section. × Group A. ● Group B. ▲ Group C. □ Group D.

The $\delta^{13}C$ value of soil carbon dioxide must lie between $-27‰$ (if all the plants producing the soil carbon dioxide use the Calvin photosynthetic cycle) (Troughton 1972) and $-12‰$ (if all use the Hatch–Slack cycle). Carbonates of non-biogenic origin occur as calcium and magnesium carbonates (Table 1), which, in the presence of soil moisture and carbon dioxide, form soluble bicarbonates:

$$CaCO_3 + CO_2 + H_2O \rightleftarrows Ca(HCO_3)_2.$$

Thus the $\delta^{13}C$ value for groundwater originating from rainwater percolation is usually between -12 and $-20‰$. However, groundwater originating only from river recharge has a $\delta^{13}C$ value similar to that of atmospheric carbon dioxide ($-7‰$). Table 2 shows that the $\delta^{13}C$ values for group A water are well outside the expected range for rainwater percolation and close to the value for river recharge. However, rainwater percolation would be expected to make a significant contribution to surface aquifer recharge in areas away from the river or irrigation channels. The influence of rainwater percolation is shown when the $\delta^{13}C$ value for bore 2/1 ($-6{\cdot}0‰$ and

Table 2. Total carbonate, percentage modern carbon and $\delta^{13}C$ values for groundwater sampled in Namoi Valley

Results in each group were averaged; readings with footnotes were not considered

Group A Bores < 25 m deep				Group B Bores 25–50 m deep				Group C Bores 50–75 m deep				Group D Bores 75–100 m deep				Group E Bores > 100 m deep			
Bore no.	Total carbonate (mM/l)	Modern carbon (%)	$\delta^{13}C$ (‰)	Bore no.	Total carbonate (mM/l)	Modern carbon (%)	$\delta^{13}C$ (‰)	Bore no.	Total carbonate (mM/l)	Modern carbon (%)	$\delta^{13}C$ (‰)	Bore no.	Total carbonate (mM/l)	Modern carbon (%)	$\delta^{13}C$ (‰)	Bore no.	Total carbonate (mM/l)	Modern carbon (%)	$\delta^{13}C$ (‰)
1/1	2·60	112·1	−8·1	1/2	2·46	97·6	−14·1	1/3	3·60	77·1	−12·6	1/4	5·52	38·4	−10·1	10/6[b]	4·42	67·2	−13·8
2/1	4·60	104·9	−6·0	2/2	2·68	101·4	−10·7	2/3[a]	2·66	97·4	−13·6	3/3[d]	12·24	1·0	−6·0	15/2	2·76	1·7	−5·4
3/1[c]	15·80	28·5	−6·0	5/2	2·66	96·3	−13·2	2/4	5·27	50·5	−11·4	4/3	8·53	8·6	−7·1	19/2	5·20	2·3	−9·9
4/1	3·02	125·2	−7·2	6/3	2·10	91·4	−13·0	4/2	2·36	86·5	−13·3	17/2	5·68	18·2	−8·6	20/3	13·86	1·1	−6·4
5/1	2·44	102·3	−8·9	7/1	3·38	86·2	−14·2	5/3[a]	3·22	93·4	−11·1	17/3	5·87	16·8	−7·5	21/1	11·26	0·4	−5·9
				8/2	6·44	68·9	−8·8	5/4[c]	9·24	6·6	−6·9	20/2[d]	13·73	1·8	−6·1				
				8/3	6·60	49·6	−10·3	7/3	3·68	42·1	−12·2								
				9/2	3·48	91·7	−10·8	13/3	2·90	67·2	−13·2								
				10/2	2·92	86·0	−13·5	15/1	2·68	77·1	−14·7								
				11/2	8·42	52·8	−10·2	16/1	7·15	40·0	−11·7								
				11/3	7·74	54·0	−10·4	16/2	3·59	23·8	−11·5								
				12/2	15·06	34·0	−9·2	17/1	2·66	87·7	−12·1								
				13/2	2·40	97·0	−14·8	18/3	9·08	30·8	−8·9								
				14/2	4·10	51·3	−10·3	18/4[d]	9·91	3·7	−6·6								
								19/1	4·57	31·1	−9·9								

[a] Water similar to group B. [b] Water similar to group C. [c] Water similar to group D. [d] Water similar to group E.

Group	Av. modern carbon	Av. $\delta^{13}C$ (‰)	Group	Av. modern carbon	Av. $\delta^{13}C$ (‰)
A	111·1	−7·6	D	20·0	−8·3
B	75·6	−11·7	E	1·4	−6·3
C	55·8	−12·0			

sited 50 m from the river) is compared with that of bore 1/1 ($-8{\cdot}1‰$ and 1500 m from the river).

The average $\delta^{13}C$ value for water in groups B and C was about $-12‰$. This value again increases to about $-8‰$ for the deeper water in groups D and E. Group E includes bore 21/1, a flowing artesian bore (flow about 7 m^3 day^{-1}), 174 m deep, which taps the sandstone strata of the Great Artesian Basin. The water from this bore has a $\delta^{13}C$ value of $-5{\cdot}9‰$. The difference in $\delta^{13}C$ values for groups D and E, when compared with the more shallow bores represented by groups B and C, may indicate that part of the deeper water in the Namoi Valley aquifers originated from leakage of water from the Great Artesian Basin, underlying the Namoi Valley.

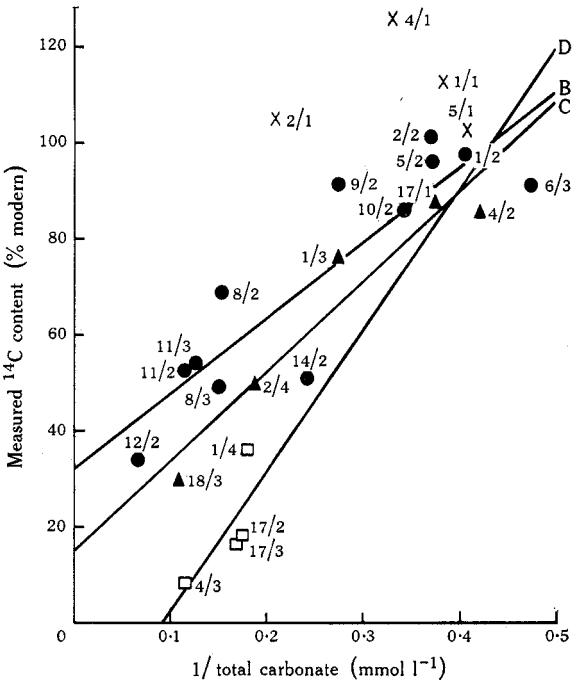

Fig. 6. Graph of measured ^{14}C content versus reciprocal total dissolved carbonate content for bores sited on Gurleigh section. Symbols as for Fig. 5.

Radiocarbon

The most interesting feature of the radiocarbon data is the decline in activity with increasing borehole screen depth (Table 2).

Results for the bores sited on the Gurleigh section (Fig. 3) are shown in Fig. 6. The three linear plots for groups B, C and D are well defined and verifies equation (4) showing that water represented by each of these groups has the same average age.

No correlation between percentage modern carbon and reciprocal total carbonate was observed for water in group A bores. However, the high measured radiocarbon activity for group A water suggests that this water is from the post-nuclear period and confirms the tritium results.

The observation that the percentage modern carbon decreases regularly with increasing bore depth (Table 2) strongly suggests that the residence time of the water also increases with depth. In order to deduce the average residence time of the water, it is necessary to assume that the aquifer was recharged under similar soil chemistry

conditions (Pearson and Swarzenki 1974). Such samples would be those in groups B and C in Fig. 6 that have a total dissolved carbonate content of about 2·5 mM/litre. The difference between the ^{14}C content of the two groups B and C at this carbonate concentration should reflect the difference in residence time between the groups. On these assumptions, the age difference between groups B and C is 8270 $(\ln 0{\cdot}943 - \ln 0{\cdot}896) = 500$ years approximately.

It must be emphasized that the standard deviation on the slopes of the lines in Fig. 6 is appreciable. Therefore this estimate of age difference is only an approximation and an error analysis shows that it is 500 ± 500 years (1 SD). This simply reflects the fact that the age difference is small (8·7%), compared with the half-life of carbon-14 and there are uncertainties in the understanding of the carbonate geochemistry on which the age calculations depend. If it is further assumed that the age of water in group B, which contains no tritium, is about 100 years owing to the high ^{14}C activity in bores 1/2, 2/2 and 5/2, then the absolute age of water in group C is about 600 years. The water from bore 21/1 contains $0{\cdot}4 \pm 0{\cdot}2\%$ modern carbon, indicating that the age is older than 35 000 years.

In Fig. 6, the intercepts of the lines for groups B and C at zero reciprocal carbonate are 32% and 15% modern carbon, respectively. These values may represent the average modern carbon content of the carbonate dissolved by water when infiltration occurred and decayed to the present time. A mean activity of 25% modern carbon has been reported for calcite in a study of the Tucson Basin (Wallick 1976). However, leakage of water from group A into group B is likely to occur, and if this is so, the system is no longer closed and equation (4) is not strictly valid. Nevertheless, it has been observed that a linear relationship does approximate the data (group B, Fig. 6). The intercept at zero reciprocal-carbonate (Fig. 6) is positive for lines representing groups B and C and negative for group D. The former is consistent with leakage of low carbonate water with high ^{14}C activity, while the latter is consistent with leakage of high carbonate water with no ^{14}C activity. Using the average radiocarbon and $\delta^{13}C$ data in Table 2 for groups C and D, and assuming that water in group D is a mixture of water from group C and artesian water of similar composition to bore 21/1, it can be shown that approximately two-thirds of the water in group D originated from artesian water.

Conclusion

Because the aquifer system in the Namoi Valley is complex, bores were classified according to the screen depth. Water pumped from depths of <25 m originates principally from surface infiltration, either from the river and irrigation channels or by direct rainfall percolation. Both radiocarbon and tritium results confirm that a significant portion of the water has percolated underground in post-nuclear times.

The results are consistent with the hypothesis that the lower aquifers are recharged by leakage from the Great Artesian Basin, which underlies the Namoi Valley.

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