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ENVIRONMENTAL ISOTOPE STUDY FOR ESTIMATING LEAKAGE AND RUNOFF OF GROUND WATERS IN THE XI'AN AREA

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ABSTRACT

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Ninety-six water samples were collected in the Xi'an area and analysed for D, T, ^{18}O and ^{14}C. Stable isotope contents of water samples from three aquifers show differences between, and mixing among, the three aquifers; the mixing ratio was 37.4% of phreatic water in the first confined aquifer and 43.8% of first mixed water to the second mixed water in the second confined aquifer. The phreatic water comprised about 43.8% × 37.4% = 16.4% of the second mixed water in the second confined aquifer. After the tritium contents in precipitation in the Xi'an region had been reconstructed by a multiple cell linear regression method, the groundwater velocity in the first confined aquifer was calculated as 30–39 m year^{-1} from an exponential flow model. A ^{14}C piston flow model gave estimates of average flow velocity in the second confined aquifer of 1.14 year^{-1}. The runoffs in the two aquifers were also calculated.

INTRODUCTION

This study is a co-operative project between the Institute of Karst Geology and the General Observation Station of Hydrogeology in Shaanxi Province. The development and use of ground water, evaluation of groundwater resources and protection of the environment had previously been investigated in the Xi'an region. A more detailed study of the prediction and management of ground water and of the environment, which employed new methodologies and new techniques, was started in 1986, using environmental isotope techniques to trace groundwater sources, leakage among aquifers and recharge of runoff to confined aquifers. For all these purposes, 92 water samples were collected for measuring D, T and ^{18}O, and four samples for measuring ^{14}C (Fig. 1).

CLIMATE AND HYDROLOGY

Xi'an, the well-known historic city, is located in the northwestern part of China. The annual average rainfall is 582.5 mm (1932–1985) on the plain and 800 mm in front of Qing Mountain; evaporation averages some 1300 mm and

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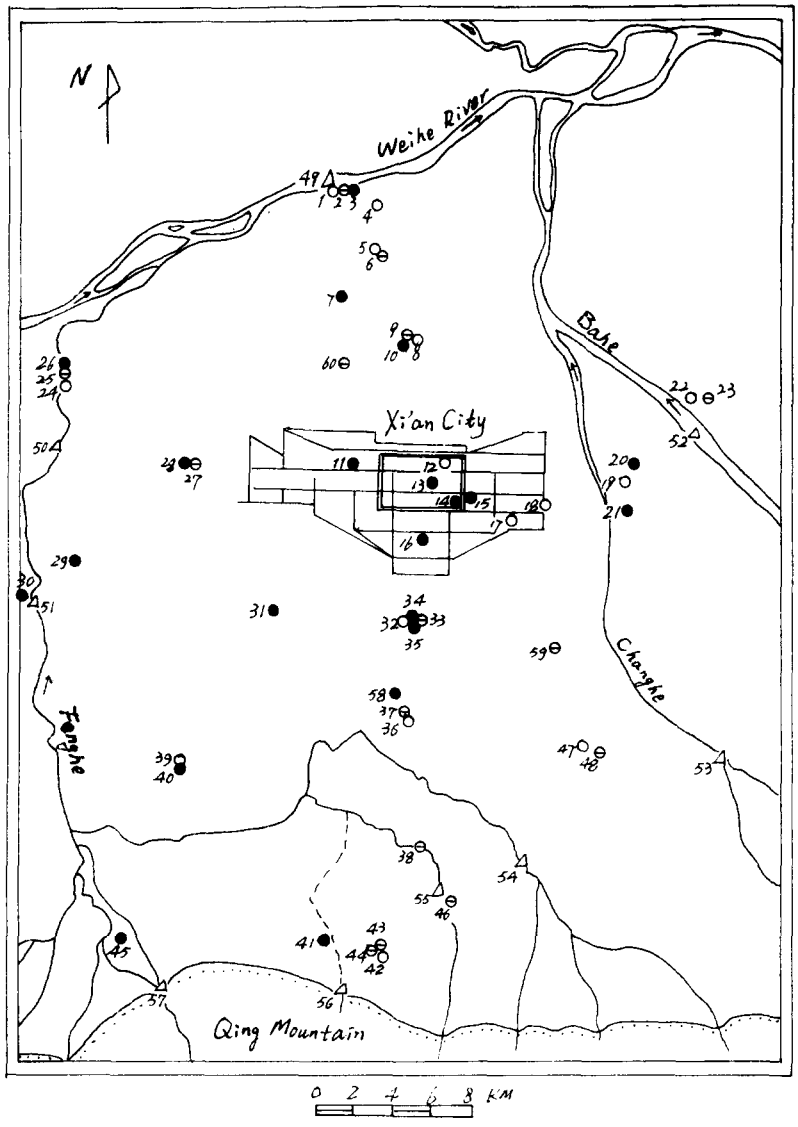

Fig. 1. Location map of sampling points in study area. △, Surface water; ○, phreatic water; ⊖, first confined water; ●, second confined water.

increases from south to north. The average temperature is 13.3°C (1950–1980) with a maximum of 43.4°C and a minimum of −20.6°C.

Among several rivers, the Weihe river is the largest; other rivers discharge waters from Qing Mountain into the Weihe river.

GEOLOGY AND HYDROGEOLOGY

The study area, situated on the south side of the middle part of the Weihe rift valley, is bounded to the south by Qing Mountain and to the north by the Weihe

river; two streams, Changhe and Fenghe, are the east and west boundary of the study area respectively. There are three geomorphological elements in the area: the pluvial plain in front of Qing Mountain and the loess plateau with a small distributed area in the southeastern part of the region, but most of the area is the alluvial plain. The elevation of the topography decreases from the south to the north; relative altitude is about 170 m except for the loess plateau. There are three aquifers to be studied: a shallow aquifer, a first confined aquifer and a second confined aquifer; the depths of beds are above 70 m, 70–150 m and 150–250 m (or 300 m) respectively. Before pumping started, groundwater flowed from south to north and upward (artesian) leakage might occur among aquifers. Both phreatic water and confined waters have been pumped extensively since 1966 (pumping in 1986 was about 120 times greater than it was in 1951). Local pumping cones of depression were formed in the shallow aquifer and the water levels of the confined waters decreased sharply; the depth of water level in the second confined aquifer decreased from 10–20 m in the late 1950s to 80–100 m at present. A large-scale pumping cone of depression has formed around the center of Xi'an city, causing a divide of ground water between Xi'an city and the Weihe river.

ISOTOPIC CHARACTERISTICS IN PRECIPITATION

To understand the characteristics of stable hydrogen and oxygen isotopes in ground waters and to study the water sources and the formation of geothermal water, 21 fracture water samples have been collected from the north slope of Qing Mountain, and four samples from the south slope of Qing Mountain.

All 24 samples were sorted into four groups for regression analysis between δD and $\delta^{18}O$ according to the sampling date and sampling altitude.

(1) $\delta D = 11.25 + 8.21\delta^{18}O$, below 1500 m (a.s.l.) October 1987, north slope;
(2) $\delta D = -14.35 + 5.63\delta^{18}O$ above 1500 m (a.s.l.), October 1987, north slope;
(3) $\delta D = 11.41 + 7.32\delta^{18}O$ April 1989, north slope;
(4) $\delta D = 17.96 + 8.01\delta^{18}O$ April 1989, south slope.

Figure 2 reflects the relationship of δD vs. $\delta^{18}O$ in the fracture ground water. With increasing altitude the δ value of stable isotope diminishes, but in October 1987, all the samples collected above an altitude of 1500 m above sea level (a.s.l.) show the reverse: increasing sampling altitude results in increasing δ values, which implies the enrichment of heavier isotopes in precipitations.

The difference between groups (1) and (2) is very obvious.

The seasonal variation of isotopes in precipitation, reflected in the groundwater values, implies rapid circulation of fracture ground water. The isotopic content also differs from the south slope to the north slope, because of the different sources of precipitation.

The altitudinal relationships of stable isotopes in the area have also been studied.

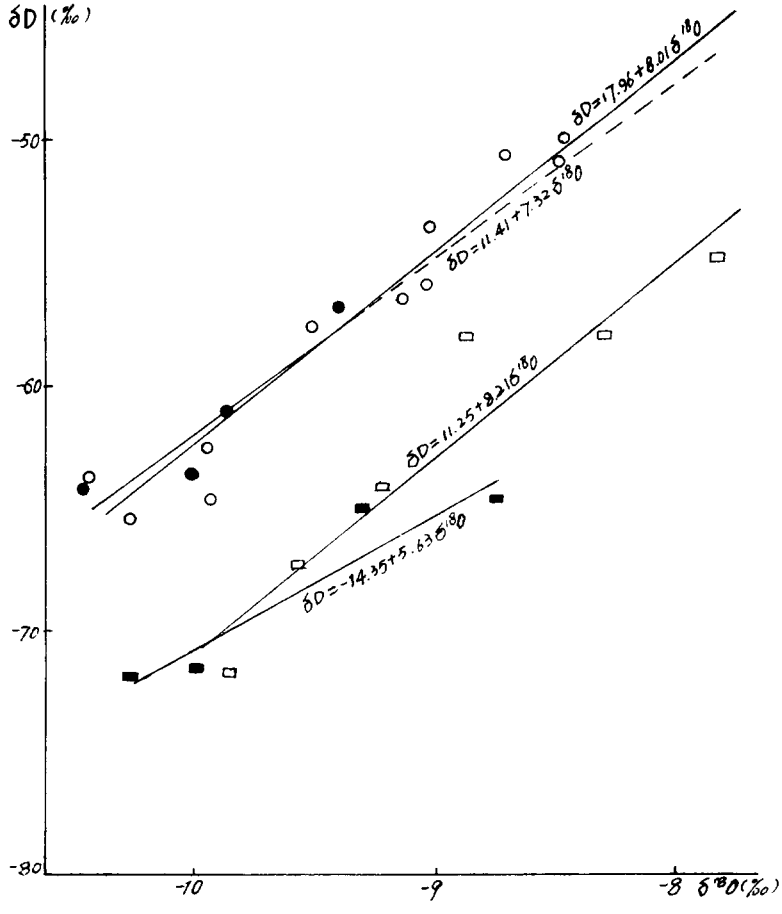

Fig. 2. Relationship between δD and δ^{18}O in fracture waters. ○, North slope of mountain (April 1989); ●, south slope of mountain (April 1989); □, north slope of mountain (October 1987), H < 1500 m; ■, north slope of mountain (October 1987), H > 1500 m.

THE RECOVERY OF TRITIUM CONTENT IN PRECIPITATION

Because tritium concentrations in precipitation are not known in China, a multiple linear regression method has been used to reconstruct tritium contents, for calculation of the mean residence time and the runoff of ground water to or from the aquifers.

Effective factors

Before 1953, tritium was created only from cosmic rays, so that production and reduction of tritium balanced at about 5–15 tritium units (TU). The total amount of tritium in precipitation was about 3–10 kg, with a distribution of

about 93% in the hydrosphere and 7% in the atmosphere. Since nuclear testing began in 1953, large amounts of artificial tritium, up to 200 kg by 1963, entered the atmosphere. Tritium contents in precipitation also increased sharply; for example, in the White-Horse region of Canada, the average tritium content was up to 10 000 TU in the winter–summer season in 1963. After 1963, when large-scale nuclear tests stopped, the tritium content in the atmosphere decreased. Nuclear tests were usually carried out at high altitude; the U.S.A.'s first atmospheric nuclear test was carried out in August 1958, at a height of about 4–7.5 km. After nuclear tritium has entered the atmosphere, it moves with the atmospheric circulation, so it can spread over the Northern Hemisphere quickly. The analysis of isotopes in precipitation shows that the distribution of tritium concentration is affected by rainfall, sampling altitude, locality of sampling and distance from the ocean or sea.

Temperature differences from low to high latitude and the Coriolis force cause the atmosphere to move latitudinally and longitudinally; this atmospheric circulation results in relatively uniform tritium concentration at the same latitude, with increases from lower latitude to higher latitude at the same longitude.

Principles and methodology

The general form of the multiple linear regression formula is

$$Y = a0 + a1X1 + a2X2 + \ldots + anXn$$

TABLE 1

Equations from multiple linear regression method

Year	Regression equation	Coefficient of regression
1961	$TU = 217.4 - 2.0387L + 1.3181H - 0.0384P$	($r = 0.9688$)
1962	$TU = 325.2 + 1.3601L + 0.3393H - 0.1859P$	($r = 0.9085$)
1963	$TU = 1074.0 - 2.1474L + 1.5441H - 0.8532P$	($r = 0.9491$)
1964	$TU = -80.2 + 11.2326L + 1.4528H - 0.4953P$	($r = 0.9610$)
1965	$TU = 251.5 - 0.0826L + 0.1104H - 0.0342P$	($r = 0.7332$)
1966	$TU = 51.05 + 2.6683L + 0.103H - 0.1166P$	($r = 0.8334$)
1967	$TU = 72.3 + 0.8722L + 0.1749H - 0.0885P$	($r = 0.9856$)
1968	$TU = 45.3 + 0.4402L + 0.1089H - 0.0338P$	($r = 0.8610$)
1969	$TU = 34.4 + 1.0915L + 0.0518H - 0.0473P$	($r = 0.5365$)
1970	$TU = 11.2 + 1.9477L + 0.0318H - 0.0872P$	($r = 0.8827$)
1971	$TU = 46.1 + 0.7576L + 0.0521H - 0.0485P$	($r = 0.8780$)
1972	$TU = 25.0 + 0.5644L + 0.03974H - 0.0186P$	($r = 0.7816$)
1973	$TU = 21.0 + 0.512L + 0.0242H - 0.0215P$	($r = 0.6952$)
1974	$TU = 41.7 + 0.1749L + 0.0164H - 0.0191P$	($r = 0.6837$)
1975	$TU = 14.4 + 0.6084L + 0.0532H - 0.0273P$	($r = 0.8804$)
1976	$TU = 9.0 + 0.3301L - 0.0165H + 0.0255P$	($r = 0.7733$)
1977	$TU = 29.2 + 0.5368L + 0.0238H - 0.0444P$	($r = 0.6016$)
1978	$TU = 4.30 + 0.9308L + 0.0247H - 0.0382P$	($r = 0.7876$)

TABLE 2

Calculated tritium contents from Table 1

	1971	1972	1973	1974	1975	1976	1977	1978
Xi'an (TU)	122.3	92.5	74.6	55.2	83.5	52.5	81.7	95.3
Taibai (TU)	172.6	133.1	98.3	72.2	136.1	38.0	98.6	107.8

Here, only three independent variables, longitude (L), sampling altitude (H) and rainfall (P) are considered, and the dependent variable is the tritium content (TU) in precipitation, so the regression model is

$$TU = a0 + a1L + a2H + a3P$$

Annual analysis of data from sampling stations of the International Atomic Energy Agency's (IAEA's) isotope observation network in the zone of latitude 20–35°N and longitude 0–180°E results in the equations for the years 1963–1978 in Table 1.

Tritium contents in precipitation at Xi'an and Taibai from 1971 to 1978 have been calculated and are listed in Table 2.

Correlations with the measurements at Ottawa, are as follows:

$$TU(Xi'an) = 43.9 + 0.39TU(Ot) \quad (r = 0.92)$$

$$TU(Taibai) = 66.5 + 0.52TU(Ot) \quad (r = 0.92)$$

These equations permit calculation of tritium contents from 1953 to 1970 in precipitation at both stations. From 1979 to 1988 actual measurements were made in northwest China (see Table 3).

Figure 3 shows tritium contents in precipitations from 1953 to 1988.

TABLE 3

Tritium contents estimated from measurements at Ottawa and in northwest China

	1953	1954	1955	1956	1957	1958	1959	1960	1961	
Xi'an (TU)	54.1	155.1	59.8	114.9	89.5	270.9	218.5	104.3	131.7	
Taibai (TU)	80.2	215.6	87.9	162	127	370.9	300.6	147.5	184.3	
	1962	1963	1964	1965	1966	1967	1968	1969	1970	
Xi'an (TU)	428	1165	636	344.7	261	169.2	127.7	141.9	117.6	
Taibai (TU)	581	1570	861	470.0	357	236.1	178.9	198.0	165.4	
	1971	1972	1973	1974	1975	1976	1977	1978		
Xi'an (TU)	123	92.5	74.6	55.2	83.5	52.5	81.7	95.3		
Taibai (TU)	173	133.1	98.3	72.2	136	38	98.6	107.8		
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Measured (TU)	61.4	78.2	68.5	58.2	42.8	51.4	46.8	53.6	40	38

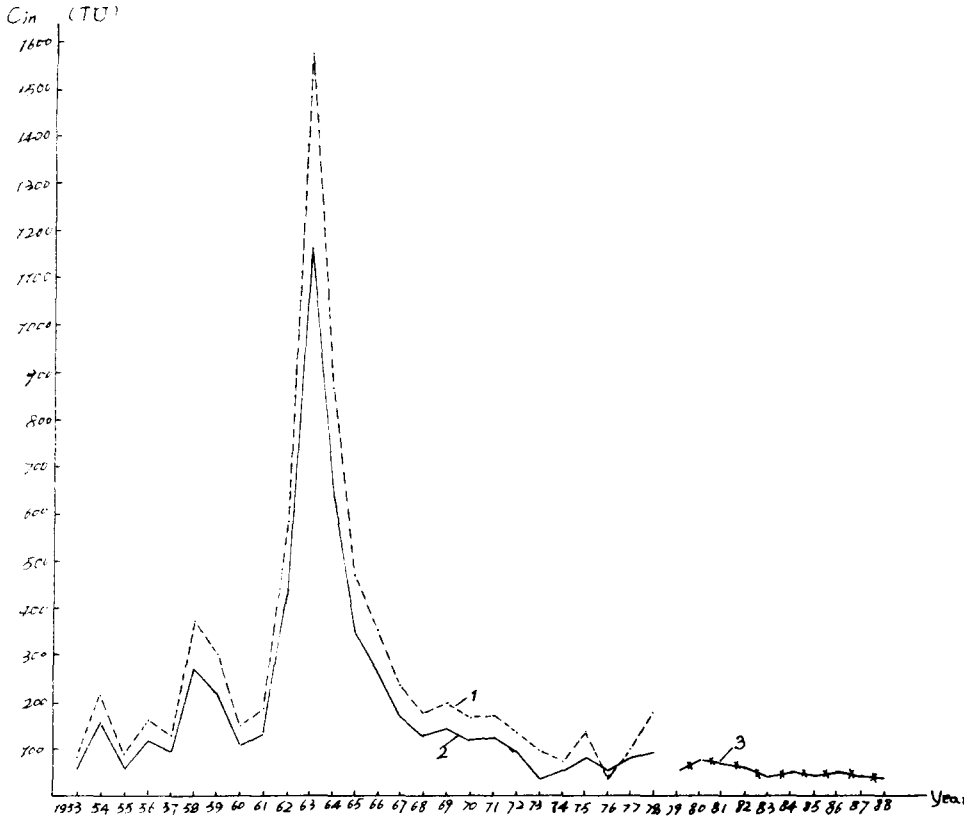

Fig. 3. Reconstructed tritium contents in precipitation in Xi'an area. 1, Upper limit; 2, lower limit; 3, measured values.

ISOTOPE AND HYDROGEOCHEMISTRY OF GROUND WATER

Stable isotopes

Figure 4, which shows the relationship between δD and δ^{18}O of groundwater, demonstrates that the D and ^{18}O of groundwater are distributed in five areas:

I — phreatic water;
II — first mixture of phreatic water and first confined water;
III — first confined water;
IV — second mixture of first water mixture and second confined water;
V — second confined water.

Phreatic water

All samples were collected from the pluvial fan of Qing Mountain in the south to the first alluvial terrace of the Weihe river in the north. The data are distributed closely; this implies that the shallow water results from vertical

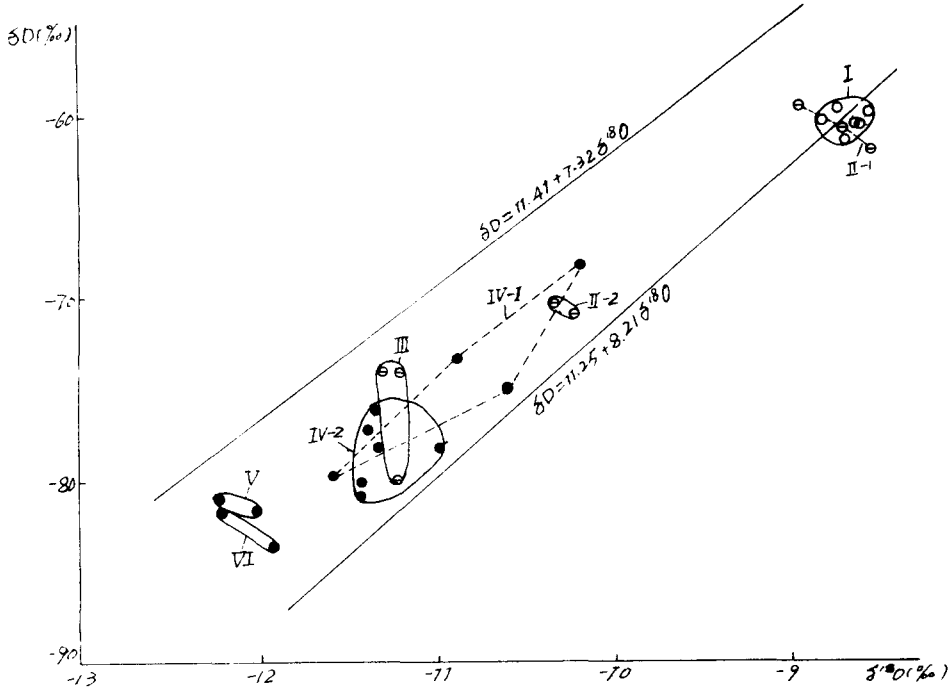

Fig. 4. Relationship between δD and δ^{18}O of ground waters. I, Phreatic water; II-1, first mixture (pumping); II-2, first mixture (leakage); III, first confined water; IV-1, second mixture (pumping); IV-2, second mixture (leakage); V, second confined water; VI, geothermal water.

recharge of precipitation. All points are close to the metoric water line, so that no evaporation has occurred from the water table.

First confined water

In this water the isotope contents are lower than those in the phreatic water. The main recharge comes from the rainfall in front of Qing Mountain and from surface water discharged from the mountainous area; the altitude effect makes the difference, for the aquifer is confined, so that, as it recharges, the δ value should not change in the absence of any other recharge. For example, $\delta^{18}O = -11.36‰$ in the pluvial fan and is still $-11.24‰$ at Dongbali village in the southern suburbs of Xi'an city 18 km away. In fact, it is leakage from the shallow aquifer to the first confined aquifer which results in increases in the δ value of ground water in this aquifer.

Second confined water

The δ values are much lower in this aquifer; they are relatively stable in a horizontal direction from south to north, with values of δD varying from $-83.7‰$ to $-81.6‰$, whereas δ^{18}O varies from $-12.20‰$ to $-12.22‰$. However, these values increase where leakage has occurred (Fig. 5).

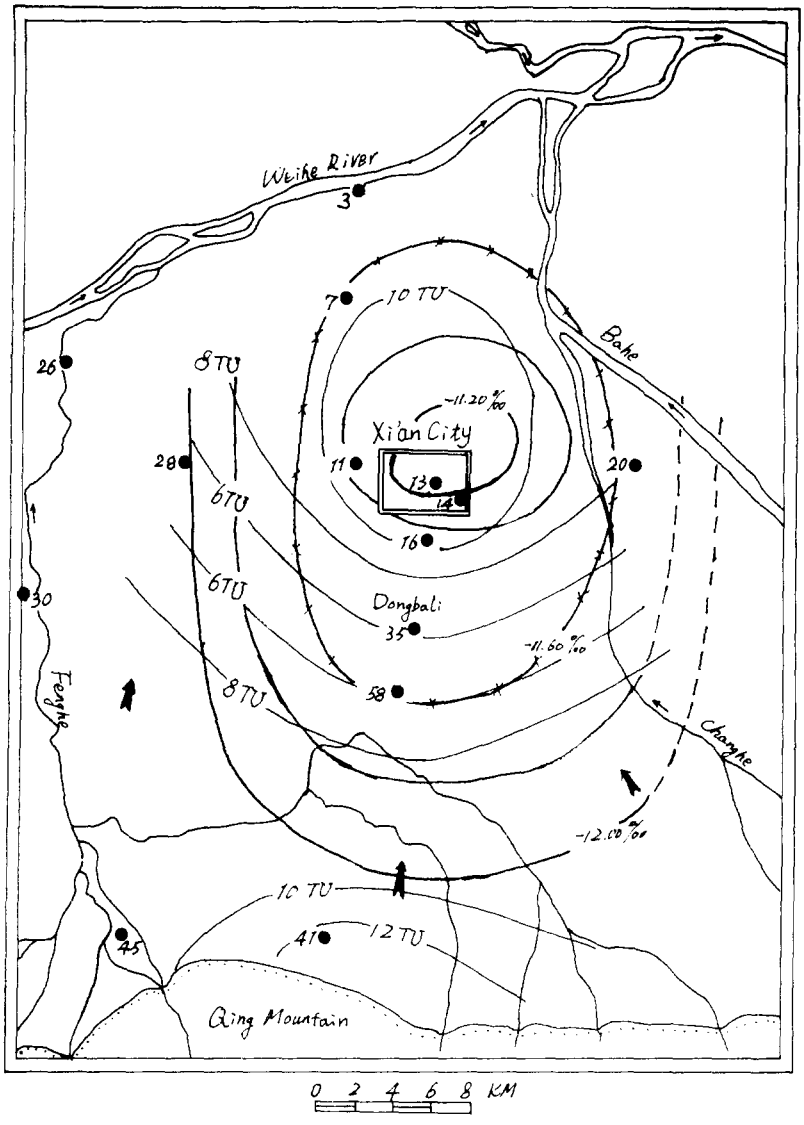

Fig. 5. Contours of tritium content and $\delta^{18}O$ of ground water in the second confined aquifer. ●, Sample locality; —TU—, contour of TU; —‰—, contour of $\delta^{18}O$; — × —, boundary of leakage zone; →, flow direction of ground water.

Radioactive isotopes

Phreatic water is mainly recharged from rainfall but some is surface runoff from Qing Mountain and some is river water; this variation and differences in sampling depth make the tritium concentration vary from place to place.

The first confined water comprises groundwater runoff from the pluvial fan in front of Qing Mountain to the pumping cone of depression in the urban area of Xi'an city. The tritium contents diminish along the direction of flow; for instance, tritium contents decrease from 20 TU at point 38 to 12 TU at point 33, but the reverse happens close to or in the centre of the cone of depression because of leakage of water of higher tritium content into the aquifer.

The second confined water is similar to the first confined water, with radioisotope content diminishing along the flow directions. Four ^{14}C water samples dated the age of the ground waters (^{14}C age corrected with Pearson's model). Immediately in front of Qing mountain, the age of the ground water is $\sim$ 13 000 years. The age becomes greater, up to 16 000 years at Dongbali village. At the centre of the city, however, ground water is younger, 9630 years, and tritium content increases, which implies mixing of older water with younger water.

Figure 5 shows the contours of tritium content and of $\delta^{18}O$ in the second confined water. The changes of both tritium and ^{18}O indicate leakage of younger water or water containing higher levels of the heavier isotope into this aquifer, and the zone of leakage can also be determined from the $\delta^{18}O$ contour.

Hydrogeochemistry

The hydrogeochemical features of ground water in different buried conditions are very typical; the classification diagram (Fig. 6) reflects the similarity of the hydrogeochemical distribution of ground water to the isotopic distribution. This means that five main zones could be found:

I — phreatic water; all points are distributed closely, anion components change little, cation components change by only $\sim$20% of milligram equivalent;

II — a mixture of first confined water with phreatic water, i.e. the first mixed water;

III — first confined water; cations are closely distributed, but anions such as sulphate and chloride increase along the direction of flow;

IV — second mixture of first mixed water with second confined water;

V — second confined water.

Type VI is polluted water, including water from the Weihe river.

All the evidence, not only isotopic but also hydrogeochemical, indicates leakage in the cone of depression around Xi'an city.

Calculations of mixing rate

Figure 7 reflects the recharge and mixing in the study area.

Water mixes not only in the aquifer but also in the pumping hole, so two forms of mixing occur in the first confined aquifer (Fig. 8, b and e) and in the second confined aquifer (Fig. 8, b and c); they are called mixing by leakage and mixing by pumping respectively. In the case of mixing by pumping, in some

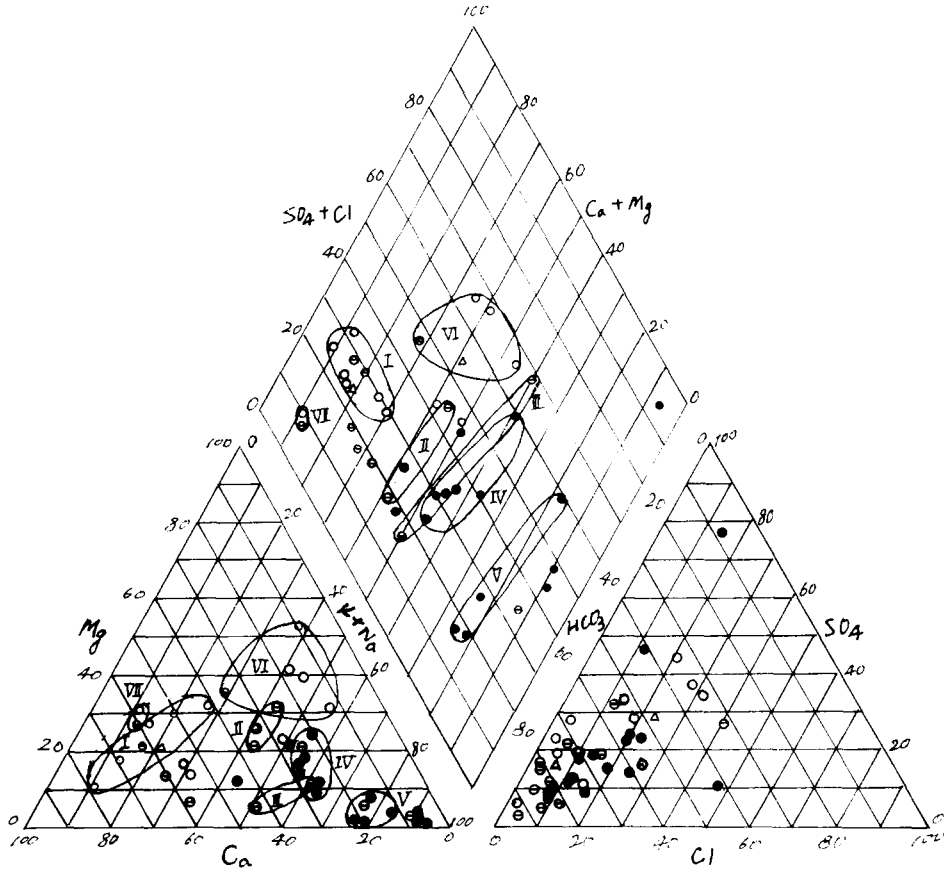

Fig. 6. Classification diagram for anion and cation facies in terms of major ion percentages in ground waters. I, Phreatic water; II, first mixture; III, first confined water; IV, second mixture; V, second confined water; VI, polluted water; VII, ground water on loess plateau.

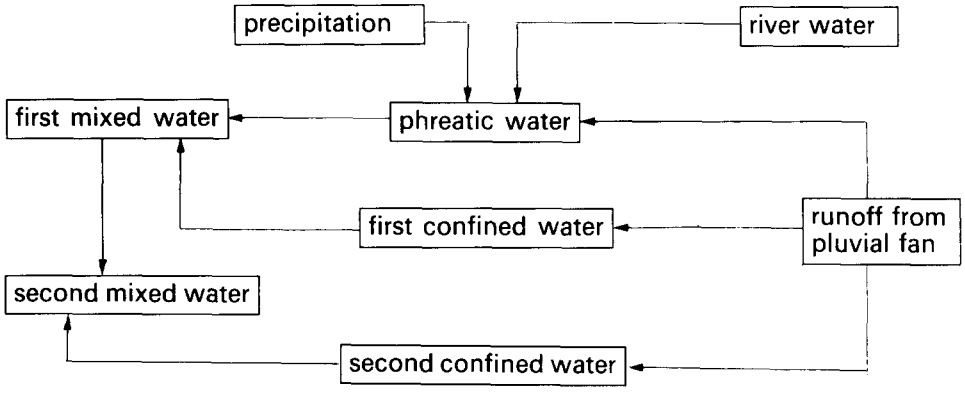

Fig. 7. Diagram of recharge and mixing of waters.

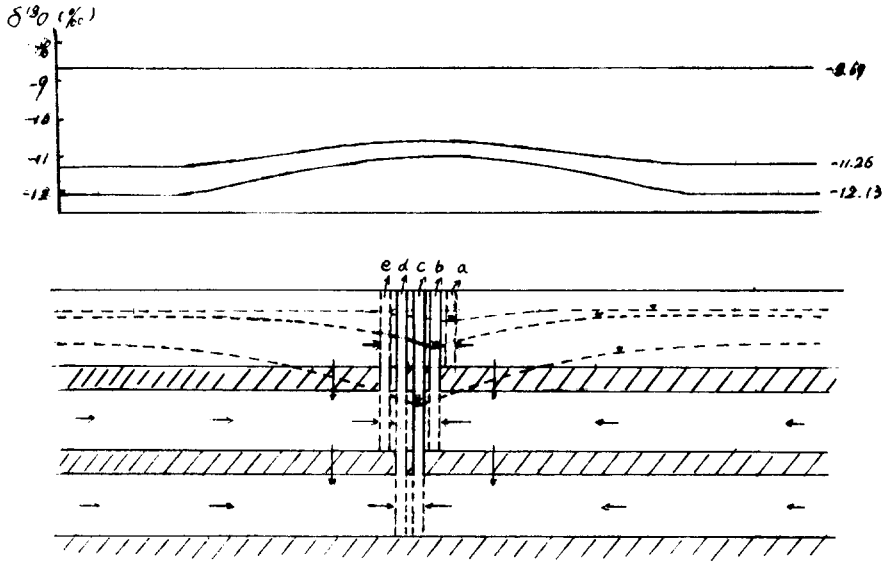

Fig. 8. Schematic map of groundwater mixing and variations of isotopic characteristics of ground waters. b.c., water mixture by leakage; d.c., water mixture by pumping.

holes, water may be pumped from two or three aquifers out of one hole (Fig. 8, d and e).

Assuming a mixing of two waters, $Q1$ and $Q2$, of isotopic contents $\delta 1$ and $\delta 2$ respectively, if the isotopic content and amount of mixed water are δm and Qm respectively, according to the law of conservation of mass and the law of water balance:

$$\delta 1Q1 + \delta 2Q2 = \delta mQm \quad (1)$$

$$Q1 + Q2 = Qm \quad (2)$$

then

$$Q1/Qm = (\delta m - \delta 2)/(\delta 1 - \delta 2) \quad (3)$$

$$Q2/Qm = (\delta m - \delta 1)/(\delta 2 - \delta 1) \quad (4)$$

Using these formulae, the mixing ratios of waters have been calculated and are listed in Table 4; $\alpha 1$ is the ratio of phreatic water to the first mixed water in the first confined aquifer, $\alpha 2$ is the ratio of first mixed water to second mixed water in the second confined aquifer. The average values are $\alpha 1 = 37.4\%$, $\alpha 2 = 43.8\%$; $\alpha 1 \times \alpha 2 = 16.4\%$ is the ratio of phreatic water to the second mixed water in the second confined aquifer.

THE MEAN RESIDENCE TIME AND RUNOFF OF GROUND WATER

Figure 9 is a schematic figure of groundwater movement in the Xi'an region,

TABLE 4

Calculated rates of groundwater mixing among aquifers

Type	Form of mixing	Sample no.	δD (‰)	$\delta^{18}O$ (‰)	α1		α2	
					δD	$\delta^{18}O$	δD	$\delta^{18}O$
I			−60.5	−8.69				
II-1	I + III	S18	−59.7	−8.98	100	88.7		
	pumping	S37	−60.9	−8.72	97.4	98.8		
	mixing	S9	−62.0	−8.56	90.4	100		
II-2	I + III							
	leakage	S17	−70.4	−10.35	36.5	35.4		
	mixing	S27	−71.0	−10.25	32.7	39.3		
	Average		−70.7	−10.30	34.6	37.4		
III			−76.1	−11.26				
IV-1	III + V	S34	−77.2	−11.13			38.7	54.6
	pumping	S21-2	−73.4	−10.90			74.5	67.2
	mixing	S7-1	−79.9	−11.6			13.2	29.0
		S31-1	−68.3	−10.21			100	100
IV-2	II-2 + V	S35	−80.1	−11.44			11.3	37.7
	leakage	S15	−77.2	−11.40			38.7	39.9
	mixing	S16	−80.9	−11.44			3.8	37.7
		S11-1	−76.2	−11.36			48.1	42.0
		S13	−78.2	−11.0			29.2	61.8
	Average						26.2	43.8
V			−81.3	−12.13				

showing the three aquifers. In this paper piston flow and exponential flow models will be used depending on the hydrogeological conditions.

Second confined aquifer

Ground water in this aquifer moves horizontally, parallel to the pluvial fan to the south of Xi'an city, so a piston flow model is

$$C(t) = f(t - \tau_0)\exp(-\lambda\tau_0) \quad (5)$$

^{14}C activities of ground water at points 45 and 35 have been used for the calculation (the small amount of younger water mixed in the second confined water is ignored), and the time lag of groundwater movement from point 45 to point 35 is $\Delta\tau_0 = 3088$ years.

The distance ΔL between points 45 and 35 is 17.5 km, so the real velocity of groundwater movement is

$$v = \Delta L/\Delta\tau_0 = 17.5 \times 10^3/3088 = 5.7\,\text{m year}^{-1}$$

Darcy's velocity should be $V = v \cdot n$, in which $n = 0.2$ (empirically given) is the porosity; then $V = v \cdot n = 5.7 \times 0.2 = 1.14\,\text{m year}^{-1}$.

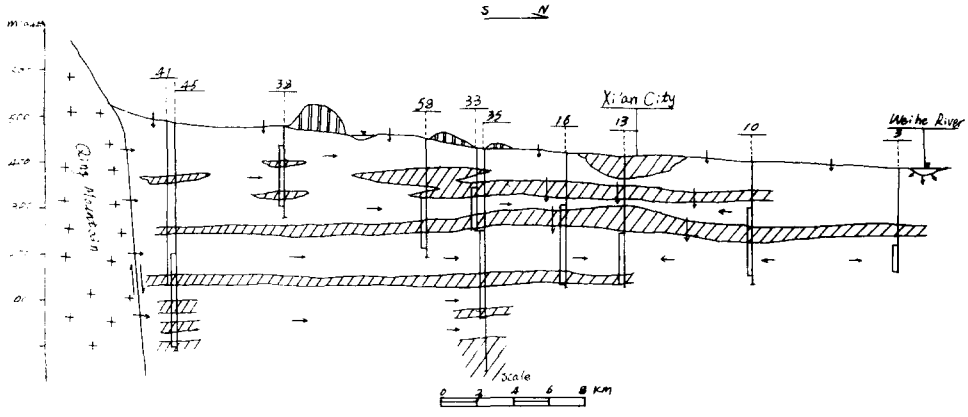

Fig. 9. Cross section of aquifers in the study area. All arrows show the flow direction of ground water.

Considering the velocity–flux relation, $Q = \omega \cdot V = \Delta M \cdot B \cdot V$, where ΔM (47 m) is the thickness of the second confined aquifer, and B (29.4 km) is the width of the cross-section in calculation. The runoff of ground water in this aquifer is then

$$Q = 47 \times 29.4 \times 10^3 \times 1.14 = 1\,575\,252\,\mathrm{m^3\,year^{-1}}$$

First confined aquifer

Although a combined exponential and piston flow model should be used in the calculation of the first confined water depending on the hydrogeological conditions, for simplicity, an exponential flow model is used:

$$C(t) = 1/\tau m \int_0^{\infty} f(t - \tau) \exp(-\tau(\lambda + 1/\tau m))\, d\tau \quad (6)$$

where τm is the mean residence time of ground water. For the convenience of calculation, eqn. (6) becomes

$$C(t) = 1/\tau m \sum_{0}^{t-1952} f(t - \tau) \exp(-\tau(\lambda + 1/\tau m)) \quad (7)$$

For tritium inputs from Table 3, the output of tritium content at different τm in 1988 has been calculated. Simulating the calculated curves with the measured results at points 38 and 33 (Fig. 10), two mean residence times have been derived at two points. Similarly, the groundwater flow velocity and runoff have been calculated using the τm values in this aquifer; the results are listed in Table 5.

In the two cases considered above, the calculated runoffs represent only part of the total recharge from the pluvial fan area; to estimate the total amount, the width of the recharge belt to Xi'an city must be determined by another method.

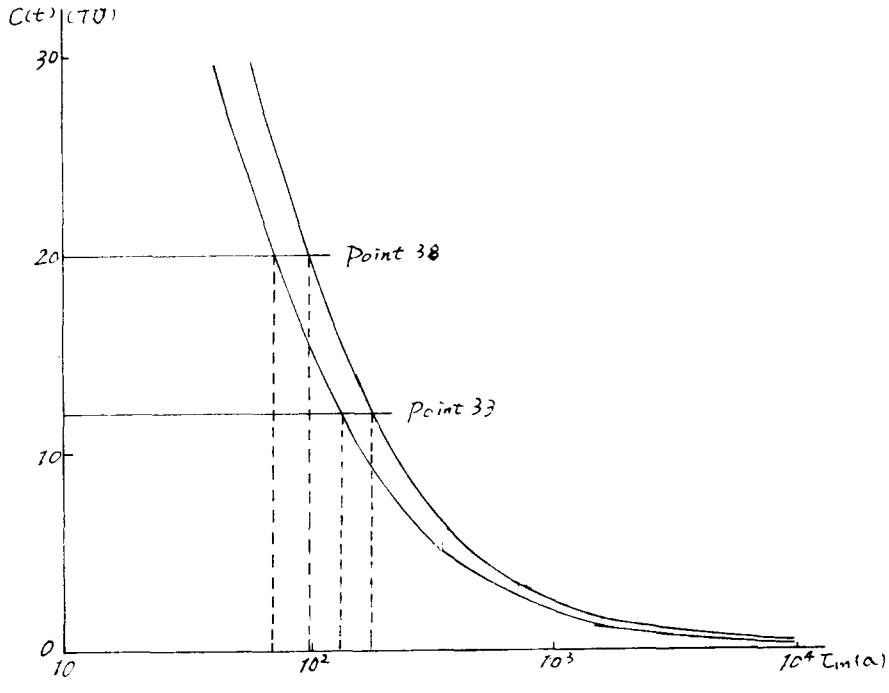

Fig. 10. Fitting of measured concentration of ground water with calculated outputs of tritium concentration.

The ground water ages in both aquifers show that the flow conditions are very different.

CONCLUSION

The distribution of stable isotopes in precipitation (altitude effect and the relationship between δD and δ^{18}O) have been investigated in the initial study of environmental isotopes in the Xi'an area. Tritium contents from 1953 to 1978 were reconstructed by multiple linear regression, to provide background information for the use of mathematical models. In particular, stable isotopes have

TABLE 5

Calculated results of flow velocity and runoff of ground water

Bound	No.	TU	τm (years)	$\Delta\tau m$ (years)	ΔL (km)	v (km year^{-1})	V (km year^{-1})	B (km)	ΔM (m)	$Q \times 10^9$ (m^3 year^{-1})
Xian	S38	20	72							
(min)	S33	12	134	62	12	0.194	0.0388	29.4	64	0.073
Taibai	S38	20	97							
(max)	S33	12	177	80	12	0.15	0.03	29.4	64	0.0564

distinguished different waters very clearly, including unmixed waters and mixed waters, so calculations of mixing depend on these differences. Phreatic water comprised about 37.4% of the first mixed water in the first confined aquifer, the first mixed water was about 43.8% of the second mixed water in the second confined aquifer, then the phreatic water entered the second confined aquifer through the first confined aquifer and comprised about 37.4% × 43.8% = 16.4% of the second mixed water. A ^{14}C piston flow model was used for the second confined aquifer, and Darcy's flow velocity of the second confined water was calculated to be 1.14 m year $^{-1}$. For the first confined aquifer, a radio-tritium exponential model was used and Darcy's flow velocity of ground water was found to be about 30–39 m year $^{-1}$. The runoffs in both aquifers have been calculated, but they are not the total recharge from the pluvial fan to the centre of the cone of depression around Xi'an city; the width of recharge must be known for this calculation.

From the analyses of stable isotopes, radioisotopes and hydrogeological conditions of thermal ground water in front of the mountain, it seems that deep circulation is occurring from the mountain area to the second confined aquifer through an existing deep fault in front of Qing Mountain. Another possibility is that the second confined water was buried in palaeoclimate conditions and was mixed with infiltrating younger surface water or mountain runoff, because of its high age and low tritium content.

The results calculated in this paper (mixing ratio and runoffs) have proved valuable in the calculation and prediction of groundwater resources.

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