# Water Circulation Rates in Urumqi and Turfan Areas, Western China, from the Viewpoint of Tritium

Koichi Kitaoka(*), Seiji Horiuchi(**), Maki Watanabe(3*), Setsuo Okuda(4*), Guijin Mu(5*) and Hongfei Zhou (5*)

* Beppu Geothermal Research Laboratory, Faculty of Science, Kyoto University
Noguchibaru, Beppu, Oita 874, Japan
Fax: +81-977-22-0965, Email: kitaoka@bep.vgs.kyoto-u.ac.jp

** Department of GeoSystem Sciences, Nihon University
3-25-40 Sakurajosui, Setagaya-ku, Tokyo 156, Japan

3* Faculty of Letters and Education, Ochanomizu University
2-1-1 Otsuka, Bunkyo-ku, Tokyo 112, Japan

4* Faculty of Science, Okayama University of Science
1-1 Ridai-cho, Okayama 700, Japan

5* Xinjian Institute of Geography, Chinese Academy of Sciences
40 South Beijing Road, Urumqi, Xinjian 830011, China

Abstract

Tritium concentrations are used to trace water circulation in Urumqi and Turfan areas in Xinjian, western China. Tritium analyses were made for 77 samples of river waters, groundwaters, spring waters, lake waters and glacier ice collected in summers in 1992 and 1994. The tritium concentrations in the waters are in a wide range from 0 to 125 TU. Tritium levels in precipitation in the area are over ten times as high as those at Tokyo. Groundwaters and spring waters in the flat regions are mainly derived from river waters originating in glacier regions. River waters contain more than 50% melt glacier in summer. Circulating meteoric water part in river water has spent a mean time of about 15 years in groundwater systems in the mountain regions. River waters take several ten years to pass the underground to most springs and wells in the flat regions, though some waters from wells and springs with low tritium content are corresponded to old river water more than 40 years ago. Taking into consideration for tritium enrichment by evaporation in closed and semi-closed lakes, the ratios of groundwater flow into salt lakes to precipitation are relatively small as against those in fresh water lakes.

## 1. Introduction

Urumqi and Turfan basins are situated in Xinjian, western China, extending for over 500 $km^2$ with several closed salt lakes. The area is essentially flat and semi-arid, surrounded by the lofty Tianshan Mountains with perpetual snow and glacier. The chemical characteristics of river water, spring water and lake water in the area have been investigated by Watanabe et al. (1995). The main sources of groundwater in the flat regions may be derived from rivers originating in perpetual snow and glacier regions, as the annual precipitation in the flat regions is less than 100 mm.

Tritium is created naturally in the upper atmosphere by the interaction of nitrogen with cosmic radiation, and is transported into groundwater systems by meteoric water. The tritium concentration in precipitation in many part of the world rose after a series of thermonuclear detonation tests in the 1950's, and by 1963 had reached a peak concentration two orders of magnitude above the previous natural level. The relatively short half-life (12.43 y) makes this isotope a valuable tracer of water movements occurring over time spans of a century or less. The tritium content of groundwater can thus give useful information on the circulation of water. In some cases, it is a good indicator of the residence time of water in the groundwater system.

Tritium concentrations are used to trace water circulation in the area. Water samples were collected from rivers, wells, springs and lakes in summers in 1992 and 1994. In 1986, tritium concentrations in precipitations, glacier, rivers, springs and groundwaters in this area were measured by the Chinese Academy of Sciences (Shi and Cai, 1989). The data for various types of water in 1986 will be compared with the new data from the hydrological viewpoint in the present paper.

## 2. Sampling and results

Samples of river water, groundwater, spring water and lake water in the area were taken twice, from 14 to 16 July in 1992 and from 27 June to 16 July in 1994. A total of 77 water samples (20 samples in 1992 and 57 in 1994) were collected for tritium and chemical analyses. The locations of sampling points are shown with sample numbers (or symbols for samples of 1992) in Figure 1.

Tritium analyses were made using the method of liquid scintillation counting. The accuracy of this counting procedure is 0.5 TU for tritium concentration lower than about 5 TU. The term TU (tritium unit) denotes the number of tritium atoms per $10^{18}$ atoms of hydrogen.

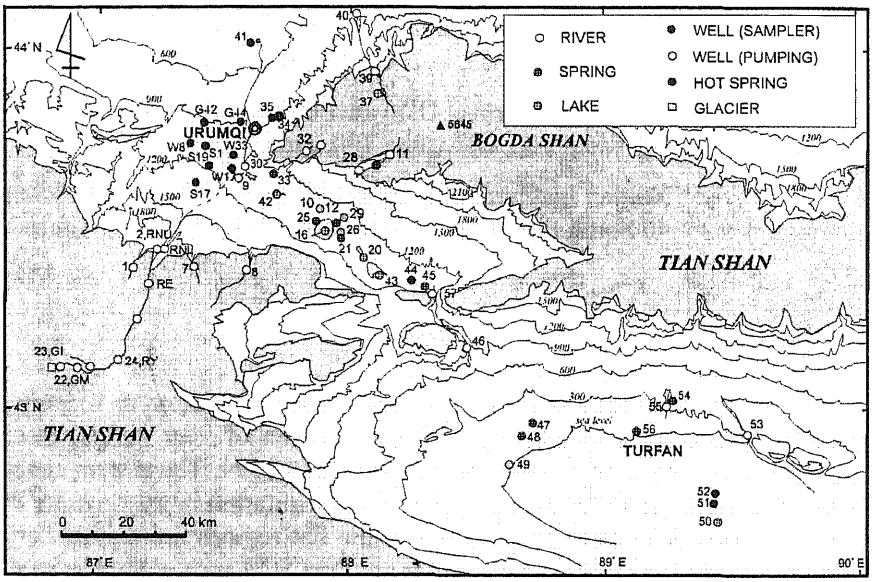


Fig. 1: Sampling points of river, spring, lake, well and glacier in Urumqi and Turfan areas in 1992 and 1994

The tritium concentrations in waters fall into a wide range of 0 to 125 TU. It is noted that the tritium concentration of Urumqi River water at the source point (at the glacier end: GM in Fig. 1) is nearly the same as those in the middle stream of the river (RY, RE and RNL), although the tritium concentration in glacier ice (GI) is very low. The tritium concentrations in Urumqi River water have a tendency to increase with distance toward downstream, and seem to decrease gradually with time during these eight years as a whole.

Most spring waters were relatively in low tritium concentration compared with river waters. Tritium concentrations in lake waters are worthy of note to be similar to those of river waters, although most lakes in the area are closed or semi-closed and salty. It is conspicuous that a series of great tritium concentration over 100 TU occurred in many groundwaters collected from wells in Urumqi City in 1992, though very low tritium contents were in some groundwaters around there. A big spring (No.45), located near the water divide between Urumqi and Turfan basins, discharged also high tritium waters in 1994.

## 3. Estimation of tritium concentration in precipitation in the area

Interpretation of tritium concentrations measured in natural waters requires an estimation of the natural variation of tritium concentration in precipitation in the area. IAEA World Survey Network Stations monitor tritium concentration in monthly precipitation at many points in Eurasia. Monitoring at Tokyo started in 1961 by IAEA, and from 1980 onward, has been made for monthly precipitation at Chiba just near Tokyo by National Institute of Radiological Sciences.

There are correlations in the annual means among stations in the Northern Hemisphere. Then the annual means of tritium concentration at Tokyo before 1960 can be estimated by using Ottawa record. Even at a station with a short observation period, the annual means in precipitation at the

station for other periods can be estimated using a regression line obtained by a correlation with those at Tokyo.

The distribution of annual mean of tritium concentration in precipitation in Eurasia obtained in this manner is shown in Figure 2. Number indicated in the Figure denotes a factor to be multiplied by the annual mean at Tokyo. The factor will be represented by a symbol $M$. At Urumqi, the measured values of tritium concentration for 4 precipitations in 1986 by Shi and Cai (1989) were 105.7, 56.5, 108.0 and 84.2 TU, whose average corresponds to a factor $M$ of 12.5 as against the annual mean of 1986 at Tokyo. Although the period and number of precipitation data measured at Urumqi are not sufficient at all to take correlation with those at Tokyo, the factor is the only instance. The value of this factor is not inconsistent with the general distribution in the central part of Eurasia.

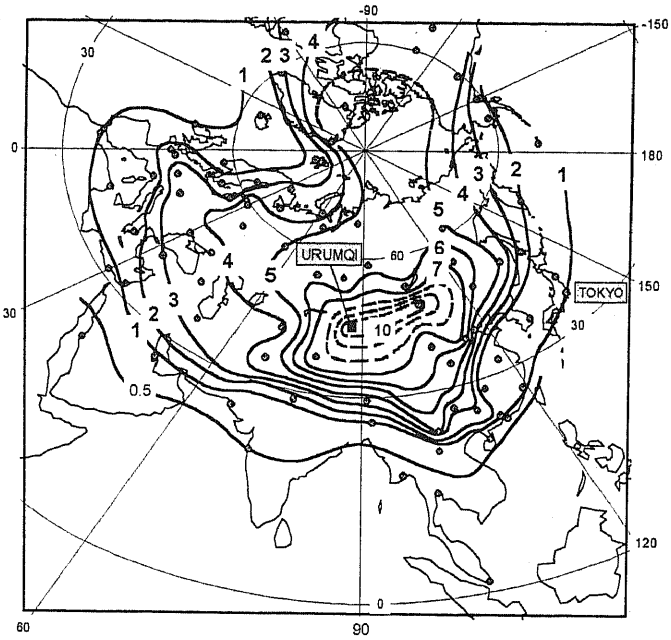


Fig. 2: Distribution of annual mean tritium concentration in precipitation in Eurasia. Figure denotes a factor ($M$) to be multiplied by the annual mean at Tokyo. That is, $M$=1 at Tokyo.

4. Effect of evaporation to tritium concentration in lake water

A lake water sample collected from Ayding Lake (No. 50 in Fig. 1) in 1994 was in great tritium concentration (47.9 TU). The site for collecting the water sample was in the muddy swamp. Water sampled was saturated with salt in puddle. Groundwaters from wells (No.51 and 52) near the sampling point of the lake were in low tritium concentration (0.0 TU and 2.7 TU, respectively). Tritium in the lake water from the swamp seems to be enriched by evaporation of recent precipitations.

According to Craig and Gordon model (Gonfiantini, 1986), the isotopic fractionation factor is composed of an equilibrium separation factor between liquid and vapor at the surface, and a kinetic factor transporting vapor from the surface to the atmosphere. The relative vapor pressure of HTO to $H_2O$ is 0.90 to 0.92 in a temperature range of 20 to 40 °C (Jacobs, 1968). As the equilibrium separation factor, which is the reciprocal of the relative vapor pressure, that is, 1.086 to 1.111, a value of 1.099 will be used. The kinetic factor, which is approximated to be proportional to the square root of the ratio of diffusion coefficients of $H_2O$ to HTO in air, is estimated to be 1.016, if the relative humidity in the atmosphere is approximated to be zero because of the arid condition. After all, the fractionation factor $\alpha$ of tritium at the lake surface is estimated to be 1.116.

A water balance in a steady state for lakes with no inflow river can be expressed as:

$$\frac{dV}{dt} = Q_P + Q_G - Q_E = 0 \qquad (1)$$

where $Q_P$, $Q_G$ and $Q_E$ are precipitation, recharge rate by groundwater and evaporation rate. $V$ is the water volume of lake, and $t$ is time. If the water in a shallow lake is assumed to mix rapidly, the mass balance will be expressed as:

$$\frac{d(CV)}{dt} = C_P Q_P + C_G Q_G - C_E Q_E - \lambda(CV) \qquad (2)$$

where $C$ is the tritium concentration in lake water, and $\lambda$ is the radioactive decay constant of tritium (0.0558 $y^{-1}$). The total flow rate $Q$ passing through the lake is equal to the evaporation rate $Q_E$ for a closed lake. We will introduce here a parameter $\beta$ defined as: $\beta = Q_P/Q$. The mean residence time of water (turnover time of water) in the lake can be defined as $T=V/Q$. By combining (1) and (2)

equations, we get the differential equation for $C(t)$:

$$\frac{dC}{dt}+\left(\lambda+\frac{1}{\alpha T}\right)\cdot C=\frac{1}{T}\cdot\left[\beta\cdot C_P(t)+(1-\beta)\cdot C_G(t)\right] \qquad (3)$$

where $\alpha$ is the fractionation factor: $\alpha = C/C_E$. The integration of equation (3) is

$$C(t)=\int_0^\infty\left[\beta\cdot C_P(t-\tau)+(1-\beta)\cdot C_G(t-\tau)\right]\cdot\frac{1}{T}\cdot\exp\left[-\left(\lambda+\frac{1}{\alpha T}\right)\tau\right]\cdot d\tau \qquad (4)$$

For the Ayding Lake (No.50, in Fig. 1), the tritium concentration in groundwater $C_G$ could be zero for the reason mentioned above. The residence time $T$ of lake water might be less than a few years at longest in such the swamp condition. At first, we will estimate the lower limit of tritium concentration in precipitation by applying the above model to the data of lake water under the extreme condition of $\beta = 1$ (i.e., zero contribution of groundwater). As a result, we can confirm that the $M$–value must be greater than about 10 to satisfy the tritium data. A factor $M$ of 12.5 obtained by averaging the precipitation data at Urumqi in 1986 is not inconsistent with this result. Although the number of precipitation data in this area are very limited, we will use reluctantly the factor $M$ of 12.5 in this paper.

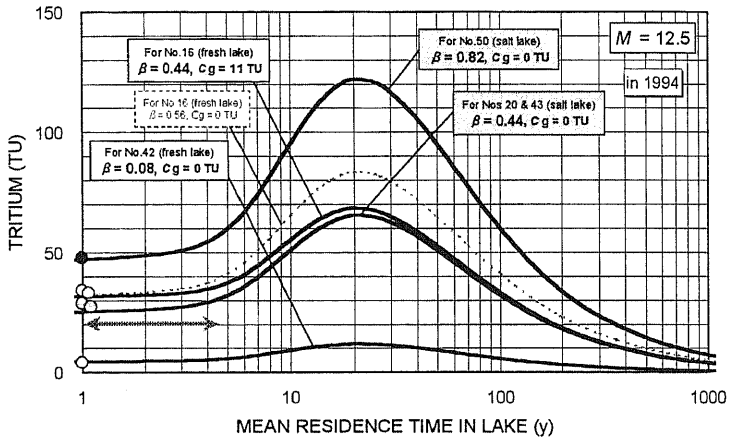


Fig. 3: Calculated relationships between tritium concentration in lake water influenced by evaporation and mean residence time of water in lake in 1994.

If the $M$-value of 12.5 is adopted as the input $C_P$ (assuming $C_G = 0$), the best fit of $\beta$ value for the Ayding Lake data is 0.82 (Fig. 3). For a small lake (No.42 in Fig. 1) whose water is fresh with low tritium concentration, small $\beta$ value of 0.08 is estimated. For the salt lakes (No. 20 and 43 in Fig. 1) in the Urumqi basin, the estimated $\beta$-values are both about 0.44 (Fig. 3).

By the way, for the fresh water lake (Chaiwopu Lake: No.16 in Fig. 1), tritium concentrations in spring waters and groundwaters near the lake are relatively high (from 8.0 to 13.1 TU). If the tritium concentration of recharge groundwater is assumed to be 11 TU during these recent several years (the mean residence time may be less than 5 years), $\beta$ of 0.44 is estimated (Fig. 3. As a reference shown by a dotted curve, if zero tritium content in the inflow groundwater is supposed, $\beta$-value is to be 0.56.). However, the $\beta$-value estimated on the lakes of No.16 and 20 should be recognized to be an upper limit, because these lakes are not closed completely (a little surface discharges from the lakes were observed in 1994 summer). As a whole, it seems that the ratio of direct precipitation to the total recharge of lake has a tendency to increase with salt concentration of lake water (Table 1).

Table 1: Tritium and chloride contents of lake waters, and the estimated ratios $\beta$ of precipitation to total flow rates passing the lakes. Lakes of No.16 and 20 are not closed completely.

| No. | Tritium (TU) | Cl (ppm) | $\beta$ | Name of lake |
|---|---|---|---|---|
| 42 | 4.2 | 45.6 | 0.08 | Hongwei Lake |
| 16 | 34.3 | 202.0 | < 0.44 | Chaiwopu Lake |
| 20 | 28.9 | 3,700 | < 0.44 | Small Salt Lake |
| 43 | 27.5 | 115,000 | 0.44 | Large Salt Lake |
| 50 | 47.9 | 100,000 | 0.82 | Ayding Lake |

## 5. Tritium concentration in river water

### 5.1 Modeling of tritium concentration in discharge water

To interpret the measured tritium concentrations in river waters, there is a need for model de-

scribing water behavior in the drainage region with respect to meteoric water infiltrated from the surface. The tritium-versus-depth profile (if obtained) in the unsaturated and saturated zones will reflect the time history of tritium concentration in the precipitation and the recharge rates. The infiltrating water is supposed to pass fast the unsaturated media because of its poor porosity.

For transport of tritium in a groundwater body, we will define the concentration $C$ as the concentration averaged over the thickness of the aquifer along a cross-section. A discharge point, such as a spring or a pumped well, can be regarded as a singular point at which various streamlines originating in the related recharge area are concentrated in a steady state. The average tritium concentration of groundwater $C(t, x)$ at the horizontal distance $x$ in the flow direction at time $t$ can be expressed as (Kitaoka, 1988):

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}=-\left(\lambda+\frac{1}{T}\right)C+\frac{C_R(t)\cdot r(t)}{T} \qquad (5)$$

where $u$ is the pore water velocity averaged over the section, $C_R(t)$ is the tritium concentration in recharge water and $r(t)$ is the weighting factor for the recharge amount at time $t$. The parameter $T$ is defined as: $T=nH/\varepsilon$, where $n$ is the effective porosity, $H$ is the thickness of groundwater and $\varepsilon$ is the recharge rate per unit area. When the start of time $t$ is put sufficiently long before the concerned point in time, the solution of the above differential equation does not depend on the initial value of concentration $C$ and the pore water velocity $u$ as long as $T$ is uniform in the flow direction. The final solution is as follows:

$$C(t)=\int_0^\infty C_R(t-\tau)\cdot r(t-\tau)\cdot\frac{1}{T}\cdot\exp\left[-\left(\lambda+\frac{1}{T}\right)\tau\right]\cdot d\tau \qquad (6)$$

Tritium concentration $C(t)$, averaged over a cross-section of the aquifer, can be approximated by an exponential distribution of residence times of water in the aquifer. From the theory, it can be seen that the average tritium concentration $C(t)$ does not depend on the horizontal position if $T$ is uniform. The mean residence time $T$ is represented by the water volume $nH$ stored in a column of unit area divided by the recharge rate $\varepsilon$ per unit area. This is the same definition as so-called "turnover time" of a well-mixed reservoir system, because it denotes the ratio of the whole water volume $V$ in an aquifer to the volume rate $Q$ of water passing through the aquifer.

In order to apply the model, it will be assumed that the annual recharge amount to the groundwater system in the recharge region is constant every year. We will use the annual mean tritium concentrations of precipitation for $C_R(t)$, putting $r(t)=1$.

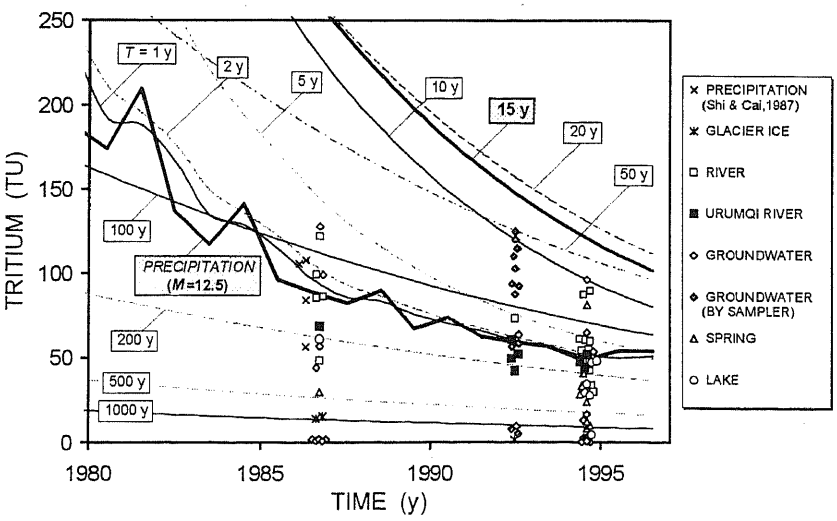


Fig. 4: Tritium data of waters from river, spring, lake, groundwater, glacier and precipitation. A line graph denotes the annual mean of precipitation (as $M$=12.5). Curves are calculated outputs of exponential model for different mean residence times $T$.

## 5.2 Output of the model

Figure 4 shows the calculated output curves using the exponential model, assuming instantaneous recharge of precipitation (as $M$ = 12.5) to groundwater systems. All the tritium data fall into a range of outputs from the exponential model. Solid squares, which denote Urumqi River, show to be corresponded "apparently" to the residence time of 150 to 200 y. Most river waters fall into a range between 50 y and 300 y. These apparent

residence times of water seem too long.

5.3 Runoff of melt glacier

The high-water season of rivers in the area is in high-air-temperature periods. This suggests that the river waters in summer contain melt snow and ice from mountain areas. The melt glacier may be tritium-free water precipitated a great while ago. It will be assumed that river water can be separated into two parts: discharges from circulating water including melt from newly deposited snow, and discharges from melt glacier originated from very old precipitations. Here, we will call the former as meteoric water and the latter as glacier ice, for the convenience of simplicity.

If the tritium content of glacier ice is assumed to be zero, and that of precipitation is prescribed as $M = 12.5$, we can estimate the proportion of meteoric water to river water for the measured tritium data of river water by using the exponential model. That is, the proportions of meteoric water to river water can be estimated by dividing the measured tritium concentration by the output concentration of the exponential model due to the direct input of the prescribed precipitation for various residence times at the concerned time of data. In Figure 5, the calculated proportions of meteoric water to river water are shown by thin curves (solid, dotted and broken curves) for 8 tritium data of Urumqi River water collected in 1986, 1992, and 1994.

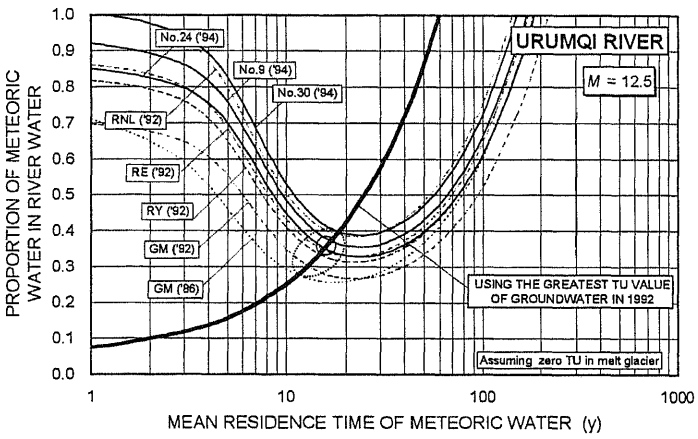


Fig. 5: Meteoric water proportion to river water versus mean residence time calculated by using exponential model and measured data for Urumqi River water. Also shown a bold curve by using the greatest TU value of groundwater in a well in 1992. These calculations are based on the assumption of no tritium content in melt glacier.

On the other hand, the groundwaters from wells in Urumqi City in 1992 were in high tritium concentration, as mentioned above. The main source of the groundwaters is considered to be river water from the Urumqi River, because the infiltration from the ground surface in the flat region must not be predominant in the arid environment, even though irrigation canals are dispersed in the flat region. It is likely that such the groundwaters in high concentration were derived from Urumqi River when the river water had been in high tritium levels in the past. We will assume here that the highest concentration (124.8 TU in 1992) of the groundwaters corresponded to the highest concentration of the river water in the past. Using this highest concentration of groundwater, we can estimate the proportion of meteoric water to the water for various residence times of meteoric water. A bold curve in Figure 5 indicates the proportion of meteoric water to river water with respect to this highest concentration of groundwater in 1992.

Thus, we can obtain the relations between the meteoric water contribution to river water and the mean residence time of meteoric water, in two different ways. Using Figure 5, the meteoric water proportions to river water could be obtained to satisfy both the relations estimated by the two independent ways. As the result, the mean residence times of meteoric water increase from about 11 to 18 y with the proportion of meteoric water to river water from 0.27 to 0.4. The meteoric water proportions seem to have a tendency to increase with distance toward downstream from the original point at glacier end. Using the tritium data in the middle stream, the proportion of meteoric water to river water is about 0.35 (i.e., 0.65 proportion of melt glacier to river water), and the mean residence time of the meteoric water part is about 15 y, as indicated in Figure 5.

The mean residence time of 15 y for meteoric water inferred from the tritium concentrations in Urumqi River water may reflect hydrologic states over a wide area of the recharge regions including perpetual snow and glacier regions. Let's suppose a tentative hydrologic condition such as the

annual recharge ($\varepsilon$) of 400 mm per unit area to the groundwater systems in the recharge regions. Then, the mean residence time of 15 y ($T$) corresponds to a water volume of 6 m per unit area ($nH=\varepsilon T$, a height of water column). The water volume for the groundwater flow system could correspond to a vertical range of 300 m to 3,000 m, if the effective porosity ($n$) in the rock formations is assumed to be in a range of 0.02 to 0.002 in the mountain region. Even such the rough calculation does not seem to provide so unrealistic vertical range of groundwater flow for the lofty Tianshan Mountains.

## 5. Contribution of melt glacier to river water

A thin solid curve in Figure 6 is the output of meteoric water with 15 y mean residence time. A bold curve in the Figure denotes the estimate for the discharge with 0.35 proportion of 15 y meteoric water to river water. This bold curve is calculated for the Urumqi River water in summer. The data of the river water collected in summers are plotted by solid squares.

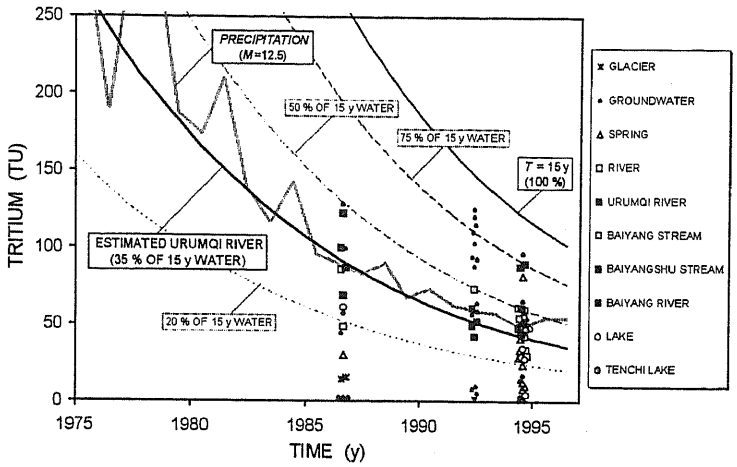


Fig. 6: Variations of tritium concentrations estimated for river waters. Plots are tritium data for various types of water. A thin solid curve represents the output of meteoric water from a system of 15 y mean residence time due to direct input of precipitation. A thick curve is the estimate for Urumqi River assuming to contain 65 % melt glacier of no tritium. Dotted and broken curves are 20, 50, 75 % content of 15 y meteoric water.

On the other hand, Sangong River (No. 37, 39 and 40 in Fig. 1), which also originates in glacier regions in the lofty Bogda Shan, are in similar tritium values as those of the Urumqi River. Tenchi Lake (No. 37) located in the upper-reach of the river shows the same value of tritium concentration to the river water in the lower-reach. Both the mean residence time of meteoric water and the proportion of meteoric water to river water for Sangong River are similar to those for Urumqi River.

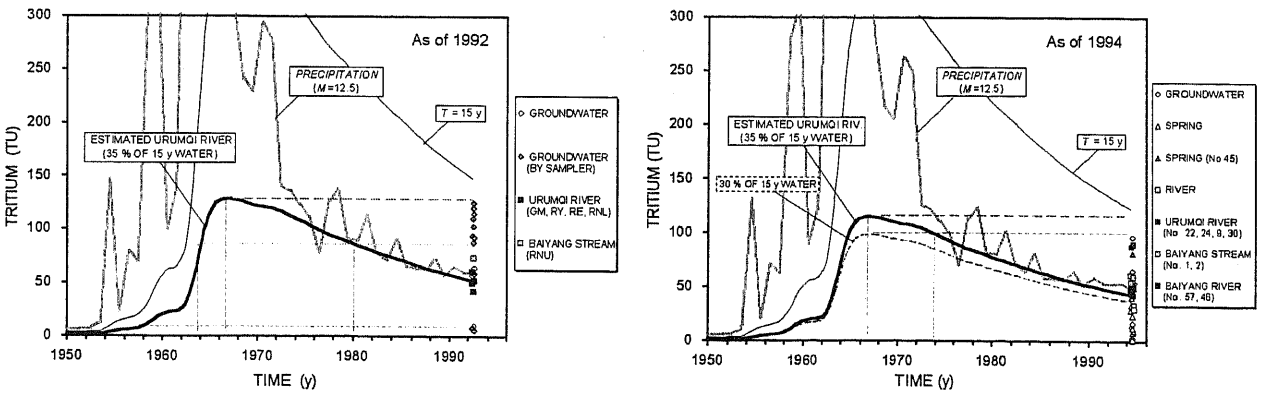


Fig. 7 and 8: Tritium concentrations as of 1992 and 1994, respectively. Plots are measured data in 1992 and 1994, respectively. Thin curve is the output of meteoric water from a system of 15 y residence time. Bold curve is the estimate for Urumqi River water assuming to contain 65 % melt glacier of no tritium.

Bold curves in Figure 7 and 8 show the variation of tritium concentration of river water calculated under the meteoric water proportion of 0.35 to river water. All the TU values of precipitations and calculated curves are converted as of 1992 and 1994, respectively, by radioactive decay, to be

compared with data. The data of Urumqi River are shown by solid squares.

The highest TU value (96.2 TU) in 1994, which was of groundwater from a well (No. 49) located in western part of Turfan basin, could correspond to the peak of the estimate calculated under 0.3 proportion of meteoric water to recharge water, as shown in Figure 8. The proportion of meteoric water is similar to that of Urumqi River. The relatively high tritium concentrations in 1994 for the spring water (81.4 TU) of No. 45 and the river waters (89.4 TU and 87.2 TU at No. 46 and 57, respectively) originated from this spring correspond apparently to a high meteoric water proportion of about 0.7 (Fig. 6), as the spring water may be supplied by underground stream from the Bogda Shan Mountains. If the river water in the upper reach contains 15 y meteoric water and its proportion to river water is similar to that of Urumqi River, the river water must have taken about 15 to 30 y to pass the underground to the spring (Fig. 8).

Most river waters contain meteoric water in a proportion range of 0.2 to 0.5 (Fig. 6). For rivers originating in relatively small altitudes in mountains (compared with Urumqi River) such as Baiyang stream (No. 1, 2) and Baiyangshu stream (No. 11, 28), it is noticed that the proportions of meteoric water to river are relatively large as compared with that of Urumqi River. This may suggest the difference of relative contribution of melt glacier to river waters. In these circumstances, tritium contents in river waters in the area are substantially influenced by melt glacier, and may depend on the areal proportion of glacier in the upper part of the drainage basin.

The travel time of the underground stream water from the end of river to an observation point, such as a well or a spring, can be estimated by using Figure 7 or Figure 8. Tritium concentrations of most spring waters are corresponded to around 30 y of age, though some of spring waters are corresponded to about 10 y, or more than 30 y. Most groundwaters of relatively high tritium content may have traveled under the ground for a range of 12 to 28 y. Groundwaters in very low tritium concentration are corresponded to the river water more than 40 years ago. The main source of underground water in the foothills and the flat regions can thus be considered to be river water, and to contain predominantly melt glacier in summer.

*Acknowledgement*

A part of this work was made as part of studies for the underground water development project in the Urumqi area by the study team organized by Environmental Assessment Center Company Limited (President K. Shiosaka), Shizuoka, Japan.

References

Gonfiantini, R., 1986. Environmental isotopes in lake studies. In "Handbook of Environmental Isotope Geochemistry" edited by Fritz, P. and Fontes, J. Ch., Vol. 2: 113-168, Elsevier.

Inoue, Y., Miyamoto, T. K., Iwakura, T. and Ueki, C., 1983 to 1991. Environmental tritium survey. Report of Radioactivity Survey, NIRS-R 10 to 22, National Institute of Radiological Sciences, Chiba, Japan (in Japanese).

International Atomic Energy Agency, 1969, 1970, 1971, 1973, 1975, 1979, 1983, 1986, 1990 and 1994. "Environmental Isotope Data", Nos 1-10, World Survey of Isotope Concentration in Precipitation (1953-1991), International Atomic Energy Agency, Vienna.

Jacobs, D. G., 1968. "Sources of tritium and its behavior upon release to the environment". U.S. Atomic Energy Commission, TID-24635, pp.90.

Kitaoka, K., 1988. A model of quality distribution in groundwater with reference to natural tritium concentration. J. Groundwater Hydrology, 30: 77-93.

Shi, H. and Cai, Z., 1989. A preliminary isotonic study on conversion of water resources in the north beach of the Chaiwopu Lake, Urumqi. In "Water Resources and Environment in Chaiwopu-Dabancheng Region" (edited by Shi, Y. and Qu, Y.): 97-105, Science Publishing House, Beijing, China (in Chinese).

Watanabe, M., Itota, C. and Horiuchi, S., 1995. Water regime in arid regions – A case study in Xinjian –. Proceedings of the Institute of Natural Sciences, Nihon Univ., 30: 87-97 (in Japanese).