Application of ^{36}Cl for Hydrology

V. Lazarev, A. Blinov [a], H. Reithmeier, and E. Nolte
[a] Department of Cosmic Research, Physical-Technical University of St. Petersburg

Introduction

Cosmogenic ^{36}Cl ($T_{1/2}$=300 ka) is produced in spallation reactions on atmospheric argon induced by high-energy particles of cosmic rays (CR). When the ^{36}Cl amount in water systems is studied, also the anthropogenic ^{36}Cl should be considered. Over Europe, the largest contributions of anthropogenic ^{36}Cl were due to the atom bomb tests in the late 50th and the Chernobyl accident on April 26, 1986.

To compute the distribution of the ^{36}Cl fallout the atmospheric transport model [1] was improved. The input function was calculated using the distribution of the ^{36}Cl production rate due to CR [2] and the estimated altitude dependence of the ^{36}Cl injection from each nuclear explosion performed near the ocean. The obtained latitude distribution of the cosmogenic and the bomb-produced ^{36}Cl are shown in Tab. 1.

	Northern Hemisphere		Southern Hemisphere	
Latitude	Natural flux, at m^{-2} s^{-1}	Bomb fluence, 10^{11} at m^{-2}	Natural flux, at m^{-2} s^{-1}	Bomb fluence, 10^{11} at m^{-2}
5	6.0	4.0	5.6	2.6
15	9.1	6.8	9.0	2.9
25	13.4	9.3	13.0	4.1
35	21.7	15.2	20.9	7.0
45	28.4	19.8	29.9	10.2
55	26.1	15.4	27.8	8.1
65	17.5	8.0	16.4	3.6
75	12.1	4.5	11.9	2.1
85	9.1	2.9	7.2	1.1

Table 1: Latitudinal distribution of the ^{36}Cl natural fluxes and of the ^{36}Cl bomb-produced fluences

The distribution of the Chernobyl ^{36}Cl was calculated using the known ^{137}Cs deposition and the normalization coefficient $9 \cdot 10^{10}$ atoms of ^{36}Cl per 1 kBq of ^{137}Cs activity.

The measurements of ^{36}Cl concentration in lakes with flushing times from 10 to a few hundred years showed a good agreement with the calculations [3]. Thus, the possibility to model the atmospheric input and the distribution of ^{36}Cl from different sources was proved experimentally.

On the opposite, if the hydrological parameters of a water system are not known, they can be deduced from the measurements of the ^{36}Cl concentration in the lake. The application of the method is illustrated on two examples below.

Closure time of Lake Issyk-Kul

Lake Issyk-Kul is the fifth deepest lake in the world. It was formed in Lower Carboniferous and it was fresh at that time. Later its bottom sank and the lake became closed. The methods of the closure age determination are typically based on the conservation of a trace element in the lake, while the water evaporates. The corresponding estimates vary from 6,900 a [4] to 190,000 a [5]. The high ambiguity can be explained by unknown long-term input function of the trace element and by its possible biochemical removal.

The method of ^{36}Cl uses the persistence of the ^{36}Cl production rate due to CR and the high conservative properties of the chlorine. The local ^{36}Cl fluxes depend on the temporary weather conditions and show large fluctuations. However, the meteorological situation becomes of the minor importance if the values averaged over tens thousand years are investigated. The mean natural ^{36}Cl flux for the latitude of the Lake Issyk-Kul was calculated to be 26 at m^{-2} s^{-1}. With the lake's catchment area of 22080 km^2 the annual ^{36}Cl input is $\Phi = 1.8 \cdot 10^{19}$ at a^{-1}. The product of the ^{36}Cl concentration in Issyk-Kul and the lake's volume gives the present number of the ^{36}Cl atoms $N = (3.6 \pm 0.7) \cdot 10^{24}$ in the lake. Anthropogenic ^{36}Cl is responsible for less than 1% of this amount and thus can be neglected. After the lake had become closed the only output of ^{36}Cl was due to its decay. Thus, the basin closure age can be found as

$$T = -\tau \cdot \ln\left(1 - \frac{N}{\Phi\tau}\right) = 270,000 \text{ a},$$

where τ is the life-time of ^{36}Cl. Thus, the cosmogenic ^{36}Cl proves to be an important tool for the age determination of old lakes.

Groundwater outflow from Lake Balkhash

Lake Balkhash is another lake without surface outflow. However, its salinity does not increase because of the groundwater. Unfortunately, no reliable data on its flow rate is available. According to [6] the groundwater outflow exceeds the inflow by about 0.38 km^3 a^{-1}. This contradicts the estimates of the absolute groundwater inflow of 0.08 km^3 a^{-1} and outflow of 0.028 km^3 a^{-1} [7].

Say-Isek Peninsula separates lake Balkhash into two parts with low mixing between each other. The water flow from the western to eastern parts varied from 2.7 km^3 a^{-1} to 2.1 km^3 a^{-1} in the period from 1961 to 1999 [8]. The ^{36}Cl concentration of $(59 \pm 11) \cdot 10^7$ at l^{-1} measured in West Balkhash shows that the bomb-produced ^{36}Cl leaves the water reservoir with a typical time of about 17 years. This corresponds to a water flow from the western to the eastern part of about 2.9 km^3. The obtained value is in a good agreement with the estimates [8]. This proves that the ^{36}Cl input was described correctly.

If the same procedure is applied to East Balkhash, the residence time of ^{36}Cl in this basin can be found. Thus, the ^{36}Cl bomb pulse can be used for the determination of the groundwater flow rate.

References

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