Temporal and spatial variations of $\delta^{18}O$ along the main stem of the Yangtze River, China

BAOHONG LU[1], TINGTING SUN[1], CHUNYAN WANG[1], SU DAI[1,2], JIAN KUANG[3] & JIYANG WANG[1]

1 *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China*
lubaohong@126.com; lubaohong@hotmail.com

2 *Flood-control Division, Taihu Basin Authority of MWR, Shanghai 200434, China*

3 *Hydrology Bureau of MWR, Beijing 10053, China*

Abstract The isotope compositions of δD and $\delta^{18}O$ in river water are very useful tools for interpreting hydrological processes related to climate changes and anthropogenic activities. Since 2003, 170 water samples recovered from the first water campaign and 1-year regular sampling at four stations along the main stem of the Yangtze were analysed for δD and $\delta^{18}O$ composition. The results revealed that temporal and spatial variations in the oxygen- and hydrogen-isotopes of water samples along the main stem of the Yangtze strongly relies on the isotope pattern of the regional precipitation. Secondary signals deriving from influx of evaporatively enriched waters from several major lakes or reservoirs along the system are also apparent. The peaks of the river water isotopic temporal variations are clear, corresponding to the boundary of the beginning or ending for annual flooding period at-site. It can used as an indicator to split flooding or low water standing period at a given location for a water year.

Key words flooding period; indicator; river water isotopic monitoring; temporal and spatial variations; water campaign; Yangtze River

INTRODUCTION

The Yangtze River is the largest river in China, the third largest in the world. The river snakes its way 6397 km from western China's Qinghai-Tibet Plateau to the East China Sea near the city of Shanghai, crossing nine provinces and spanning 90°33′ to 122°25′E and 24°30′ to 35°45′N. Its watershed has an area of about 179.93 × 104 km^2, including approx. 20% of China's total land area and 25% of its total farming land area. About 350 million people live near the Yangtze River and its 700 tributaries.

The river from origin to estuary crosses three main physiographic regions in China corresponding to the three main reaches, which are upstream, mid-stream and downstream. From the headwaters to Chongqing, the upstream portion of the river flow is located on the uplands of the Tibetan Plateau. The downstream portion of the river extends from the mouth of Poyang Lake to the estuary in the lowland region. The portion of the river in between these regions is located on an intermediate step and is referred to as the mid-stream. The headwaters of the Yangtze are situated at an elevation of about 4876.8 m in the Kunlun Mountains in the southwestern section of Qinghai, in which, north of the Himalayas at the Yangtze's origin, the Tibetan Plateau has mighty glaciers and continuous snow cover that melt into the River. The famous three gorges are located in the medium-stream; all four of the largest freshwater lakes of China are distributed in the medium and low reaches of the river.

Flood inundation, water shortages caused by environmental pollution, soil erosion and geological disaster are a few of the major issues facing the Yangtze River basin because of intensive human activities and unsuitable land use. To ensure sustainable economic and social development, a better understanding of hydrological processes and the water cycle is very important at the watershed scale. Watershed hydrology requires integrating knowledge of the hydrosphere, biosphere and atmosphere. Previous studies have shown that the commonly-used hydrological approaches cannot completely recognize intrinsic characteristics and mechanisms of hydrological processes and the water cycle.

River discharge is composed of snow melt, surface runoff and groundwater seepage, and is a very important linkage of the global hydrological cycle. It integrates all of the information on all three disciplines mentioned above which impact on the watershed. Much valuable information is contained in the isotopic composition of river discharge. Isotopic signatures in the river discharge can potentially provide information about how the hydrological cycle is impacted by both climate change and land use. Stable isotope measurements of river discharge are now used in the studies of watershed hydrology, e.g. to describe major flow pathways of groundwater, to trace water mixing history; to determine mean residence time, surface water and groundwater exchange and renewal rates, as well as evaporation–transpiration partitioning; to split hydrograph. Dansgaard (1964) first proposed the use of the value d, to characterize the deuterium excess in global precipitation. The value d is defined for a slope of 8, and is calculated for any precipitation sample as $d = \delta^2H - 8\delta^{18}O$. On a global basis, d averages about 10. It changes due to variations in humidity, wind speed and sea surface temperature during primary evaporation (Clark & Fritz, 1997). The parameter d has been widely used to estimate the impacts of global climate changes and anthropogenic activities on the large scale water cycle.

IAEA has accumulated lots of rainfall isotopic data. However, application of isotope techniques to the study of large-scale rivers has been limited by the lack of discharge isotopic data. To support isotope techniques applied in the large-scale watershed, a global research project entitled "Design criteria for a network to monitor isotope composition of runoff in large rivers" was started in 2002 by IAEA. "The isotopic tracing of hydrology process of the Yangtze River basin" is one cooperative research program of the project. The main purpose of the project is to better understand the interaction of surface and groundwater, the contributions of the groundwater to stream flow and the water balance, and identification of the impact of human activities and climate changes on river runoff.

Apparently, coupling this information into atmospheric GCMs and hydrological models equipped with isotope tracers should improve the accuracy of forecasts of basin floods and water resources. The measurement of isotopic fluxes and volumetric discharge is very useful for the development, utilization and protection of water resources in a large-scale watershed.

WATER SAMPLING

The first water campaign combined with water pollution investigation was carried out by the Environmental Monitoring Center of the Water Resources Committee of the Yangtze River. It started on 13 January 2003, and was completed at the end of January 2003. A total of 74 water samples were collected for the first water campaign, 4 samples were collected for each cross-

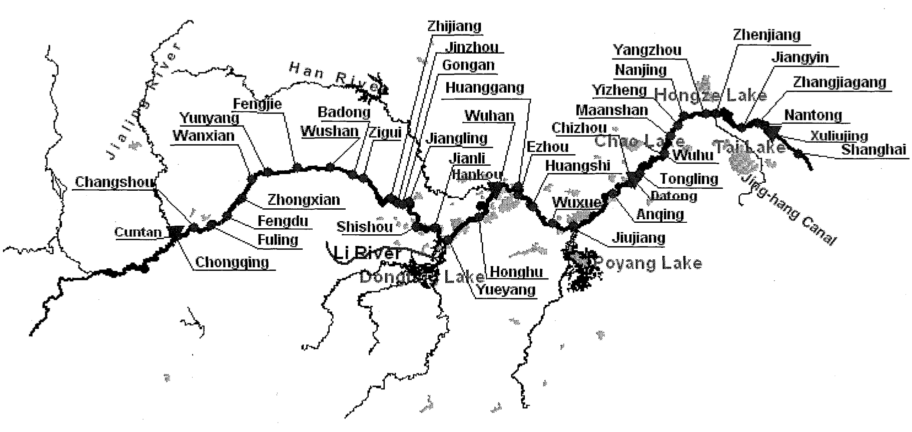

Fig. 1 Sampling sites for the 1st water campaign and the 4 regular monitoring sites (black dot and triangle represent the sampling site for the first water campaign and for the regular monitoring site, respectively).

section within the Three Gorges Reservoir, in total 11 transects and 1 sample per transect without the reservoir, in total 30 transects. At 4 regular monitoring stations, water was sampled at 8:00–8:30 h on the first day and the 15th day of the month from 1 October 2003 until 30 September 2005. Water samples were taken by using the boat measurement method at the 0.1 relative depths below the river water surface and at the 0.3 relative width apart from the right (or left) banks for each transect of the whole river. The sampling sites are demonstrated in Fig. 1.

All samples were analysed for $\delta^{18}O$ and δD in the Environmental Isotope Laboratory of the University of Waterloo (Canada) and Hydrology Isotope Laboratory of IAEA (Vienna), as well as in the Key Laboratory of IGCS (China).

RESULTS AND DISCUSSION

Relationships between runoff and precipitation isotopic compositions

The relationships between $\delta^{18}O$ and δD for precipitation and river water are demonstrated in Fig. 2. As illustrated, the real lines represented the relationships for the first water campaign in the January and a few weeks in 2003, and for 4 regular sampling sites about one year from October 2003. The corresponding trend line equations are $\delta D = 7.64\delta^{18}O + 6.93$ and $\delta D = 7.68\delta^{18}O + 5.61$, respectively. It can be seen that the local meteoric water line (LMWL: $\delta D = 7.62\delta^{18}O + 8.20$) around the whole Yangtze River is very close to the global meteoric water line (GMWL: $\delta D = 8\delta^{18}O + 10$) and appreciably higher than it (Rozanski *et al.*, 1993). The trend lines for river water along the main stem in the Yangtze River basin are also close to LMWL, and nearly parallel to the LMWL. It reflects that the river water isotopic variations along the main stem strongly depend on precipitation isotope fields. As observed, the differences of the trend lines for river water behaved as d-excess. It proves the evaporation effect because river water experiences multiple evaporation, including surface water evaporation and groundwater evaporation after the precipitation water is converted into river water, which results in a higher d-excess value of the river water than the precipitation water (Araguas-Araguas *et al.*, 2000; Martinelli *et al.*, 2004).

Spatial variations of stable isotope ^{18}O

The variation of $\delta^{18}O$ composition for the first water campaign with the distance from the headwater along the main stem of Yangtze River is shown in Fig. 3.

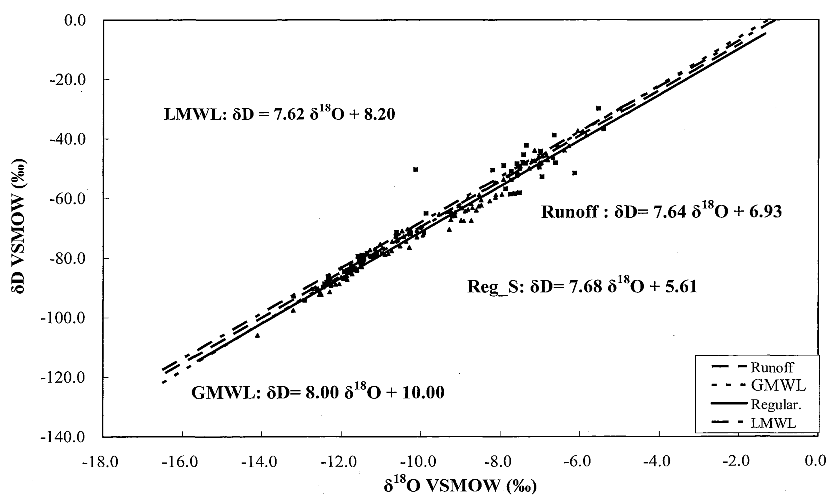

Fig. 2 D and ^{18}O relationship of the runoff and precipitation isotope in Yangtze River.

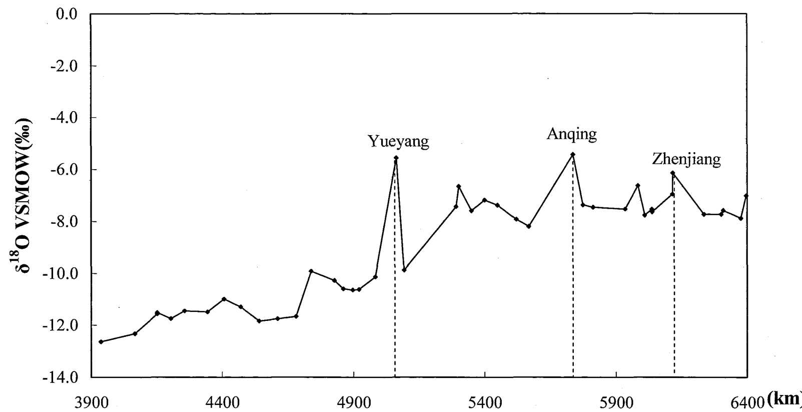

Fig. 3 Stable Isotope ^{18}O compositions changed with distance apart from the headwater of the Yangtze River.

As observed, the isotopic composition of the river water is progressively increasing along the main stem and there are three major peaks in Fig. 3. The increase of the $\delta^{18}O$ along the river course is because of the evaporation effect enhancing, due to the long distance. Along the flow path, the isotopic compositions of the water regulated by lakes or reservoirs are more positive than those unregulated waters of neighbour sites due to the evaporation, and the isotopic compositions between former and later cross-sections are obviously different, which also reveals that the isotope pattern depends on the precipitation isotope field. The largest $\delta^{18}O$ peak showing the greatest evaporative enrichment (first $\delta^{18}O$ peak) is caused by the water sample directly collected from Dongting Lake, which may consist of recharge from rice plant fields (Su *et al.*, 2003; Gibson *et al.*, 2005). The following peak is because the water sample was collected in the mixing region of Poyang Lake and the main stem of Yangtze River. The last $\delta^{18}O$ peak is at Zhengjiang where the collected water sample was a composite consisting of water from the main channel of the Yangtze River and runoff from Hongze Lake.

Temporal variations of stable isotope ^{18}O

The temporal variation of the $\delta^{18}O$ via discharge change with time is reflected in Figs 4–5.

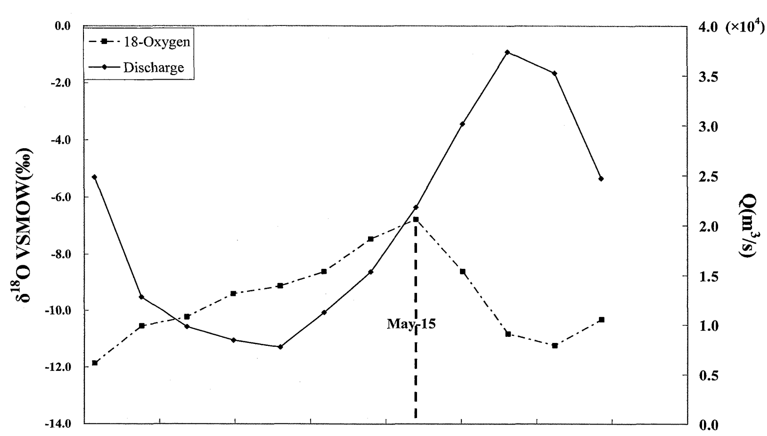

Fig. 4 Weighted $\delta^{18}O$ and monthly mean discharge change with time at Hankou Hydrological Gauge Station.

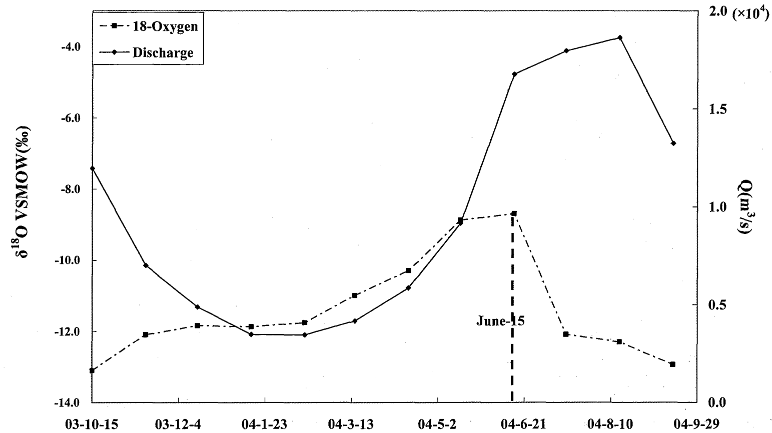

Fig. 5 Weighted $\delta^{18}O$ and monthly mean discharge change with time at Chongqing Hydrological Station.

In Figs 4 and 5, monthly average $\delta^{18}O$ is weighted by river discharge using the following equation:

$$\overline{\delta^{18}O_i} = \frac{\left(\delta^{18}O_f \times Q_f + \delta^{18}O_m \times Q_m + \delta^{18}O_e \times Q_e\right)}{\left(Q_f + Q_m + Q_e\right)}$$

where $\overline{\delta^{18}O_i}$ represents average $\delta^{18}O$ composition of the *i*th month, $\delta^{18}O_f$, $\delta^{18}O_m$, $\delta^{18}O_e$ and Q_f, Q_m, Q_e represent $\delta^{18}O$ values and river discharge at the first, the medium, and the end of the *i*th month, respectively.

River water is composed of melt water, surface water, and groundwater. At the low water standing period, the flux of river water is dominated by groundwater because of the decreasing precipitation contribution to river water.

As shown in Figs 4 and 5, the $\delta^{18}O$ peak appears before the flooding period in summer at the two sites, and the time interval before the peak could be divided into two phases: (1) winter, mainly including the last month of 2003 and the first month of 2004, river water is dominated by groundwater with higher $\delta^{18}O$ value because of the little rainwater in winter. The $\delta^{18}O$ value of the river water is more positive in the period and the $\delta^{18}O$ value is about –10‰ in Hankou station, –12‰ in Chongqing station. (2) Old water gradually drained out from the basin becomes the main composition in the river water, starting from February and ending at the $\delta^{18}O$ peak. Besides, the stronger evaporation caused by the increasing temperature also makes the $\delta^{18}O$ value become higher and higher. Eventually the value reaches the highest point at the end of the period. The flood period comes after the isotopic peak. The $\delta^{18}O$ value declines because the new water has become the main composition of the river water.

More attention should be paid to the occurrence time of the $\delta^{18}O$ peak that corresponds well to the beginning of the flooding period at the corresponding region, just as 15 June for Chongqing station, and 15 May for Hankou station. The feature could be used to split a water year into the flooding and the low water standing periods.

SUMMARY AND CONCLUSIONS

Based on the study of water stable isotopes along the main stem of the Yangtze River, pertinent conclusions can be drawn as follows:

– Temporal and spatial variations in the oxygen- and hydrogen-isotopes of water along the main stem of the Yangtze River strongly reflect the isotope pattern of the regional precipitation.

- Lakes or reservoirs influence on the isotopic compositions of the river water could be very large. They directly result in d-excess values increasing.
- Stable isotope composition peak or valley of river water is a good indicator of split flooding period and low water standing period at a given location for a water year.

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