

## **INVESTIGATION OF ISOTOPES AND HYDROLOGICAL PROCESSES IN INDUS RIVER SYSTEM, PAKISTAN**

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## ABSTRACT

Indus River, one of the longest rivers in the World, has five major eastern tributaries viz. Bias, Sutlej, Ravi, Chenab and Jhelum) while many small rivers join it from the right side among which Kabul River is the biggest with its main tributaries, the Swat, Panjkora and Kunar. All these main rivers are perennial and originate from the mountains. Basic sources of these rivers are snowmelt, rainfall and under certain conditions seepage from the formations. Different water sources are labeled with different isotope signatures which are used as fingerprints for identifying source and movement of water, geochemical and/or hydrological processes, and dynamics (age of water). Monitoring of isotopes in rivers can also enhance understanding of the water cycle of large river basins and to assess impacts of environmental and climatic changes on the water cycle. Therefore, a national network of suitable stations was established for isotopic monitoring of river waters in Indus Basin with specific objectives to study temporal variations of isotopes ( $^2\text{H}$ ,  $^{18}\text{O}$  and  $^3\text{H}$ ), understand water cycles and hydrological processes in the catchments of these rivers, and to develop comprehensive database to support future isotope-based groundwater studies in the basin on recharge mechanism, water balance and monitoring of ongoing environmental changes. Water samples were collected during 2002-2006 on monthly basis from more than 20 stations at the major rivers and analyzed for  $^{18}\text{O}$ ,  $^2\text{H}$  and  $^3\text{H}$  isotopes.

Headwaters of main Indus River (Hunza, Gilgit and Kachura tributaries), which are generally snowmelt, have the most depleted values of  $\delta^{18}\text{O}$  (-14.5 to -11.0‰) and  $\delta^2\text{H}$  (-106.1 to -72.6‰) due to precipitation at very high altitude and very low temperatures. Generally these waters have low d-excess showing that the moisture source is from Indian Ocean. High d-excess of some winter (November-February) samples from Hunza and Gilgit indicates dominance of moisture source from Mediterranean. Kachura station having  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  line with slope 4 and low d-excess shows evaporation effect in Kachura Lake.  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of Indus River get enriched going downstream towards Arabian Sea because of contribution from rains at low altitude plains and baseflow, and evaporation. Low tritium in some samples also indicates contribution of baseflow (relatively older groundwater).

River Chenab has the widest variation in  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ , and slope of  $\delta^{18}\text{O}$ -  $\delta^2\text{H}$  line is 6.1, which is due to variable contribution of snowmelt at high altitude and rains fallen at low altitudes. High d-excess in snowmelt and low d-excess in monsoon show that the moisture source in winter is generally western (Mediterranean) and the monsoon dominantly originates from Indian Ocean. The isotope data also reflect evaporation effect during dry periods. Kabul River has wide variation in isotopic values due to variable contribution from Swat River, which carries snowmelt. High d-excess is associated with the depleted isotopic values, while low d-excess is associated with enriched isotopic values generally during summer monsoon. Therefore, slope of  $\delta^{18}\text{O}$ -  $\delta^2\text{H}$  line is 7, which seems mainly due to dominance of moisture source from Mediterranean in winter (having depleted isotopic values and high d-excess) and from Bay of Bengal in summer with relatively high d-excess. River Jhelum and its tributaries upstream of Mangla Lake have enriched  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  due to low altitude of its catchment. The precipitation in the catchment of river Ravi results from the moisture source from Indian Ocean and there is not any significant effect of evaporation. The isotopic variation seems mainly due to water diversions from the western rivers through link canals.

*Keywords:* isotopes, Indus River System, Pakistan, temporal variations, hydrological processes

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# INVESTIGATION OF ISOTOPES AND HYDROLOGICAL PROCESSES IN INDUS RIVER SYSTEM, PAKISTAN

## 1. INTRODUCTION

Water flow in most of the river systems has two principal components: surface run-off of precipitation and groundwater (baseflow). Their respective contributions differ in each system and depend on physical setting of the drainage basin as well as on climatic parameters. Water in a river may thus vary in its isotopic composition i.e. large seasonal variations are observed in rivers and lakes in which surface run-off dominates the discharge. Isotope signals in river discharge can potentially contribute to better understanding of the continental portion of the hydrological cycle including information such as water origin, mixing history, water balance, water residence time, surface- groundwater exchange and renewal rates, and evaporation-transpiration partitioning. Applications could range from input into water management programme to model verifications [1, 2]. Stable isotopes also provide information on the source of moisture in rains, especially the monsoon circulation [3].

Pakistan, lying between latitudes  $24^{\circ}$  and  $37^{\circ}$  north and longitudes  $61^{\circ}$  to  $76^{\circ}$  east, possesses quite complicated and attractive physiographical features. There are very often a series of mountain ranges, and at places possessing deep broad valleys in-between. It includes the famous valley of the Indus that has been the cradle of ancient civilization like those of the delta area of Nile and the valley of the Tigris Euphrates. Indus River is one of the longest rivers in the World. It has five major tributaries viz. Bias, Sutlej, Ravi, Chenab and Jhelum joining from eastern side, while a number of small rivers join the Indus on the right side. The biggest is the Kabul with its main tributaries, the Swat, Panjkora and Kunar [4].

All the main rivers of Pakistan are perennial and originate from the mountains. Physiography and climate of the catchments of these rivers vary widely. Going from the catchment of the River Ravi to the catchment of Indus River, altitude increases and temperature decreases. In Northern Areas, mountains are covered

with glaciers and some of the peaks are higher than 8000 m, which get snowfall even in summer season. The basic source of these rivers is the melting of snow, rainfall and under certain conditions seepage from the formations. For certain rivers the source of snow is seasonal which falls in winter and melts in summer. From the middle of March to the breaking of monsoon, in mid July, river water is drawn from the melting of snow. During monsoon, rainfall run-off is added to the rivers over and above that from melting of snow so their discharge increases manifold.

### **1.1. Drainage Basins**

Hydrologically, Pakistan consists of three drainage basins which are Kharan Desert, Makran Coastal Basin and the Indus Basin in the eastern part extending from northeast to southwest. Kharan Desert is a closed inland basin which lies in southwestern part of Pakistan in the province of Balochistan. The major streams in this basin are Pishin, Kashkel and Baddo. The water is discharged into shallow lakes and ponds which get dried readily as the rainfall is low and evaporation rate is very high. The extreme southwest corner of Pakistan houses the Makran Coastal Basin which lies to the south of Kharan Desert Basin. In this basin, there are several small streams which drain into Arabian Sea individually. The main streams of this hydrologic unit are Desht, Hingol, Porali and Kud. The perennial flow of these streams remains insignificant as the area is a dry desert but at times rains in their catchment produce flash floods [4].

Among the above-mentioned three hydrological units, only Indus Basin carries vital importance because of its volume of water and extensiveness. The watershed of Indus Basin spreads over the areas of Pakistan, India, Jammu and Kashmir, Tibet and Afghanistan. Total watershed area of the Indus Basin is 934,000 km<sup>2</sup> which is larger than the total area of Pakistan i.e. 796,000 km<sup>2</sup>. Out of this area about 60 % lies in Pakistan and independent part of Kashmir, 15 % in Indian held Kashmir, 10 % in Tibet, 8 % in India and 7 % in Afghanistan. The longest river of the Indus Basin is the Indus River itself. Up to Thatta area in the southwest of Pakistan, the Indus River traces a length of about 3200 km. During

its journey to the Arabian Sea, it meets a number of rivers which are its tributaries and are Gartang, Shyok, Shigar, Gilgit, Hunza, Astore, Siran, Kabul, Haro, Soan, Kurram, Tank Zam, Gomal, Jhelum, Chenab, Ravi, Beas and Sutlej. Indus River and its tributaries combined together and make a gigantic river system named as Indus River System (IRS) [4].

Table I. Catchment area [5] and river runoff

River	Rim-station	Catchment Area (km <sup>2</sup> )	Years	Mean Annual Runoff (x10 <sup>9</sup> m <sup>3</sup> )
Indus	Tarbela	168,000	2002-2004	69.81
Kabul	Nowshera	87,600	2002-2004	19.69
Indus	Kalabagh	283,000	2002-2004	89.79
Jhelum	Mangla	33,396	2002-2004	22.96
Chenab	Marala	29,513	2002-2004	27.61
Ravi	Shahdara	8,025	2002-2004	7.57
Sutlej	Sulemanki	44,010	2002-2004	8.32

The rivers of IRS get their inflows from both rainfall and snow melt. Snow line usually varies between elevations 1500 to 4800 m and occasionally, may rise to 5400 m. The main source of snow is the winter monsoon and the rains occur during summer monsoon season. Overlapping of the snowmelt and rainfall during summer monsoon season causes high floods in the rivers. The watersheds of southern rivers viz. Sutlej, Beas and Ravi are the first to be influenced by the summer monsoon rains. The upper part of the Indus River Basin receives the least contribution from the monsoon rains and the major portion of the river discharge is composed of snowmelt. In contrast to other rivers of IRS, snowmelt runoff in the Indus River is about 70 % of the total annual discharge.

## 1.2. River System

In the present study, attention has been focused on large rivers of Indus Basin i.e. Sutlej, Bias, Ravi, Chenab, Jhelum and Indus. The tributaries of these rivers and drains containing effluent from industries, sewerage systems, drainage from

Salinity Control and Reclamation Projects (SCARPs) etc. join them at different locations. A number of link canals are used to transfer water from northern rivers to the southern rivers. As a result isotopic and chemical concentrations of these rivers vary at different locations. Moreover, isotopic fractionation i.e. enrichment of heavy isotopes also occurs due to evaporation especially in dry season when the discharge is low [6]. Therefore, monitoring was extended to almost all the major dams/barrages/headworks and drainage inlets on the above said rivers.

### **1.2.1. The Indus**

The Indus originates from a spring called Singikahad near Mansarwar Lake on the north side of Himalayas Range in Kaillas Parbat in Tibet at an altitude of ~5500m above mean sea level. Traversing about 800 km in north-western direction it is joined by the Shyok River near Skardu at an elevation of 2750m. Flowing in the same direction for another 160 km before it turns round Nanga Parbat, it is joined by the Gilgit River at an elevation of 1520m. The river then flows 320 km in southwestern direction opening out in Kalabagh into the plains (elevation = about 250m). Up to Darband, the river still lies in the hilly tract at an elevation of about 600m. Below Durband near Tarbela, Siran, a small flashy stream arising from low elevation and draining alluvial lands of Mansehra, Abbotabad and a part of Haripur joins the Indus. Further 30 km downstream near Attock, the biggest western tributary of the Indus, the Kabul joins it. The drainage area of Kabul River above Warsak is 67000 km<sup>2</sup>. Citral River is one of its main tributaries which is also called Chitral River in the upper reaches. Below Warsak, another tributary the Sawat joins it, increasing the total catchment at this site to about 11000 km<sup>2</sup>. About 8 km below Attock, Harrow a small flashy stream draining the district of Attock and some area of Murree, Hassan Abdal, and Rawalpindi joins it. The catchment of this river is about 6000 sq.km up to the G.T. Road. About 12 km above Jinnah Barrage, the Soan (a stream draining the largest and worst eroded areas of Rawalpindi, Jhelum and Attock districts with catchment area equal to 12000 sq.km) joins it. Below Jinnah Barrage, the important western tributaries of the Indus are the Kurram, Gomal and Zoab. Dams and barrages on the Indus are: Tarbela Dam, Jinnah Barrage, Chashma Barrage, Taunsa Barrage, Guddu Barrage, Sukkar Barrage and Kotri Barrage [4].

### **1.2.2. The Jhelum**

Jhelum is a big eastern tributary of the Indus draining the areas in the West of Pir Punjal separating the provinces of Jammu and Kashmir. It originates from the spring of Verinag in the North-West side of Pir Punjal and flows in a direction parallel to the Indus at an average elevation of 1800 m. It drains about 6000 sq.km. of alluvial lands of Kashmir Valley and has important sources of water from glaciers on the north of the valley. At Domel near Muzaffarabad it is joined by its biggest tributary called Nelum which drains about 7000 sq.km. of snow and glaciers covered hilly area (elevation = 5000 to 6500m) lying on the eastern side of Nanga Parbat. Throughout its length of 240 km, it flows through fairly stable mountains covered by forests. Five miles below Domel, the Kunhar another tributary of the Jhelum originating at 5000 to 5500 m above sea level and draining the famous Kaghan Valley (area = nearly 2800 sq.km) joins it. One of its tributaries flows through the famous Saif-ul-Malook Lake. From Domel to Mangla in a distance of about 110 km, two streams, the Kanshi and Poonch join it. Kanshi is a flood-water stream draining eroded areas of Jhelum and Rawalpindi districts. This stream carries mainly monsoon rain or seepage water. Poonch is an important stream joining the Jhelum at about seven miles above Mangla at Tangrot. At Mangla near the head regulator of upper Jhelum Canal, Mangla Dam has been constructed. Important water storage and regulators on this river are Mangla Dam and Rasul Barrage [4].

### **1.2.3. The Chenab**

Chenab River originates in Kalu and Kangra Districts of Himachal Pradesh province of India. The two chief streams of the Chenab, the Chandra and Bagha rise on opposite side of Baralcha Pass at an elevation of about 5000 m. These join at Tandi in Jammu and Kashmir State nearly 3000 m above mean sea level. The river enters Pakistan in Sialkot district near Diawara Village and flows through alluvial plains of Punjab province. It is joined by Jhelum River at Trimmu. Further 65 km downstream, the river Ravi joins it. The Sutlej joins it upstream of Punjnad and finally about 65 km below Punjnad, the Chenab meets the Indus at



Mithankot. The total length of the river is about 1200 km. with catchment area equal to 67500 sq.km. Out of this, 28000 sq.km lie in Jammu and Kashmir State, 4500 sq.km in India and 35000 sq.km in Pakistan. The Chenab has twelve major tributaries namely, Chandra, Bhaga, Bhut Nallah, Maru, Jammu Tavi, Manawar Tavi, Doara Nallah 1, Doara Nallah 2, Halse Nallah, Bhimber Nallah, Palkhu Nallah, Aik Nallah and Bhudi Nallah. The last eight tributaries join Chenab in Pakistan [4].

Discharge of the Chenab starts rising in the later part of May and passes 1800 cumecs ( $1 \text{ cumec} = 1 \text{ m}^3/\text{s}$ ) mark in June continuing till the middle of September, the peak discharge months are July and August. From irrigation point of view, it is an important characteristic because dependable supplies can be withdrawn from the river during July to September. This river is a life-line for the Punjab having Marala Barrage, Khanki Barrage, Qadirabad Barrage, Trimmu Barrage and Punjnad Barrage [5].

#### **1.2.4. The Ravi**

Ravi, the smallest of the five main eastern tributaries of Indus, rises in the basin of Bangahal (100 km in circumference at an elevation of about 1600 m) and drains the southern slopes of the Dhanladhar. Below Bangahal, the Ravi flows through the valley of Chamba in a north-westerly direction parallel to the Dhanladhar range leaving the Himalayas at Baseeli. After passing through Gurdaspur, it enters Shakkargarh. Just after entering Shakkargarh, Ujh River joins it, 63 km downstream of Madhopur. Basantar and Bein Nallahs fall into it upstream and downstream of Jassar Bridge respectively. Important headworks on this river are: Balloki Headworks and Sidhnai Headworks [4].

Previously Balloki was a level crossing for transmitting the water brought by Upper Chenab Canal for Lower Bari Doab Canal. Now this Headworks also receives water brought in by Marala Ravi Link and Qadirabad Baloki Link Canals. The off-taking Links besides Lower Bari Doab are Balloki Suleimanki Links No.1 and No. 2. Sidhnai another headworks on this river receives water brought in by

Haveli and Trimmu Sidhnai Links. The off-taking canals at this site are Sidhnai Link Canal and Sidhnai Mailsi Link Canal [5].

#### **1.2.5. The Bias**

The Bias has now the shortest length (only 400km) out of Punjab Rivers. In 18<sup>th</sup> century it joined the Sutlej near Harike. Originally it used to join the Chenab at Punjnad. Rim station for this river is at Mandi plan near Talwara, District Hoshiarpur, India. Pando and Pong Dams have been built over it [4].

#### **1.2.6. The Sutlej**

This river originates in Western Tibet in the Kailas mountain range, near the sources of the Indus, Ganges and Bramaputra. It flows through the Punjal and Siwalik Mountain ranges and then enters the plains of Indian Punjab. The length of the river is about 1550 km and its catchment area is 75000 sq.km [4].

## **2. OBJECTIVES**

The overall objective of the study is to contribute in the CRP on Global Network of Isotopes in Rivers (GNIR) intended to enhance understanding of the water cycle of large river basins and to assess impacts of environmental and climatic changes on the water cycle. For this purpose a national network of suitable stations was established for isotopic monitoring of river waters in Indus Basin. The specific research objectives are:

- To study temporal variations of isotopes ( $^2\text{H}$ ,  $^{18}\text{O}$  and  $^3\text{H}$ ) at different control points of major tributaries of Indus River System by collecting water samples periodically and analyzing for isotopes.
- To understand water cycles and hydrological processes in the catchments of these rivers.

- To develop comprehensive database to support future isotope-based groundwater studies in the basin on recharge mechanism, water balance studies and monitoring of ongoing environmental changes.

### 3. METHODOLOGY

Existing data on discharge of the rivers, infrastructure, water quality, inflow, drainage system and the related literature from different institutes was collected. This information was analyzed and action plans were formulated to conduct the study. Selection of the sampling sites was made by PINSTECH in consultation with Water and Power Development Authority (WAPDA) and Irrigation Departments (IDs). Locations of the sampling stations along with their coordinates (longitudes and latitudes) are given below and marked in Fig. 1 [7].

<b><u>River Indus and Tributaries in Northern Areas</u></b>	<b><u>Lat. (N)</u></b>	<b><u>Long.(E)</u></b>
Hunza River at Dainyor (Daintar)	36° 22´	74° 08´
Indus River at Sakardu	35° 19´	75° 40´
Gilgit River at Gilgit	35° 54´	74° 18´
Indus River at Besham Qila	34° 56´	72° 52´
Tarbela Dam Reservoir	34° 04´	72° 38´
Swat River at Chakdara	34° 39´	72° 01´
Kabul River near Nowshera	33° 52´	72° 13´
Jinnah Barrage at Kalabagh	35° 58´	71° 33´
Chashma Barrage	32° 33´	71° 25´
Taunsa Barrage	30° 32´	70° 47´
Punjad Barrage	29° 30´	71° 30´
Sukkar Barrage	27° 41´	68° 64´
Kotri Barrage (Hyderabad)	25° 23´	68° 18´
<b><u>River Ravi</u></b>		
Balloki Headworks	31° 12´	73° 52´
Sidhnai	30° 31´	72° 15´
<b><u>River Chenab</u></b>		
Marala Barrage	32° 42´	74° 21´
Khanki Headworks	32° 23´	73° 59´

Trimmu Headworks	31° 11′	72° 07′
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**River Jhelum**

Jhelum River at Domel	34° 21′	73° 29′
Kunhar River at Talhata Bridge	34° 50′	74° 21′
Mangla Dam	33° 08′	73° 38′
Rasool Barrage	32° 43′	73° 32′



*FIG. 1. Map of Pakistan showing locations of sampling stations in Indus River System*

The sample collection was carried out with the collaboration of WAPDA and provincial IDs. River samples were collected in double stoppered, leak proof polyethylene bottles of one litter capacity from pre-selected sites on monthly/bimonthly basis. River discharge data of control points was also collected.

The collected water samples were analyzed for environmental isotopes ( $^{18}\text{O}$ ,  $^2\text{H}$ ,  $^3\text{H}$ ).  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  of the water samples were determined relative to V-SMOW on

mass spectrometers. The  $\delta^{18}\text{O}$  of water was measured by the  $\text{CO}_2$  equilibration method [8]. Water samples were reduced to hydrogen gas by zinc shots for  $\delta^2\text{H}$  measurement [9]. Measurement uncertainty for  $\delta^{18}\text{O}$  is about  $\pm 0.1\text{‰}$  while that of  $\delta^2\text{H}$  is  $\pm 1.0\text{‰}$  [10]. Tritium content of the samples was determined by liquid scintillation counting after electrolytic enrichment [11]. The standard error of measurement is of the order of  $\pm 1$  TU [12].

Environmental isotopic ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$  and  $^3\text{H}$ ) data were processed to find out different correlations and preparation of histograms, temporal variations and plots like  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$  vs. distance from sea, etc. Discharge data of rivers collected from Indus River System Authority (IRSA) were also processed and temporal variations were plotted along with  $\delta^{18}\text{O}$  of samples collected from the same control points.

#### 4. RESULTS AND DISCUSSION ON IRS

Results of isotope analyses are summarized in Table II.

Table II. Summary of the results of isotope analyses

Station	$\delta^{18}\text{O}$ (‰)			$\delta^2\text{H}$ (‰)			Tritium (TU)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Hunza	-14.5	-11.2	-12.7	-106.1	-72.6	-88.5	14.1	20.3	17.8
Kachura	-14.3	-11.9	-13.0	-102.1	-81.2	-94.4	21.5	21.6	21.6
Gilgit	-13.4	-11.0	-12.1	-95.6	-75.8	-82.9	15.9	19.4	17.6
Besham	-13.1	-9.6	-11.9	-98.9	-68.3	-83.4	13	20.7	16.6
Tarbela	-14.2	-10.3	-12.6	-101.7	-71.2	-87.7	12.5	20.4	14.7
Chashma	-12.1	-8.0	-10.1	-77.8	-54.7	-67.8	13.4	19.8	16.7
Taunsa	-13.5	-8.6	-11.5	-87.9	-53.6	-74.8	10.0	22.1	15.9
Sukkur	-11.0	-7.6	-9.6	-72.4	-45.7	-63.1	14.7	18.1	16.3
Kotri	-10.3	-6.2	-7.9	-68.4	-43.8	-54.9	13.0	16.7	15.1
Chakdara	-9.0	-5.8	-7.4	-58.1	-36.0	-46.8	10.0	22.1	13.7
Noshehra	-11.7	-6.6	-9.5	-79.8	-43.8	-63.6	14.6	18.7	16.4
Balloki	-10.6	-6.1	-8.3	-64.9	-34.1	-51.2	10.0	21.0	16.8
Sidhnai	-10.7	-5.7	-8.6	-76.8	-29.2	-54.5	12.0	14.3	12.9
Marala	-14.9	-5.5	-9.2	-95.5	-32.0	-56.1	9.1	18.8	13.9
Khanki	-10.4	-5.6	-7.8	-65.4	-31.3	-47.9	11.1	20.0	15.4
Trimmu	-13.0	-4.6	-9.1	-79.6	-33.8	-57.7	17.0	24.0	20.7
Punjnad	-11.4	-5.5	-8.8	-72.6	-38.4	-57.9	4.9	20.0	16.3
Kunhar	-8.8	-6.2	-7.5	-58.3	-41.0	-47.9	11.8	15.0	13.0

The River Indus starting from the highest altitude in Northern Areas (Himalayans) has the most depleted isotopic values. The main source of its tributaries is snowmelt originating from glaciers. The most depleted values of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  are at Hunza ranging from -14.5 to -11.6‰ and from -106 to -84‰ respectively. Similarly the other Himalayan tributaries at Kachura and Gilgit are also depleted in heavy isotopes. At Besham, the discharge represents combined flow of different tributaries in the Himalayans and there is significant variation in the ranges of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (-13.1 to -9.6‰ and -99 to -68‰, respectively). This station is at much lower altitude and the isotopic enrichment can be attributed to the mixing of streams, which originate from catchments at lower altitude having relatively enriched isotopic values. The river Chenab originates from Jammu and Kashmir area. At Marala, it has large variations in isotopes ( $\delta^{18}\text{O}$  from -14.9 to -5.3‰ &  $\delta^2\text{H}$  from -95.5 to -32‰). The river Ravi, which enters Pakistan from India, originates from the lower altitude. Its  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  at the first monitoring point at Baloki varies from -10.6 to -6.4‰ and -65 to -34‰ with the average values of -8.3‰ and -51‰. Generally the highly depleted values are encountered when there is high contribution of snowmelt and/or rain coming from higher altitudes and enriched values are found due to major contribution of local rains at lower altitudes. Therefore, altitudes of catchments play important role in establishing the isotope indices of these rivers.

$\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  plot of all the samples collected from all the rivers is shown in Fig. 2. It gives general idea that the river Indus in the upper reaches is the most depleted in  $^{18}\text{O}$  and  $^2\text{H}$  and relatively enriched at the tail stations. The river Chenab points are scattered all along the GMWL showing wide variation. The samples of Ravi River fall in the middle, while the river Jhelum is the most enriched in  $^{18}\text{O}$  and  $^2\text{H}$ . At Trimmu, the confluence of Chenab and Jhelum, some samples are plotted well below the GMWL indicating evaporation effect. Sometimes the river has very low discharge mainly contributed from baseflow which undergoes evaporation. Two stations Noshera and Chakdara on Kabul River and Swat River are also relatively enriched as compared to upper reaches of Indus River.

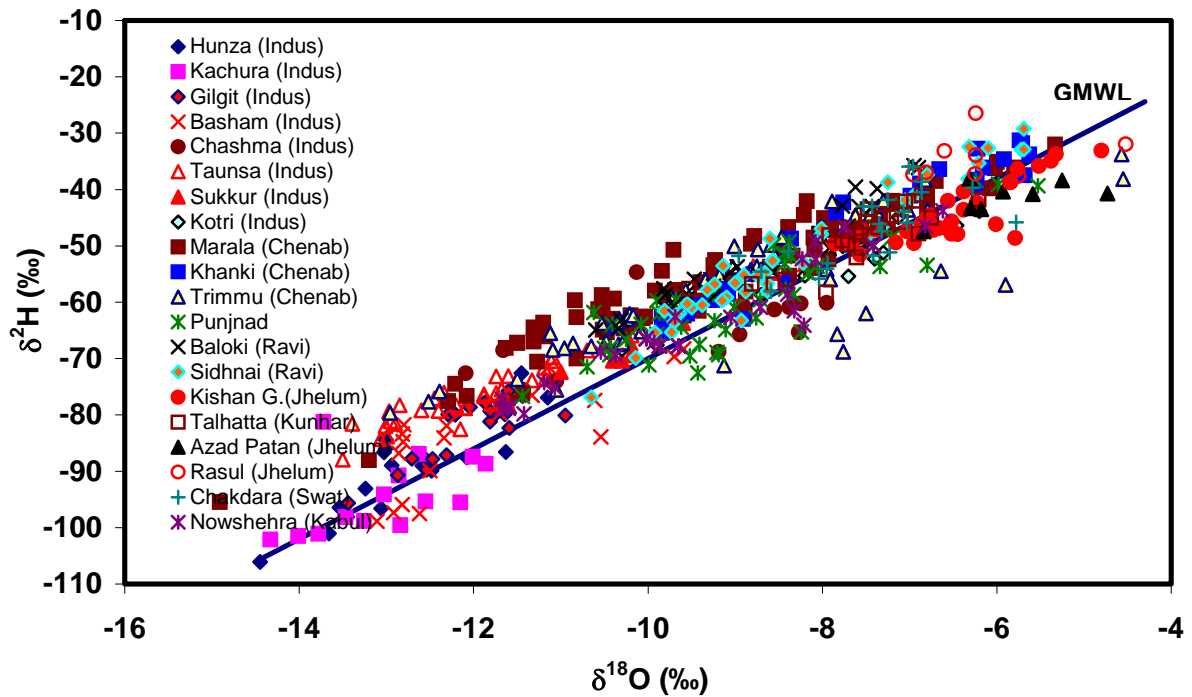


FIG. 2. Plot of  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  of selected locations at all rivers of Indus River System

$\delta^{18}\text{O}$ – $\delta^2\text{H}$  correlation has slope 6.5 and intercept -0.1 which is very different from the GMWL. Data of individual rivers are discussed below.

#### 4.1. Main Indus River

Hydrographs of all the control stations at Main Indus River are given in Fig. 3, which resembles with a mountain. Discharge starts increasing from April due to contribution of snowmelt and becomes highest in August with the added contribution of monsoon rains. After August it decreases at faster rate. The peaks on the main hump are due to high rainfall events.

Plot of  $\delta^{18}\text{O}$  vs. distance from Arabian Sea for the main river Indus (Fig. 4) clearly indicates enrichment in  $^{18}\text{O}$  with decrease in distance. There are three possibilities of enrichment of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ :

- Contribution of precipitation at low altitudes enriched in heavy isotopes in the river flowing towards the sea,
- Enrichment due to evaporation
- Contribution of base-flow in the river discharge, which must be enriched in heavy isotopes due to recharge from local rains.

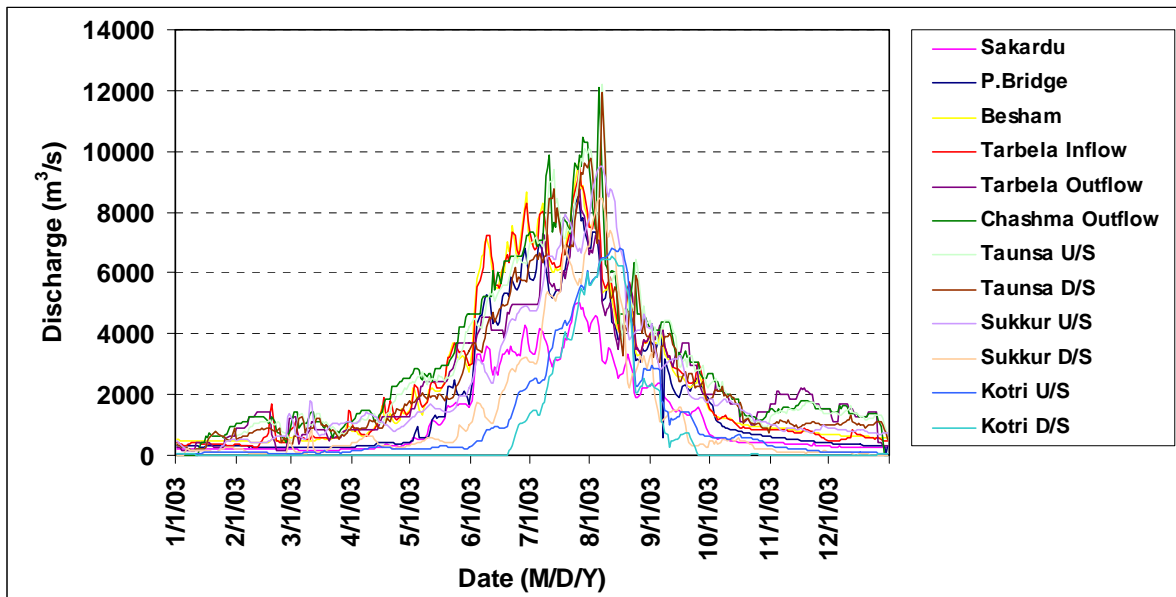


FIG.3. Hydrographs at control stations of Main Indus River

Fig. 5 shows  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  plot of samples collected from Himalayan tributaries and the control points in Indus plains. In this plot, the samples pertaining to the upper reaches of the river Indus (Hunza, Gilgit, Kachura and Besham) are located towards the more negative side while the points representing downstream stations lie towards the enriched side. Although the samples from Kachura are depleted but they lie below the regression line. Actually this tributary originates from Kachura Lake and due to evaporation effect these points are shifted downward [13]. A significant number of data points from both the areas have d-excess more than 20 and lie above GMWL indicating their origin from Mediterranean source.



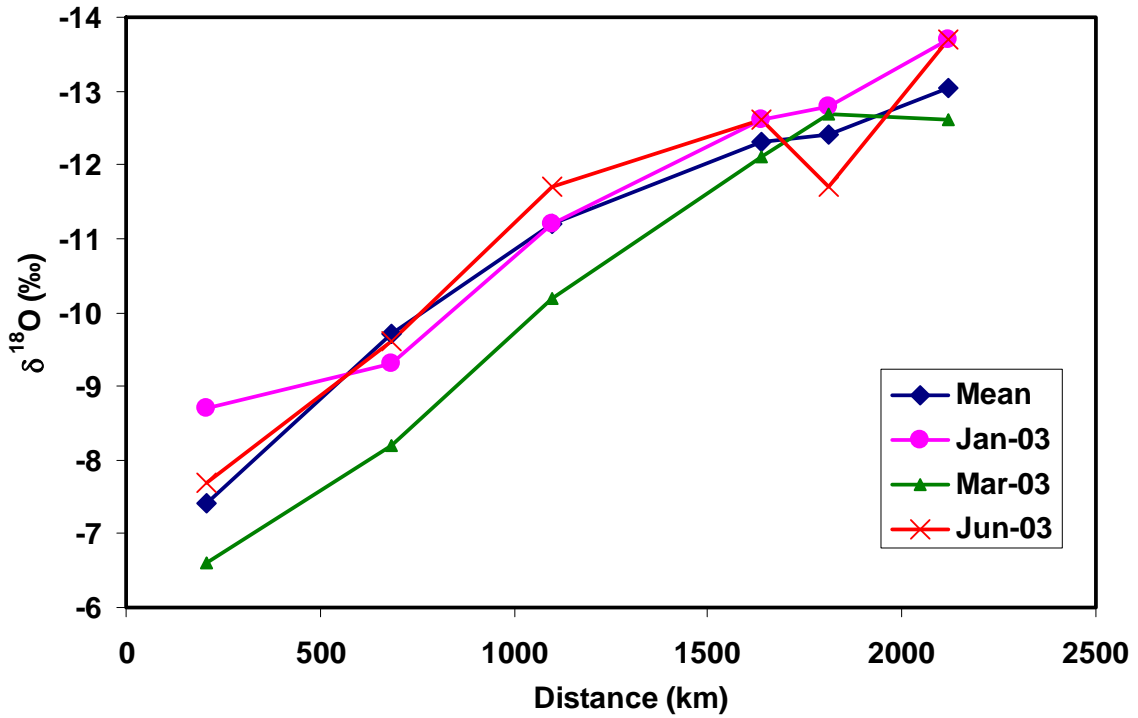


FIG. 4. Plot of  $\delta^{18}\text{O}$  vs. distance from Arabian Sea of sampling stations at Indus River

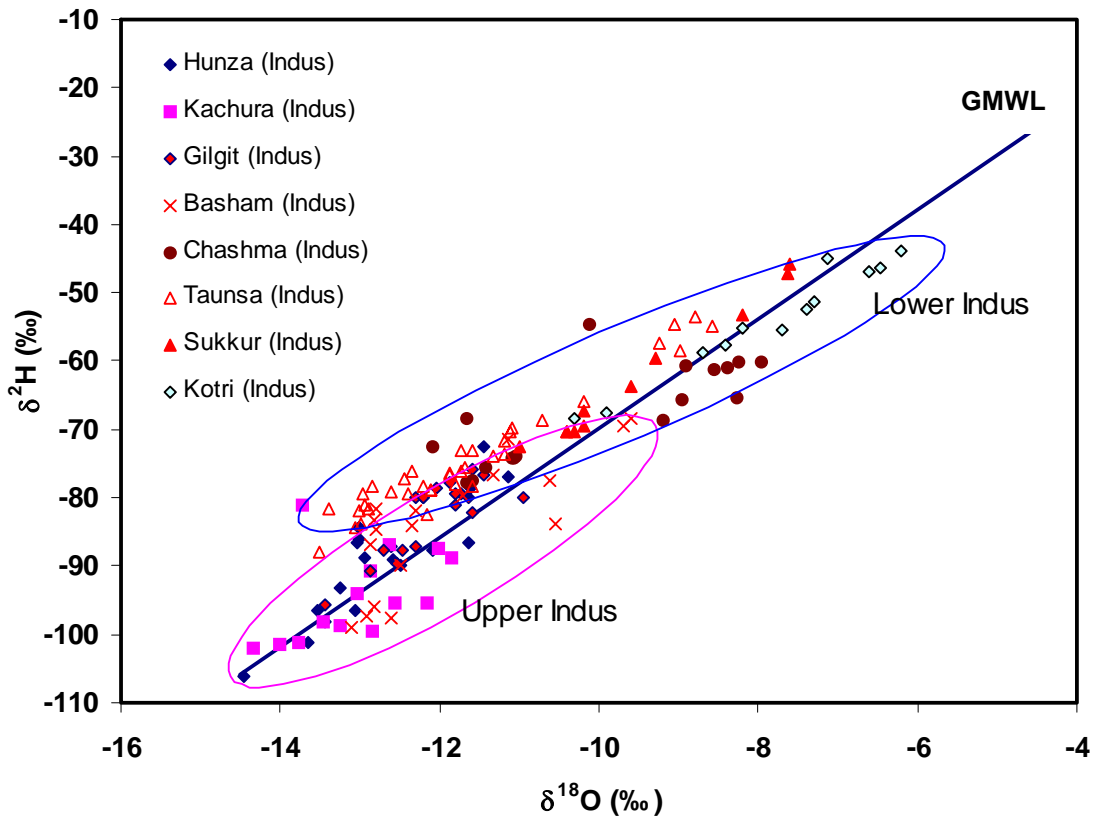


FIG. 5. Plot of  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  of samples collected from main Indus River

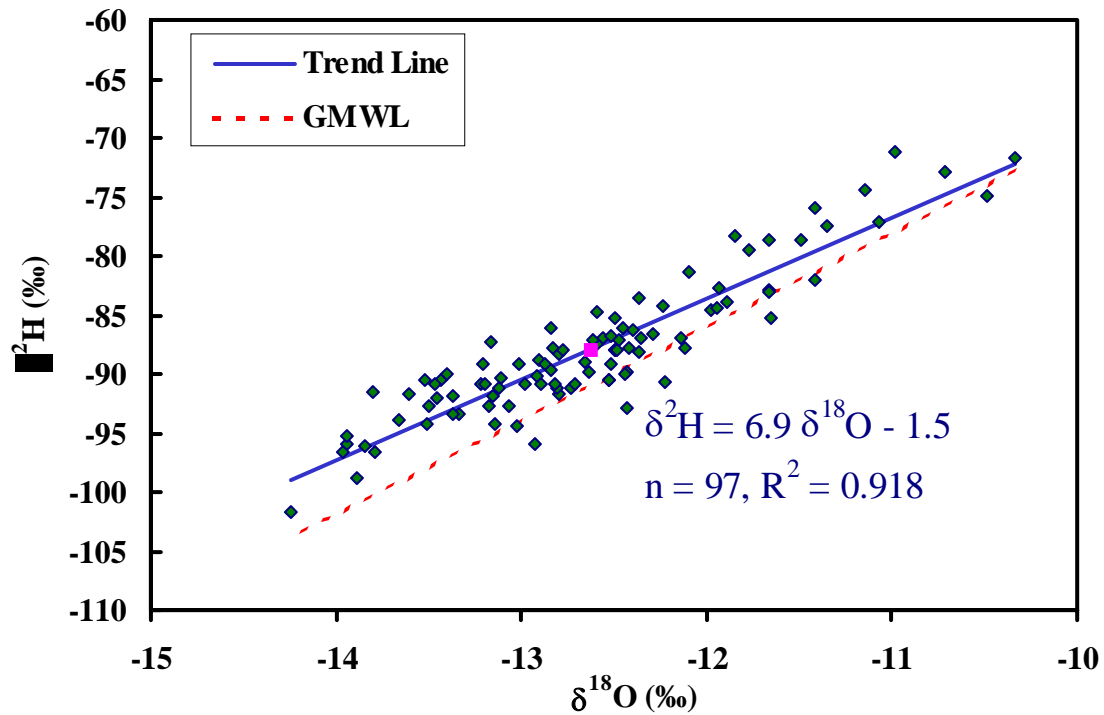


FIG. 6. Plot of  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  of samples collected from Tarbela Lake

Fig. 6 presents  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  data plot for the river Indus at Tarbela Dam outlet along with regression line (RL) and GMWL. The slope of RL is significantly less than that of GMWL. Most of the data points lie above the GMWL. The departures of the points having the most depleted values of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  are more than that of points corresponding to the enriched samples. Therefore the slope becomes less than that of GMWL. Ahmad et al. determined the d-excess of precipitation for Himalayan Mountains in the Northern Areas of Pakistan as 16‰ [14], which is greater than that of low lying areas e.g. 10.9‰ for Islamabad (unpublished data). As mentioned above, the highly depleted values are due to major contribution of water from melting of snow deposited on high mountains during winter. This suggests that the moisture from Mediterranean Sea may be the major source of winter precipitation in these parts of Himalayans. Temporal variations of  $\delta^{18}\text{O}$  and the reservoir level of Tarbela Dam on the basis of data collected by Sajjad et al. [15] and additional data for a longer period are shown in Fig. 7. Both the parameters show year wise cyclic behaviour. The most depleted values of  $\delta^{18}\text{O}$  are in August-September when the reservoir level is generally highest and the most enriched  $\delta$  values are found during April-May when the reservoir is at its

minimum level. Amplitude of  $\delta^{18}\text{O}$  wave varies from 1.5 to 3.8‰ having the average value of 2.4‰. If we consider the d-excess ( $= \delta^2\text{H} - 8 \delta^{18}\text{O}$ ) of all the samples, it does not have any significant correlation with  $\delta^{18}\text{O}$  and reservoir level. Therefore this cyclic enrichment is not dominantly due to evaporation effect. As the main input source of the reservoir is snowmelt, which is maximum from May to September and makes the reservoir full. In the Northern Areas, the snowmelt drained by rivers has average  $\delta^{18}\text{O} = -13.8\text{‰}$  and  $\delta^2\text{H} = -94\text{‰}$  [14]. Due the major contribution of this snowmelt, the  $\delta^{18}\text{O}$  is most depleted during full/highest level of the reservoir. When the reservoir level is low during April-May, groundwater of nearby areas having low altitude drains into the reservoir. As this water is recharged by low altitude rains, it is much enriched as compared to the main input. Sajjad et al. found  $\delta^{18}\text{O}$  of groundwater around the reservoir generally in the range of -7 to -6‰ [16]. The rain index of  $\delta^{18}\text{O}$  of this area is also about -6‰. Therefore at the low level, the contribution of the groundwater increases the  $\delta^{18}\text{O}$  of the reservoir.

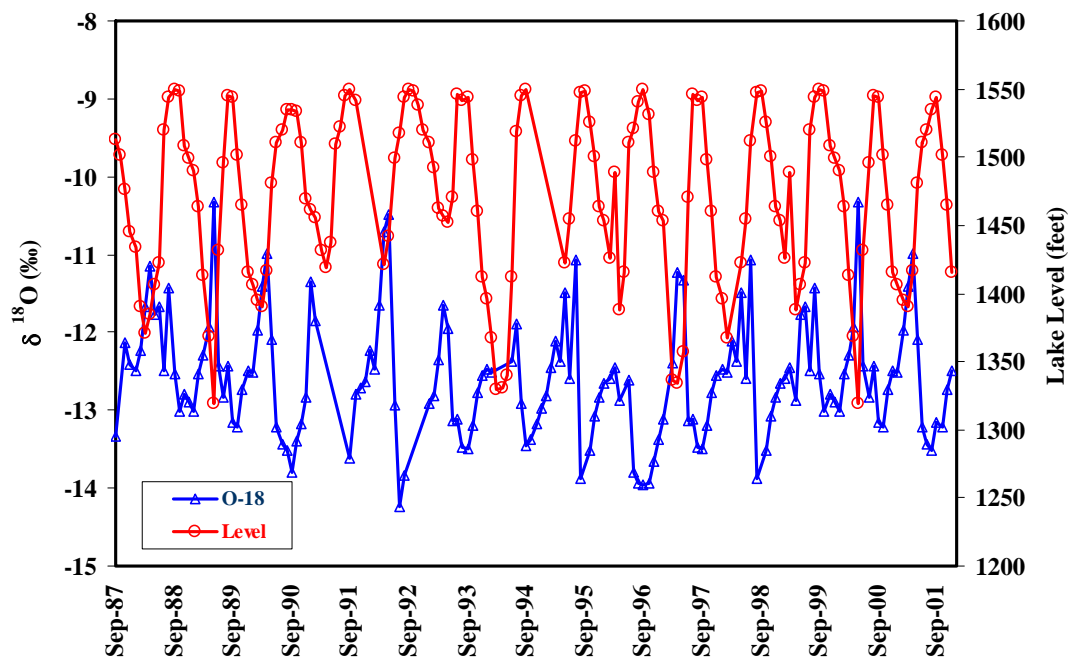


FIG. 7. Temporal variation of  $\delta^{18}\text{O}$  and reservoir level of Tarbela Dam at Indus River

Hydrograph and temporal variation of  $\delta^{18}\text{O}$  of Indus River at Taunsa, downstream of Chashma storage barrage, are given in Fig. 8.  $\delta^{18}\text{O}$  increases from January to

May even with the increase in discharge during snowmelt period, it did not decrease. Actually, most of the snowmelt is stored in Tarbela Dam Reservoir and the increase in discharge at Taunsa is mainly from the Chashma storage, which might have undergone evaporation and resulted in enrichment of heavy isotopes. From June to August during the peak discharge, the  $\delta^{18}\text{O}$  decreases reflecting contribution of snowmelt.

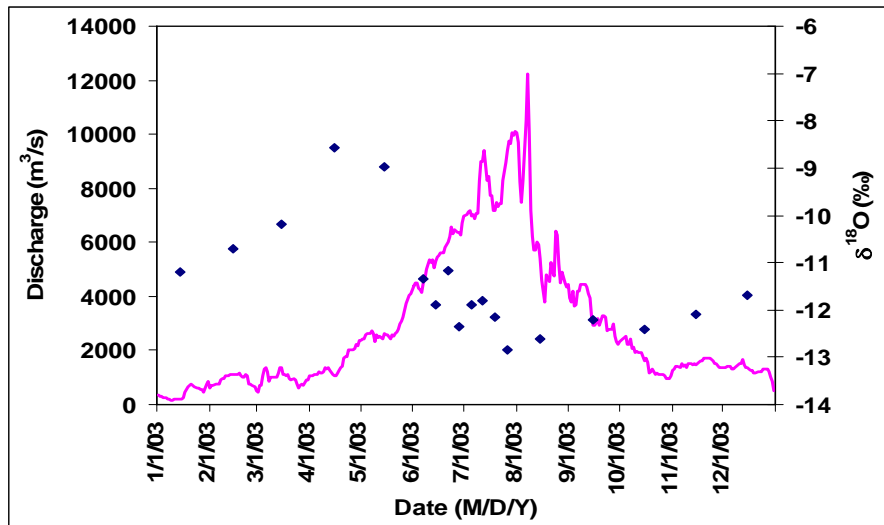


FIG.8. Hydrograph and seasonal variation of  $\delta^{18}\text{O}$  at Taunsa, Main Indus River

$\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  plot (Fig. 9) of last two stations indicates that all the data points of Sukkur are plotted on the LMWL, while the data of Kotri (downstream station) follow an evaporation trend with slope 5.9. Monthly variation of  $\delta^{18}\text{O}$  and discharge of Indus River at Sukkur and Kotri are shown in Fig. 10. Upto September, the river discharge downstream of Sukkur is more than that at upstream of Kotri, which indicates water loss from this section possibly due to evaporation and recharge to groundwater. From September to December, the downstream discharge at Sukkur is less than the upstream discharge at Kotri indicating the water gain. This gain is definitely due to return flow from groundwater into the river (baseflow).

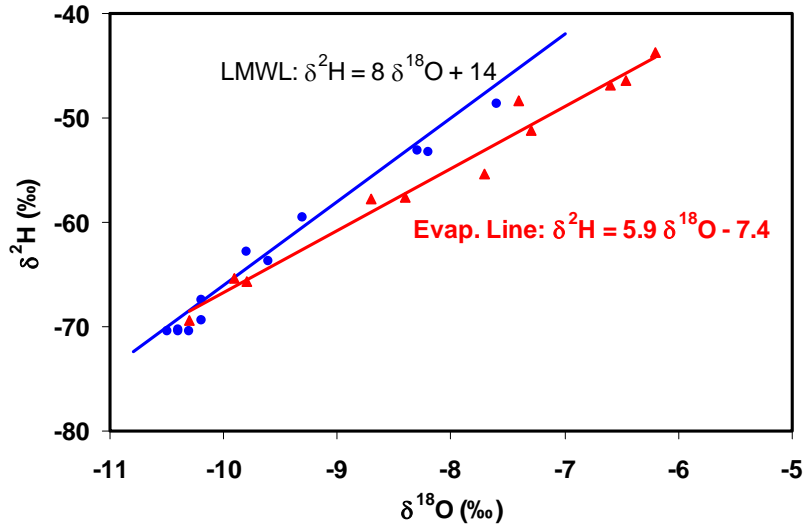


FIG. 9. Plot of  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  of samples collected Sukkur and Kotri (last two control points of Indus River)

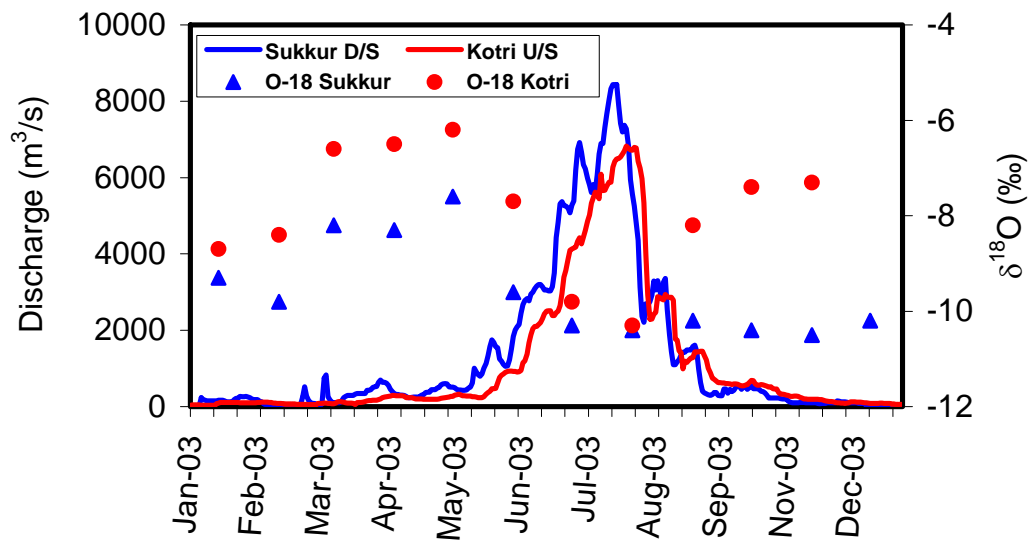


FIG. 10. Monthly variation of  $\delta^{18}\text{O}$  and discharge of Indus River at Sukkur and Kotri

#### 4.2. Kabul River

Hydrographs of Kabul River at Noshera along with variation of  $\delta^{18}\text{O}$  is depicted in Fig. 11. The first major rise in discharge is from April to June, which seems only due to snowmelt. The highest peak in July is due to both the sources i.e. snowmelt and rains.  $\delta^{18}\text{O}$  is generally low at high discharge because snowmelt coming from higher altitudes is depleted in heavy isotopes but during July at

highest discharge  $\delta^{18}\text{O}$  is also highest which is mainly due to major contribution of local monsoon rain enriched in heavy isotopes. At low discharge,  $\delta^{18}\text{O}$  is enriched maybe due to evaporation and contribution of local sources from low altitudes like local rains and base-flow into the river.

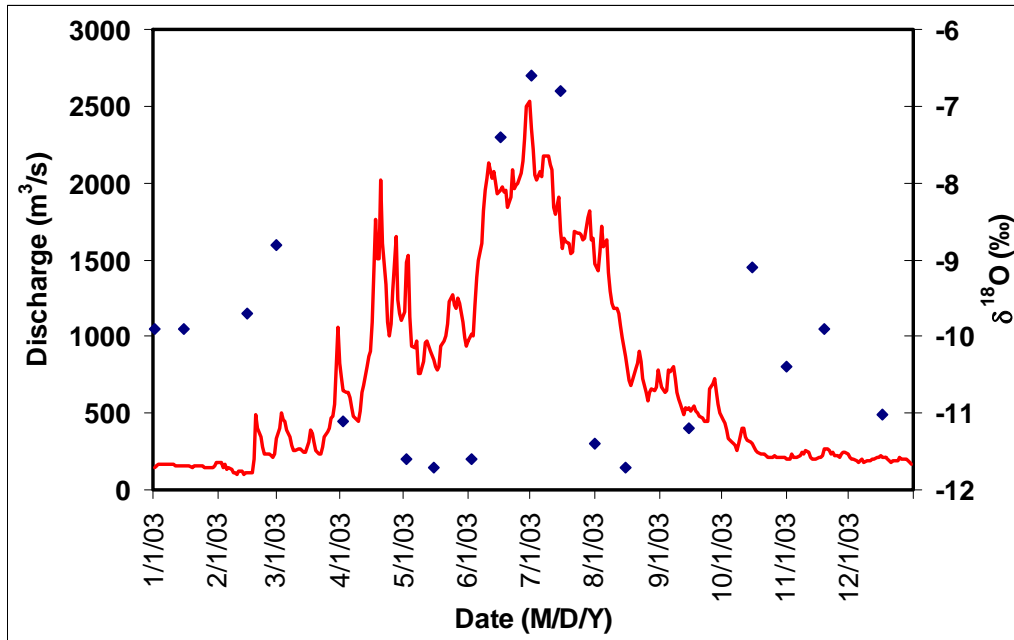


FIG. 11. Hydrograph and seasonal variation of  $\delta^{18}\text{O}$  of Kabul River at Noshera

### 4.3 Chenab River

In  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  plot (Fig. 12), samples from Marala, Khanki and Trimmu have similar trends. Almost all the data points lie above the GMWL and most of the depleted samples ( $\delta^{18}\text{O} < -8\text{‰}$ ) lie above LMWL having slope of 8 and intercept of 14. Frequency distribution of d-excess (Fig. 13) of Marala samples has two model classes indicating d-excess of most of the samples about 15 and 23. Negative correlation between d-excess and  $\delta^{18}\text{O}$  (Fig. 14) suggests that the higher d-excess is associated with depleted  $\delta^{18}\text{O}$ , which is generally found in the winter precipitation, especially the snow originating from the Mediterranean moisture. In general, the summer monsoons dominantly originate from Bay of Bengal, while the winter rains result from western disturbances, which originate from Mediterranean [17]. Due to different climate at sources of moisture, different isotopic values and d-excess are encountered. Fig. 15 depicts temporal variation

of  $\delta^{18}\text{O}$  and d-excess reflecting depleted  $^{18}\text{O}$  and high d-excess mostly during snowmelt period. There is lot of scatter because of varying contribution from local rains and snow-melt/rain runoff from higher altitudes.

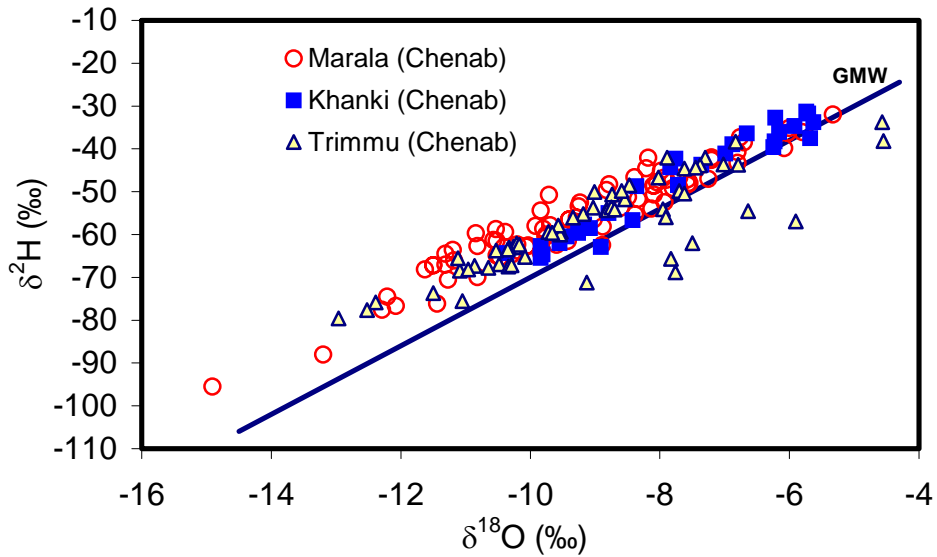


FIG. 12. Plot of  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  of samples collected from Marala, Khanki and Trimmu Barrages

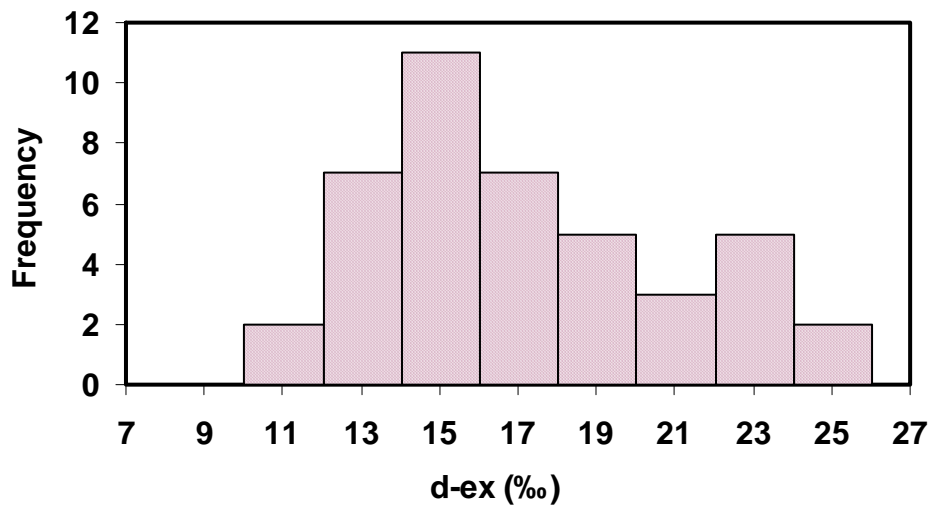


FIG. 13. Frequency distribution of  $\delta^{18}\text{O}$  of samples collected Marala

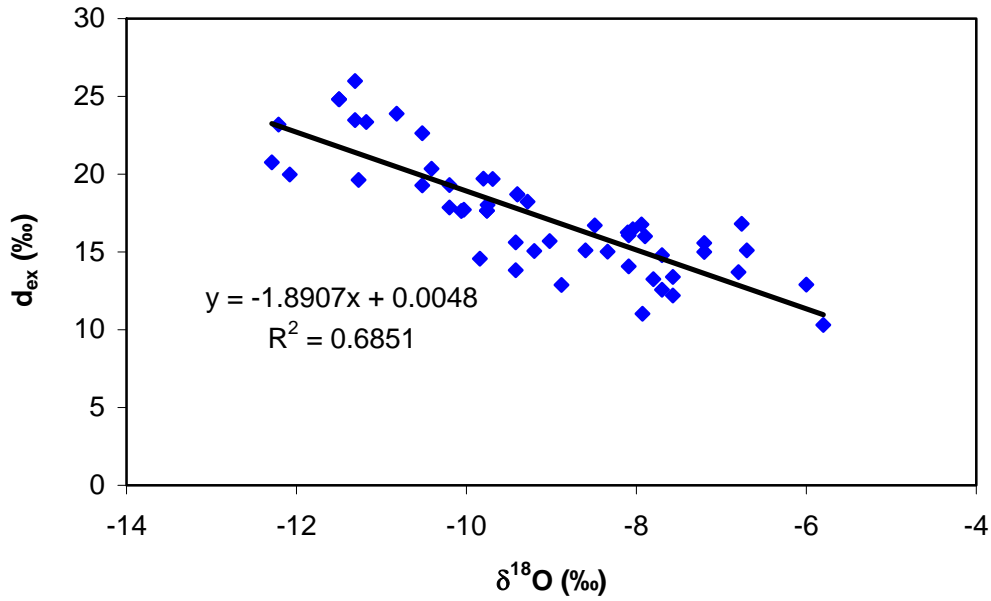


FIG. 14. Plot of  $d$ -excess vs.  $\delta^{18}\text{O}$  of samples collected from Marala

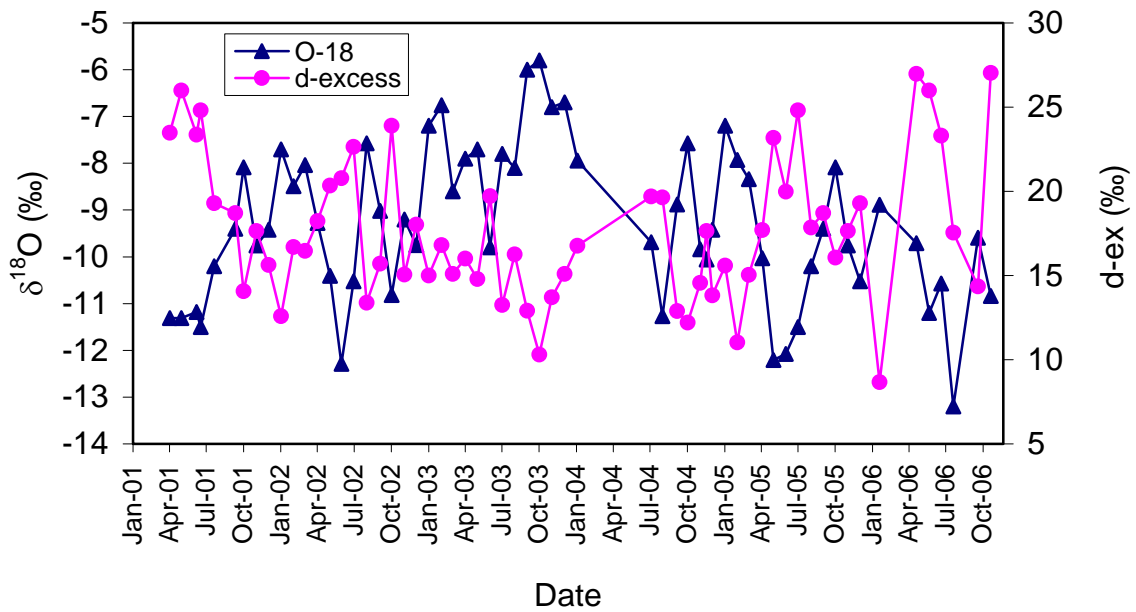


FIG. 15. Temporal variation of  $\delta^{18}\text{O}$  and  $d$ -excess at Marala Barrage

Hydrograph along with  $\delta^{18}\text{O}$  of Chenab River at Marala is given in Fig. 16. Just upstream of Marala, three rivers join and the  $\delta^{18}\text{O}$  may not be representative due to lack of complete mixing.



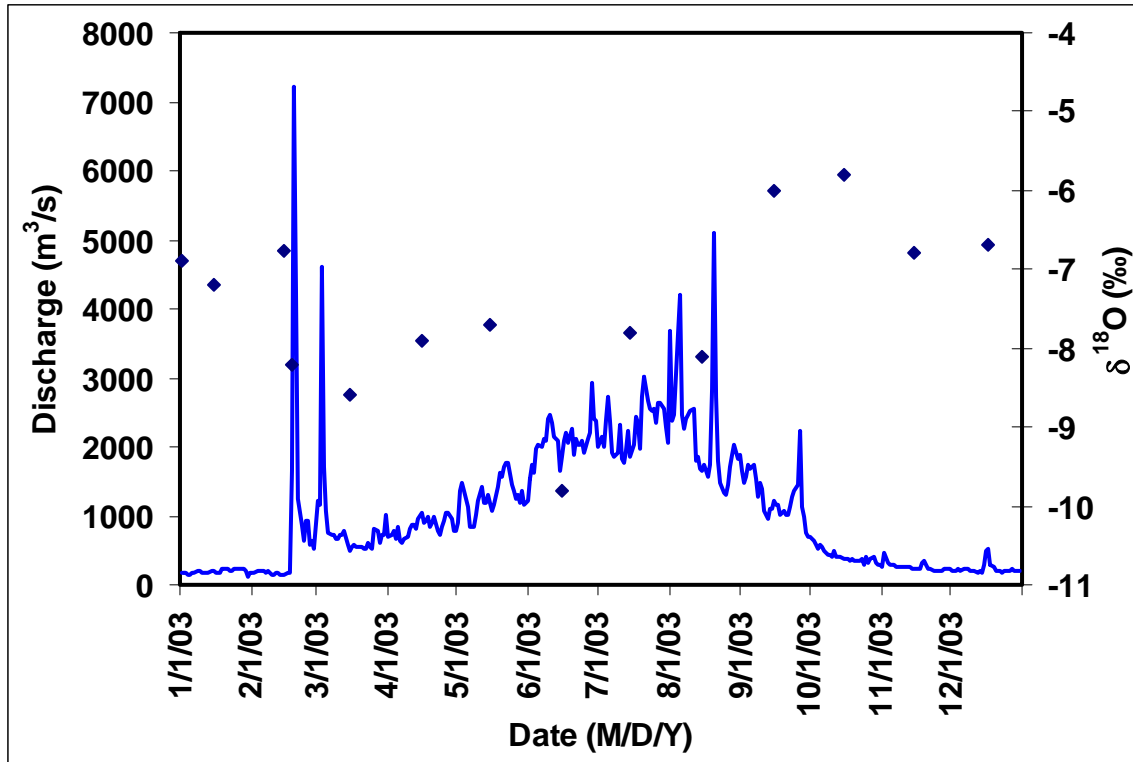


FIG.16. Hydrograph and seasonal variation of  $\delta^{18}\text{O}$  at Marala, Chenab River

#### 4.4. Ravi River

Although, the water from the river Chenab is diverted to the river Ravi upstream of Baloki and link canals from the Jhelum and Main Indus are also contributing upstream of Sidhnai, still the water samples collected from Baloki and Sidhnai are relatively more enriched than those from other rivers. As mentioned above, the altitude of catchment of river Ravi is significantly less than that of the other rivers. In  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  plot (Fig. 17), samples from Baloki and Sidhnai have similar trends. Almost all the data points lie around LMWL. Some of the samples have higher d-excess due to mixing of Chenab water, which has very high d-excess during snowmelt.

Hydrographs along with  $\delta^{18}\text{O}$  of Ravi River at two stations (Baloki and Sidhnai) are given in Fig. 18. Water diverted from other rivers is added in the river Ravi, therefore variation of  $\delta^{18}\text{O}$  cannot be explained with the hydrographs.

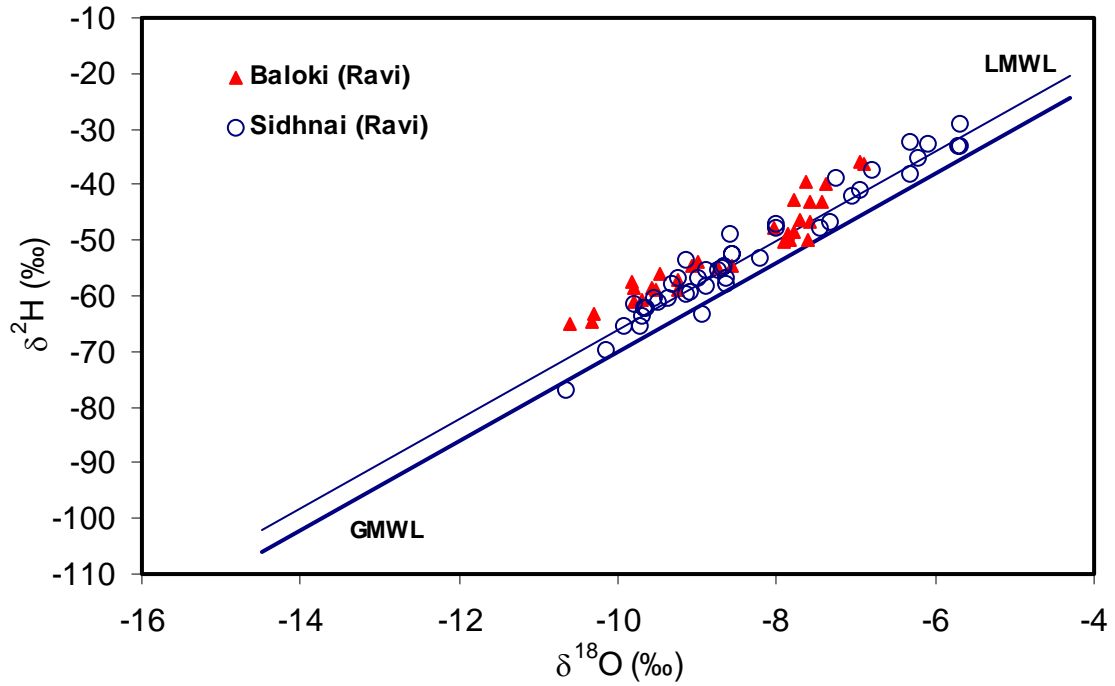


FIG. 17. Plot of  $\delta^2\text{H}$  vs  $\delta^{18}\text{O}$  of samples collected from Baloki and Sidhnai Barrages

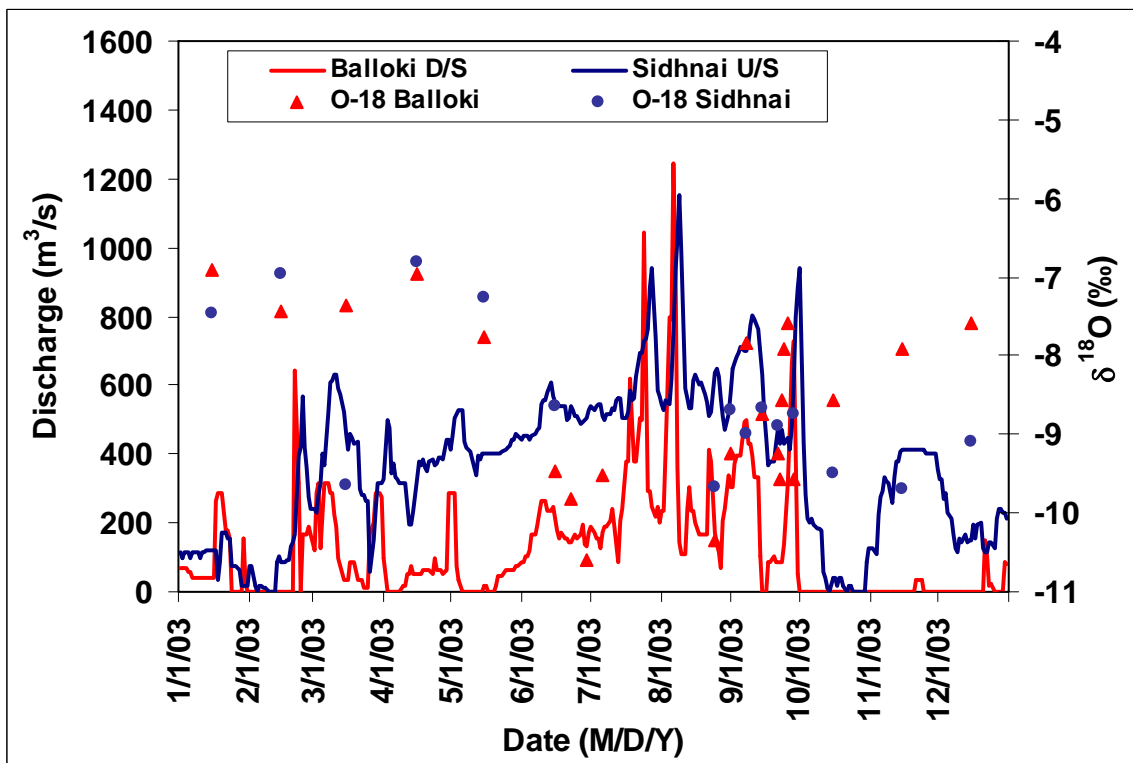


Fig.18. Hydrograph and seasonal variation of  $\delta^{18}\text{O}$  at Balloki and Sidhnai, Ravi River

## 5. CONCLUSIONS

Headwaters of main Indus River (Hunza, Gilgit and Kachura tributaries), which are generally snowmelt, have the most depleted values of  $\delta^{18}\text{O}$  (-14.5 to -11.0‰) and  $\delta^2\text{H}$  (-106 to -73‰) due to precipitation at very high altitude and very low temperatures. High d-excess of some winter (November-February) samples from Hunza and Gilgit indicates dominance of moisture source from Mediterranean. Kachura station having  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  line with slope 4 and low d-excess show evaporation effect in Kachura Lake. Isotopic values of Indus River get enriched going downstream towards Arabian Sea because of contribution from rains at low altitude plains and baseflow having recharge contribution from local rains. At the tail stations, evaporation and contribution from baseflow are responsible for isotopic enrichment. Low tritium in some samples also indicates contribution of baseflow (relatively older groundwater).

River Chenab has the widest variation in  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  and slope of  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  line is 6.1, which is due to variable contribution of snowmelt at high altitude and rains fallen at low altitudes. High d-excess in snowmelt and low d-excess in monsoon show that the moisture source in winter is generally western (Mediterranean) and the monsoon dominantly originates from Indian Ocean. The isotope data also reflect evaporation effect during dry periods.

Kabul River has wide variation in isotopic values probably due to variable contribution from Swat River, which carries snowmelt. High d-excess is associated with the depleted isotopic values, while low d-excess is associated with enriched isotopic values generally during summer monsoon. Therefore, slope of  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  line is 7, which seems mainly due to dominance of moisture source from Mediterranean in winter having depleted isotopic values and high d-excess, and Bay of Bengal in summer with relatively low d-excess.

River Jhelum and its tributaries upstream of Mangla Lake have enriched  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  due to low altitude of its catchment.

The precipitation in the catchment of river Ravi results from the moisture source from Indian Ocean and there is not any significant effect of evaporation. The isotopic variation seems mainly due to water diversions from the western rivers through link canals.

## **6. FUTURE WORK PLAN**

Monitoring of Indus River will be continued for long period. For this purpose, two stations in Himalayas (i.e. Besham on main stem and Marala on River Chenab, the major tributary), one station in the middle (Taunsa) and one station on the tail (Sukkur) will be monitored on monthly basis and samples will be analyzed for  $^{18}\text{O}$ ,  $^2\text{H}$  and tritium. Discharge data will also be collected.

## **ACKNOWLEDGEMENT**

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