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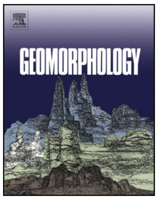

Oxygen, deuterium, and strontium isotope characteristics of the Indus River water system

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ABSTRACT

Understanding the sources and compositional characteristics of waters and sediments in the Indus River system is extremely important as its water availability is one of the primary factors for sustenance of the irrigation activities and the socioeconomic status of a very densely populated region of the world. Here we used stable isotopic compositions (δD and $\delta^{18}O$) and strontium isotopic ratio ($^{87}Sr/^{86}Sr$) in the Indus River water, its tributaries and its small streams (nallahs) in the Indian territory to understand the regional hydrology, water sources, and catchment processes (evaporation, transpiration, recycling, and mixing). The $\delta^{18}O$ values in the Indus River system (IRS) ranges from −16.9‰ to −12.5‰ and δD from −122.8‰ to −88.5‰. The Indus River and its major tributaries (such as the Zanskar, Nubra and Shyok rivers) are characterized by relatively lower $\delta^{18}O$ values, whereas TangTse and other small streams contributing to the Indus are relatively enriched in ^{18}O. The local meteoric water line for the IRS was found to be $\delta D = 7.87 \times \delta^{18}O + 11.41$, which is similar to the Global Meteoric Water Line (GMWL) indicating meteoric origin of the water and insignificant secondary evaporation in the catchment. The Deuterium excess (d-excess) in the IRS varies between 6.5‰ and 14.9‰ with an average of 11.7‰, which is mostly higher than the long-term average for the Indian summer monsoon (~8‰). The higher d-excess value is because of the contribution of moisture from westerlies; a simple mass balance shows ~26% water in the main Indus channel is contributed by the westerlies originated from the Mediterranean Sea. The Sr isotope ratio in IRS varies between 0.70515 and 0.71291; wherein the Indus, and its tributary rivers Shyok and Nubra, are characterized by relatively high Sr isotope ratios (avg. 0.71086–0.71243) compared to the Zanskar and TangTse tributaries (Sr ~ 0.709) because of the variation in silicate rock weathering component and carbonate rock weathering component ratios respectively.

1. Introduction

Understanding the sources and processes that govern the river flow is important especially in the context of global warming, which may influence the flow in major rivers fed by glaciers by altering/reducing the glacier cover. The stable isotopic compositions ($\delta^{18}O$ and δD) in river water are powerful integrative recorders of key processes (such as evaporation, transpiration, recycling, and mixing) that happen in the catchment areas. They also provide information about the river recharge sources such as direct precipitation, runoff, lakes, snow, glacier, soil water, and groundwater (e.g., McDonnell et al., 1990; Liu et al., 2008; Jasechko et al., 2013). Various other hydrologic processes that may modify the isotopic compositions in river water are seasonally different fractional inputs of water from surface and groundwater sources (Buttle, 1994; Lambs, 2004), enrichment in heavier isotopes owing to watershed evapotranspiration and in-stream evaporation (Simpson and Herczeg, 1991; Telmer and Veizer, 2000), and isotopic fractionation during snowmelt (Taylor et al., 2002). Though all these processes may significantly modify the isotopic composition of the river discharge in space and in time, still seasonal variations of the isotopic composition of river water are assumed to reflect the regional and continental isotopic variance in precipitation (Rozanski et al., 1982; Araguás-Araguás et al., 1998; Feng et al., 2009). Therefore, the stable isotopes in river water are also useful to understand the seasonal water vapor dynamics in the catchment areas (e.g., Laskar et al., 2014) and extend it to paleoclimate study in the downstream sediment deposits (Laskar et al., 2010, 2013; Sridhar et al., 2015; Singh et al., 2015, Tewari et al., 2015). In general the isotopic compositions in river discharge depend on the catchment elevation and its distance from the oceanic source water because of the altitude and continental effects on isotopes (Longinelli and Edmond, 1983; Ramesh and Sarin, 1992; Pawellek et al., 2002). Evapotranspiration in the catchment as well in the stream may increase the $\delta^{18}O$ and δD values and decrease the d-excess along

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the downstream direction. High-altitude Rivers such as the tributaries of the major Himalayan Rivers (e.g., Indus, Ganga, Brahmaputra) may be ephemeral, dominated mostly by snowmelts that are depleted in heavier isotopes (Halder et al., 2015). The rivers of Himalayan origin contain their discharge originating from different sources such as surface runoff from the recent precipitation, snowmelt/surface-icemelt/subglacial-melt generating, and groundwater/spring generating base flow. The relative contributions of these components in a river basin vary according to basin morphology, local climate and human intervention by changing landuse (e.g., construction of dams, reservoirs, irrigation usages, etc.). The $\delta^{18}O$ and δD in river water reflect the weighted average of isotopic ratios of the contributing components in the discharge. Therefore, they are dominantly governed by the isotopic ratio of the principal discharge component. While $\delta^{18}O$ and δD values in smaller streams are governed by the local hydrology, for bigger rivers such as Indus owing to their large basin size, these isotope ratios become representative of the regional hydrology.

In the first stable-isotope-based study in a major Himalayan river (Ganga), Ramesh and Sarin (1992) reported the southwest (SW) monsoon as the origin of moisture in the Ganga headwater. They observed significant evaporation in the lowland regions resulting in enrichment in the heavier isotopes in the downstream Ganga water. An altitude effect of ~0.19‰/100 m altitude was reported, which they showed to be half of that in the local precipitation. Pakistan territory of Indus has been studied in greater detail using stable isotopes (Karim and Veizer, 2000, 2002; Ahmad et al., 2012). They observed that the headwaters of the main Indus River (the Hunza, Gilgit, and Kachura tributaries) had the lowest $\delta^{18}O$ (-14.5 to -11.0‰) and δD (-106.1 to -72.6‰) values owing to precipitation at very high altitudes and very low temperatures and that the values gradually increase downstream towards the Arabian Sea because of the contributions from rains at lower altitude and baseflow mainly recharged by local rains. They also observed high d-excess in the headwaters of Indus in winter and low d-excess associated with enriched isotopic values in summer showing the dominance of moisture from the Mediterranean and SW monsoon from the Indian Ocean in winter and summer respectively. Pande et al. (2000) carried out stable isotopic studies in the Indus River water and its tributaries along with some lakes, glaciers, and hot springs. For the river water, they observed $\delta^{18}O$ and δD in the ranges of -11 to -17‰ and -70 to -124‰ respectively and derived a meteoric water line significantly different from the GMWL. A systematic study of the stable isotopes along the river course of another major Himalayan river, viz. Brahmaputra, shows a gradual decrease in the isotopic composition with increasing elevation. At an elevation of 4000 to 5000 m asl at the headwaters of the Brahmaputra and its tributaries, the lowest $\delta^{18}O$ value of -20‰ was observed (Hren et al., 2009). Lambs et al. (2005) carried out stable isotope analysis of nine major Himalayan Rivers and found heavy isotope enrichment in peninsular rivers and depletion in snow and glacier-melt-derived waters of the Himalayan Rivers. The enrichments in the former are from evapotranspiration in the plains. The authors also showed that the $\delta^{18}O$ values of Indian rivers correspond roughly to the $\delta^{18}O$ values of the rains falling over the subcontinent.

Though, the Indus River is a lifeline for a large population in the region; its sector in Indian territory has been studied to a very limited extent. This is mainly because of the difficulties in sample collection as the river flows through the Trans-Himalayan rugged terrain. The main objective of the present studies to characterize the Indus River and its tributaries in the Indian territory using stable water isotopic compositions. The present study would complement previous studies carried out in the Pakistan territory (Karim and Veizer, 2002) and bring new insights to our understanding, particularly the spatial sources of moisture and other hydrological processes such as evapotranspiration, recycling, and mixing that happen in the catchment areas. In addition, Sr isotope ratios would help to study the lithological control on Sr isotope systematics and establish the source of sediments in the river and its tributaries and streams.

2. Study area

The Indus River originates from the northern slope of Mount Kailash near Mansarovar Lake in Tibet, forms one of the world's largest fresh water systems, comprised of several west-flowing rivers of the western Indian subcontinent, finally debouching into the Arabian Sea. The Indus River System covers a drainage area of 912,000 km^2 extending across Tibet (China), India, Afghanistan, and Pakistan (Fig. 1). The total length of the Indus trunk river is 3180 km, originating at an elevation of 6714 m in the northern slopes of Mount Kailash and follows a well-defined valley parallel to the Indus-Tsangpo Suture Zone. In the initial 1125-km length (conveniently referred by earlier workers as upper Indus River basin; upstream of Tarbela Dam in Pakistan; Karim and Veizer, 2000), the river flows through high mountain ranges in alternating meandering and braiding patterns. In its ~422 km long route in Indian territory, the river mostly flows through Trans-Himalayan cold dessert of the Ladakh region, in which the river flows in a narrow, constricted, and meandering path except in parts of Chumathang and Leh valleys where it becomes ~2–3 km wide and transforms into a braided stream. The slope, stream order, and drainage map of the study area shows three different watershed basins viz. Indus (with Zanskar), Shyok-Nubra, and TangTse (Fig. 2). The highest stream order observed is seventh order encountered in the NW corner of the study area in the Indus River basin. It is pertinent to note that within the basin the tributaries of the Indus River, i.e., Zanskar, Shyok-Nubra, and TangTse, attain either fifth- or sixth-order, indicating that the structural setup and drainage basin morphometry are responsible for the multiple order drainages resulting into a huge supply of water and sediment to the Indus basin (Fig. 2). Fluvial terraces, moraines, and palaeolacustrine sediments are seen scattered all along the course of the river (Phartiyal et al., 2005, 2013). The Zanskar River is a major tributary and joins it near Nimmu. Overall, the Shyok River, the biggest tributary of Indus, largely flows in a wide valley, which becomes even wider at the confluence with the Nubra River. Shyok and Nubra have an unusual course, originating from the Rimo and the Siachin glaciers respectively: initially they flow in a SE direction but subsequently take a NW trend and join the Indus near Skardu in Pakistan (Fig. 1). The details of the lower Indus basin as well as the bottom part of the upper Indus basin are discussed by Karim and Veizer (2000, 2002, and references there in).

2.1. Climate and vegetation in the catchment of the Indus River

The Ladakh Himalaya (commonly referred as Trans-Himalaya) lies in the NW part of the Indian subcontinent. Climatically, it is the only region that falls in the rain shadow for the Indian monsoon clouds and comes under the westerlies effect making it a cold dessert (Fig. 1). The average precipitation in this part is ~100 mm only; however, palaeoclimate records show that often high monsoon winds penetrate to the Trans-Himalayan region (Pande et al., 2000; Thompson et al., 2000; Dalai et al., 2002; Bookhagen and Burbank, 2006). The main source of water is winter snowfall on mountains, which is stored there for months as snow, ice, and glaciers and runs off in summer as meltwater streams. The general altitude of the region is ~3000 m, but no part of it is situated at an elevation < 2600 m. Because of elevation and scanty vegetation, the proportion of oxygen is less than in many other places at a comparable altitude and where no atmospheric moisture to temper the effects of harsh climate. Although the illumination of the sun is enough to ripen the crops, higher albedo keeps the temperature low in the region (Bolch et al., 2012). Large diurnal variation makes frost action the most effective process of weathering, which is evidenced in the form of fierce and jagged crests of the mountains. Intense wind also plays a major role in weathering and sediment distribution as observed in the formation of sand dunes in the region (Phartiyal et al., 2005). The

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