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Evaporative fractions and elevation effects on stable isotopes of high elevation lakes and streams in arid western Himalaya

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SUMMARY

Isotopes of oxygen and hydrogen in water from streams, snow, and lakes were used to model the ratio of evaporation to total inflow (*E*/*I*) of four high elevation lakes in closed basins in the Indian Himalaya. Air temperature and relative humidity (*h*) data from meteorological stations and global climate grids (GMAO-MERRA) were used as input to the model. A second model of the volume of inflow during snowmelt constrained the magnitude of seasonal variability in isotopic composition. Similar to other areas of the Himalaya, elevation was a strong determinant of isotopic composition of stream water, suggesting that heavier isotopes rain out at lower elevations. Deuterium excess (*d*) in stream water suggests that summer precipitation originating from the Bay of Bengal rather than winter precipitation from Central Asia is the dominant source of precipitation. For the largest and deepest lakes (>15 m), *E*/*I* was 77–87%, and 18–50% for two shallow lakes (<2 m). Modelled *E*/*I* was sensitive to *h*; ground-level measurements of h are needed to constrain *E*/*I* estimates in arid mountain regions, though *h* from GMAO also produced reasonable *E*/*I* values. The results suggest that some lakes in closed basins in the Himalaya lose a significant fraction of their inflow to groundwater, particularly shallow lakes with a low ratio of lake volume to watershed area. Isotopic values from the mainstem of the Indus River suggest that evaporatively enriched waters have limited impact on both wet and dry season discharge at the basin scale. Lakes with a high evaporative fraction may be uniquely sensitive to climate, and isotopic analysis can help identify lakes that may be vulnerable to climate fluctuations and change.

1. Introduction

Lakes play important roles in the hydrology and ecology of mountainous regions. Lakes can either increase dry season streamflow by recharging local or regional groundwater, or decrease dry season streamflow by increasing evaporation (Bullock and Acreman, 2003). Significant uncertainty remains about the influence of high elevation lakes on monthly and annual streamflow. The hydrology of lakes in closed basins, which have no surface outlet, can be particularly difficult to determine since the main outflow is through recharge to groundwater. Lakes in closed basins may impact regional hydrology through subsurface flow, which is difficult to quantify, and is usually calculated as a residual in the water balance. Given the likelihood of significant changes in the hydrology of the Himalaya due to climate change (Immerzeel et al., 2010), it is imperative to understand the role that high elevation lakes play in the seasonal and annual water balance of Himalayan river systems. There is currently very little information on the role of evaporation and subsurface flow in the annual hydrologic budget of Himalayan lakes in closed basins. An interannual water balance on one of the largest lakes in the Tibetan Plateau (Nam Co) suggests that more than half of the inflow to the lake is lost through groundwater seepage, with important implications for the water balance of the Tibetan Plateau and receiving water bodies (Zhou et al., 2013).

Evaporation as a fraction of inflow to a lake (*E*/*I*) can be calculated using oxygen (^{18}O) and deuterium (D) isotopes and a model of isotopic fractionation during evaporation (Dincer, 1968; Gibson and Edwards, 2002; Krabbenhoft et al., 1990; Zuber, 1983). *E*/*I* models are based on the evaporative enrichment of ^{18}O and D, which evaporate at lower rates than ^{16}O and ^{1}H. The

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departure of $\delta^{18}O$ and δD in a sample from the global meteoric water line (GMWL) is proportional to *E*/*I*. Isotopic techniques are particularly useful where there are no discharge measurements to constrain a water balance, as is the case for many remote regions. Applications of *E*/*I* models include regional sampling in the Canadian Arctic (Gibson and Edwards, 2002; Gibson et al., 2002), where *E*/*I* decreased with increasing latitude. While regional surveys of the isotopic composition of water have been conducted in the Himalaya (Bartarya et al., 1995; Pande et al., 2000), and isotopes have been used to quantify surface–groundwater exchange in lakes at the foothills of the Himalaya (Nachiappan and Kumar, 2002), the meteorological data required to perform an isotopic water balance have not typically been available, nor have isotopic measurements been used to estimate *E*/*I* for lakes in the Himalaya.

Both stable isotopes of water (^{18}O and D) can be used to estimate *E*/*I* and to test the validity of model assumptions. Zuber (1983) applied the *E*/*I* model to several lakes that had complementary water balance data, and documented that the field-observed kinetic enrichment of D during evaporation is sensitive to humidity (*h*), showing significant departures from values determined in laboratory experiments under conditions of moderate to low h (<70%). This is potentially important for modelling the water balance using isotopic methods in semi-arid and arid regions.

The meteorological data required to implement isotopic *E*/*I* models include air temperature and *h*, which may not be readily available in remote regions. Global gridded data, like that from the Global Meteorological Analysis Office (GMAO) could be used as input, though their cell sizes (e.g. 0.67°) may complicate their use in mountainous environments. *E*/*I* values may also be impacted by seasonal inflow of isotopically light water that has not been impacted by evaporation, including snowmelt (Gibson et al., 2002). Implementation of *E*/*I* models requires an estimate of uncertainty and evaluation of model sensitivity to meteorological inputs and model assumptions.

Isotopes of water have also been used to reconstruct paleoelevations of mountain ranges based on the relationship between elevation and isotope composition in modern and paleowater samples (Garzione et al., 2000). Regional variations in the elevation–isotope relationship complicate such reconstructions (Hren et al., 2009), and the elevation–isotope relationship may weaken at high elevations (Pande et al., 2000), so additional documentation of the elevation–isotope relationship in sparsely-sampled environments is required, particularly at high elevations in remote regions of the Himalaya. Data on ^{18}O and D, in particular the deuterium excess (*d*) can also help identify the dominant sources of moisture in precipitation, streams and groundwater (Weyhenmeyer et al., 2002). In the Himalaya, they have been used to quantify the relative contribution of moisture from the Bay of Bengal to the east during the Indian Summer Monsoon and from central Asia to the west and north during the winter (Hren et al., 2009; Karim and Veizer, 2002; Maurya et al., 2011).

The objective of this study is to use a combination of water balance modelling, meteorological measurements and isotopic analyses of stream water, lake water and snow to estimate the roles of evaporation and subsurface discharge in the annual water balance of four high elevation lakes located in closed basins in the Indian Himalaya. A secondary objective is to document the regional elevation–slope relationship and deuterium-excess and compare them with other regional studies. The main research questions are: What fraction of the inflow to high elevation lakes is evaporated, estimated using an *E*/*I* model and data on ^{18}O and D? How sensitive are *E*/*I* estimates to input meteorological data and potential seasonal variations in isotopic composition? Are differences in the evaporative fractions related to lake depth or watershed characteristics? How does stream water isotopic composition change with elevation? What do deuterium excess values in streamflow suggest about the dominant sources of moisture for precipitation?

2. Study area

The study area includes four lakes in the Ladakh region of the Indian Himalaya in the State of Jammu and Kashmir, south and east of the city of Leh (Fig. 1, Table 1). Two lakes are relatively deep, and two are shallow (Table 1). The first and largest lake, Tso Moriri, lies at an elevation of 4535 m.a.s.l. Its watershed is part of the Sutlej sub-basin of the Indus River. Based on Landsat TM imagery from 1972–2009, the surface area of Tso Moriri ranges from 139.7 to 145.1 km^2 (Lesher, 2011) compared to 148.8 km^2 recorded by Hutchinson (1937). The mean and maximum depths are 55 m and 75.5 m (Hutchinson, 1937). Two main tributaries enter the lake, one each at the northern and southern ends (Fig. 1). Visual interpretation of daily satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) between 2001 and 2010 suggest that Tso Moriri is frozen between 77 and 138 days of the year, with ice-on between 4 January and 16 February and ice-off between 29 April and 31 May (Lesher, 2011). The lake and nearby wetlands provide habitat for several important bird species, including the black-necked crane (Mishra and Humbert-Droz, 1998).

The second deep study lake, Kyagar Tso (elevation 4736 m), receives inflow from a watershed area of 64 km^2, and has a maximum depth of 21.2 m (Hutchinson, 1937). Topographically, it lies in the Tso Moriri watershed, but there is no visible evidence of surface water linkage between the two lakes, so the Kyagar Tso watershed is considered hydrologically closed (Hutchinson, 1937). The two shallow lakes (Tso Kar and Startsapuk Tso) are 40 km northwest of Tso Moriri in the Zaskar sub-basin of the Indus River. The smaller lake, Startsapuk Tso, has lower salinity and a surface outlet to the larger Tso Kar. The most commonly observed depths are approximately 1 m (Startsapuk Tso) and 2 m (Tso Kar) (Table 1). The two shallow lakes have a combined watershed area of 630 km^2.

The four lakes differ in the ratio of lake volume to watershed area (Table 1). The deeper lakes have a large volume:area ratio, indicating that they may be less sensitive to interannual variability in watershed inputs and likely have longer residence times than the two shallow lakes.

The region has very low annual precipitation. Records from the Indian Meteorological Department at Leh indicate that mean annual precipitation was 92 mm/year from 1973 to 1994 and 270 mm/year from 2002 to 2006. Between 1973 and 1994, 35% of the precipitation at Leh fell between June and September and 52% fell between December and March. Data from 2002 to 2006 suggest that most precipitation that falls between November and March or April is snow, so snow represented approximately 50% of total precipitation from 1973 to 1994. From 2002 to 2006, winter precipitation (December–March) represented a higher percentage of total annual precipitation (70%) compared to 1973–1994.

The lakes lie south of the Indus-Tsangpo Suture Zone in the Zanskar mountain range in the western section of the Himalayan-Tibetean orogen. The geology underlying the lakes includes sedimentary and metamorphic rock overlain by Quaternary sediments (Bagati and Thakur, 1993; Hedrick et al., 2011). The three smallest lakes lie entirely on the Tso Moriri nappe, which consists of Ordovician granite-gneiss and Precambrian to Cambrian metasediments (Schlup et al., 2003). Tso Kar is bounded on its northwestern end by Precambrian and Cambrian metasediments. Tso Kar and Startsapuk Tso are underlain by Quaternary fluvial and lacustrine deposits ranging from sandy gravel to clay (Bhattacharyya, 1989). Tso Moriri lies on the Tso Moriri nappe in