Journal of Hydrology 478 (2013) 132–147

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Diagnostics of Western Himalayan Satluj River flow: Warm season (MAM/JJAS) inflow into Bhakra dam in India

Indrani Pal[a,b,*], Upmanu Lall[c], Andrew W. Robertson[b], Mark A. Cane[d], Rajeev Bansal[e]

[a] Department of Civil Engineering, University of Colorado Denver, CO 80204, United States
[b] International Research Institute for Climate and Society, The Earth Institute at Columbia University, Palisades, NY 10964, United States
[c] Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, United States
[d] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, United States
[e] Bhakra Beas Management Board, Punjab, India

ARTICLE INFO

*Article history:*
Received 17 May 2012
Received in revised form 9 October 2012
Accepted 22 November 2012
Available online 3 December 2012
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Matthew Rodell, Associate Editor

*Keywords:*
MAM
JJAS inflow
Bhakra dam
Satluj River
Western Himalaya
Diagnostics

SUMMARY

Here we analyze the variability of MAM (March–April–May) and JJAS (June–July–August–September) seasonal Satluj River flow into the Bhakra dam in India through Pearson anomaly correlation and composite analyses with antecedent and concurrent seasonal climatic and atmospheric circulation patterns. The MAM seasonal inflow of Bhakra dam is significantly correlated with winter (DJF/FM) precipitation and temperature of the Satluj basin while the correlation with FM was more prominent for precipitation (snow = +0.72, rainfall = +0.60), and temperature (diurnal temperature range (DTR) = −0.76 and maximum temperature ($T_{max}$) = −0.57). The JJAS inflow was also positively correlated with DJF/FM as well as JJAS precipitation of the Satluj basin while the correlation with basin average FM was the largest (+0.54). These suggested that both MAM and JJAS inflow anomalies are linked with DJF/FM climate over the Western Himalayas and adjoining north and central Indian plains, which were also found to be linked with the fluctuation of equatorial concurrent Sea Surface Temperature anomalies over the western Indian Ocean (max anomaly correlation was > +0.70) and mean sea level pressure over western pole of the Southern Oscillation sea-saw region (max Pearson anomaly correlation was ~ +0.60). Low (high) MAM inflow was found to be associated with negative (positive) precipitation anomalies over the basin and north India in DJF and FM while FM precipitation anomaly is more concentrated over the Western Himalayas. In addition, low (high) JJAS inflow is also associated with negative (positive) precipitation anomalies over the basin and north India in DJF and over the Western Himalaya in FM and JJAS. Negative geopotential height anomaly at 500 h Pa (Z500) over Siberia and northwestern pacific in DJF, and positive Z500 anomaly over the northwest India in FM were noticed in low MAM inflow years. Whereas high inflow in MAM was linked with a negative Z500 anomaly between two positive Z500 anomaly regions – one over eastern Siberia stretched up to northern Pacific and second over the Eastern Europe in DJF, which gets stronger in FM. We also found southwesterly (northeasterly) wind vectors at 850 h Pa pressure level (uv850) bringing more (less) moisture to the Western Himalayas in DJF and FM in high (low) MAM/JJAS flow years.



## 1. Introduction

The major river systems of the Indian subcontinent that originate in the Himalayas are expected to be very sensitive to climate change because of substantial contributions from the snow and glacier melt (Singh and Jain, 2002). Winter precipitation in the form of snow over the Western Himalayas feed the glaciers, which serve as a vast storehouse of freshwater for the Indus river basin, which provides the primary water supply for the breadbaskets of India and Punjab. The supply of water through these rivers is important for ecological habitats, power generation and irrigation in the following seasons.

The Bhakra dam across Satluj River in north India is the major point of water supply (irrigation to 10 million acres of land) and electricity generation (1325 MW) for the neighboring states of Punjab, Rajasthan and Haryana, including the national capital territory of Delhi. The irrigation canal systems connected with Satluj River and Bhakra dam in India turned the Punjab into the breadbasket of the country, providing the agrarian economic foundation for the arid provinces and feeding the majority of the populations approximately since early 1960s. Bhakra inflow is a joint contribution of the flow from Satluj River and Beas Satluj Link channel,

* Corresponding author. Address: Department of Civil Engineering, University of Colorado Denver, CO 80204, United States. Tel.: +1 303 352 3804.
*E-mail address:* indrani.pal@ucdenver.edu (I. Pal).

0022-1694/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2012.11.053

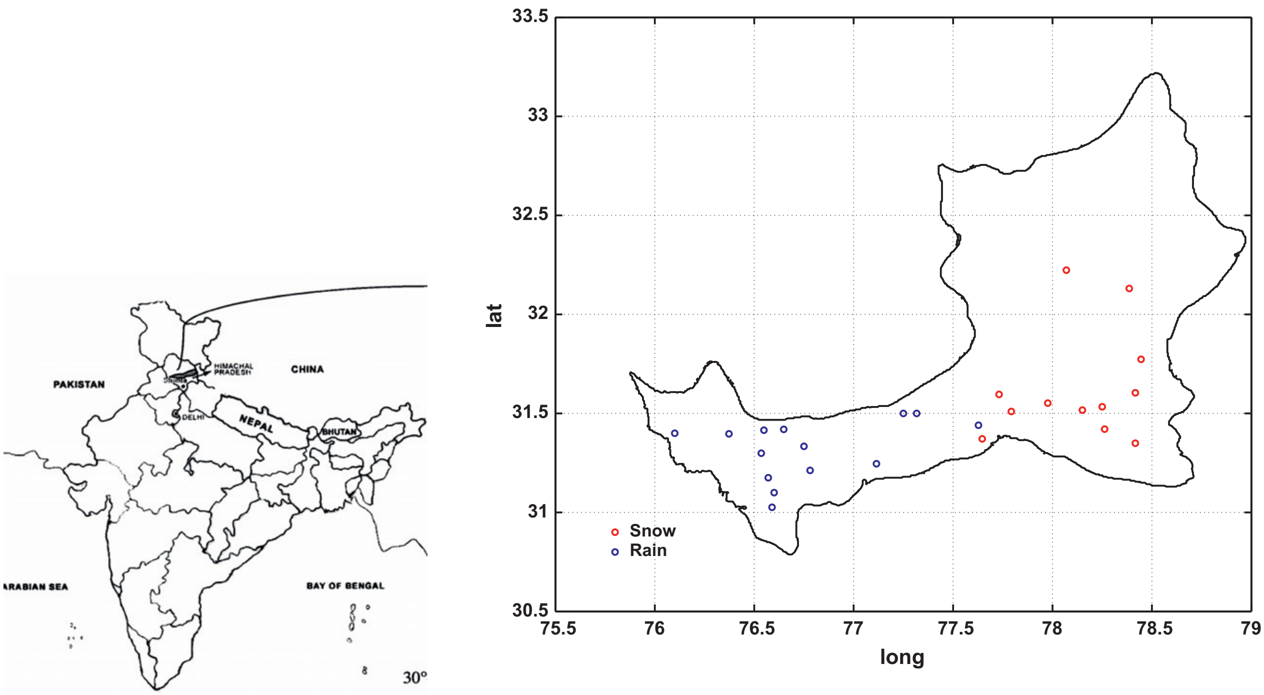


**Fig. 1.** Indian part of Satluj River basin up to Bhakra reservoir with location of hydro-meteorological stations.

which came into effect in 1977. Thus, cold season precipitation in the Western Himalayas in the form of snow has the major contribution to the total volume of MAM inflow of Bhakra. That also contributes to some extent to JJAS flow in addition to summer monsoon precipitation (Singh and Quick, 1993). Melting snow and ice provides the water supply to much of the north Indian regions under Bhakra command before summer monsoon starts.

Satluj and Beas Rivers originate from the Western Himalayas at different elevations. Through a diversion (Beas Satluj Link/BSL) Beas River is one of the major tributaries of Satluj River. Both are major tributaries of the Indus River; together with another tributary Ravi carrying about 1/5th of annual Indus River flow (~112 km$^3$) (Sen Gupta and Desa, 2001). NDJFM (winter) precipitation in the Western Himalayas is mainly associated with the midlatitude jet stream and low-pressure synoptic systems known as Western Disturbances (WD) (Dimri, 2005, 2006; Yadav et al., 2009). WDs originate over the Mediterranean Sea or North Atlantic Ocean, with secondaries developing over the Persian Gulf and Caspian Sea either directly or as a result of the arrival of low-pressure systems from southwest Arabia, and travel eastward over southwest central Asia (including countries such as Iraq, Iran, Afghanistan, Turkmenistan, Uzbekistan, Kazakhstan, as well as parts of eastern Europe), Pakistan, and northwest India (Mariotti, 2007; Dimri, 2007). In the NDJFM months the midlatitude depressions move to their lowest latitudes and in their pathway travel across the north and central parts of India in a phased manner from west to east, disturbing the normal circulation patterns (Yadav et al., 2009, 2010). Past theoretical and synoptic studies indicated that the development of WDs in the mid-latitudinal synoptic system is associated with baroclinic activity and therefore potential energy residing in the latitudinal temperature gradient is the main source of energy (Rao and Rao, 1971; Dimri et al., 2004).

Past diagnostic studies have focused on DJF circulation patterns during the years of extreme precipitation events (deficit and surplus) over Western Himalayas considering the region of 15°S–45°N and 30°E–120°E (Dimri et al., 2004; Dimri, 2005, 2006; Yadav et al., 2009, 2010). The large-scale land–ocean interaction and teleconnections and especially the effects of Indian Ocean or

**Table 1**
Information about different meteorological stations in Satluj River basin in India.

| Station name | Latitude (N) | Longitude (E) | Elevation (mAMSL) |
|---|---|---|---|
| *Rainfall* | | | |
| Berthin | 31°25′11″ | 76°38′55″ | 668 |
| Bhartgarh | 31°6′0 | 76°36′0 | 284 |
| Daslehra | 31°24′56″ | 76°32′56″ | 562 |
| Ganguwal | 31°24′ | 76°6′ | 1220 |
| Ghanauli | 31°1′33″ | 76°35′22″ | 293 |
| Kahu | 31°12′43″ | 76°46′52″ | 526 |
| Lohand | 31°10′31″ | 76°34′14″ | 288 |
| Naina Devi | 31°17′56″ | 76°32′8″ | 985 |
| Nangal | 31°23′50″ | 76°22′21″ | 369 |
| Rampur | 31°26′24″ | 77°37′40″ | 987 |
| Suni | 31°14′43″ | 77°6′53″ | 701 |
| Kasol | 31°30′0″ | 77°19′0″ | 2614 |
| Kotla | 31°30′0″ | 77°15′0″ | 2824 |
| Swarghat | 31°20′ | 76°45′ | 1220 |
| *Snow measurement* | | | |
| Bahli | 31°22′17″ | 77°38′48″ | 2285 |
| Chitkul | 31°20′59″ | 78°25′0″ | 3327 |
| Giabong | 31°46′24″ | 78°26′44″ | 2926 |
| Jangi | 31°36′15″ | 78°25′0″ | 2721 |
| Kalpa | 31°31′60″ | 78°15′0″ | 2662 |
| Kaza | 32°13′25″ | 78°4′11″ | 3618 |
| Kilba | 31°31′0″ | 78°9′0″ | 1988 |
| Nichar | 31°33′7″ | 77°58′34″ | 2225 |
| Phancha | 31°35′45″ | 77°43′54″ | 2348 |
| Sangla | 31°25′14″ | 78°15′44″ | 2780 |
| Sarhan | 31°30′34″ | 77°47′34″ | 2144 |
| Tabo | 32°7′51″ | 78°23′11″ | 4201 |
| *Maximum temperature* | | | |
| Bhakra[a] | 31°24′56″ | 76°26′5″ | 554 |
| Kasol | 31°30′0″ | 77°19′0″ | 2614 |
| Nangal[a] | 31°23′50″ | 76°22′21″ | 369 |
| Rampur | 31°26′24″ | 77°37′40″ | 987 |
| Suni | 31°14′43″ | 77°6′53″ | 701 |

[a] Also minimum temperature stations.