

Inventory of Two Decades for Glaciers and Glacial Lakes in Satluj River Basin of Himachal Pradesh

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ABSTRACT

Himachal Pradesh a mountain state in Indian Himalayas covers an area of over 55 thousands sq. km. The unique geography of the state produces a wide spectrum of climates. In general, the area above 4000 m above sea level is mostly covered with snow and ice throughout the year. The perpetual glaciers some create many glacial lakes, which are the source of the headwaters of many rivers in the region. Himachal has four major rivers basins namely Satluj basin, Beas, Chenab and Ravi. Satluj basin alone covers 45 per cent of the total geographical area of Himachal Pradesh (23645 sq. km.) and is considered to be the most active basin. This basin experiences regular floods causing widespread damage. Many times these floods are caused by glacial lake outburst caused by excessive snow melt. The present study reports the complete inventory of glaciers and glacial lakes as affected by global warming in Satluj basin.

The study revealed that there are 945 glaciers altogether as per inventory with a cumulative area of 1217.70 sq. km. and estimated ice reserve of 94.45 km³. The aspect of the glaciers in the Satluj basin was randomly distributed in all directions. The glaciers with north, north-west or north-east aspect constitute 50 per cent in number and occupied 69.3 per cent of the area. The distribution of glaciers in southern aspect covers about 37 per cent of the total glaciers. Eastern and western aspect had 5 and 6 per cent of total glaciers. The inventoried glaciers have been classified into seven types i.e. ice, apron, ice cap, mountain, mountain basin, niche and valley glaciers. Areas occupied by these glaciers were 697.51, 173.4 and 272.7 sq. km., respectively. Maximum number of glaciers (416) was of mountain basin type. There were 40 lakes identified in this basin with an area of 136.4 sq. km. About 35 were found to be associated with glaciers. There were maximum number of moraine dammed lakes (20) followed by super-glacial (6) and valley (2). Valley lakes constitute 99.5 per cent of the area covered by lakes. Trend analysis carried out for rainfall in the upper catchments of Satluj basin indicated a average decreasing rate of rainfall amount to the tune of 17.01 mm annually based on the data for past 15 years. The rate of decrease in snowfall was 82.7 mm annually based on past 20 year database. The annual average rainfall and snowfall of the basin were 1181.7 mm and 4685 m, respectively. The water inflow in Bhakra dam which is the only outlet for the entire Satluj basin revealed 12 times less rate of decrease than precipitation annually. The study clearly revealed that glacier reserves are depleting at a rate 12 times faster than the water inflow from the basin.

Key words : Glaciers, glacial lakes, water reserves, inventory, Himachal Pradesh

Introduction

Water is a precious natural resource supporting ecosystems and human activities. The IPCC panel experts revealed that scarcity of water, droughts and floods would be the common phenomenon in various river basins of India due to climate change. Depletion of water resources and disintegration of ecological function are of local, regional and global concern.

Himachal Pradesh is a mountain state in Indian Himalayas covering an area of 55,673 Sq. Km. The unique geography of this mountain state produces a wide spectrum of climates. In general, the area 4000 m above sea level is mostly covered with snow and ice throughout the year (Bhagat et al. 2004). The glaciers and glacial lakes are the sources of head waters of many rivers in the region. The glaciers some of which consists of huge amount of perpetual snow and ice, create

many glacial lakes. Glaciers and glacial lakes play an important role in maintaining ecosystem stability as they act as buffers and regulate runoff water supply to plains during both dry and wet seasons. The glaciers and glacial lakes are generally located in remote and inaccessible areas. The inventories are only possible using time series remote sensing data and geographic information system (GIS) technology. The mountain ecosystems are fragile and highly susceptible to global climate changes. Evidences of global climate changes could be clearly deciphered from physical observations like receding rain and snow precipitation retreating glaciers and drying up of the kaawn Perennial hill springs in the river basins.

Himachal Pradesh has four major river basins namely Satluj, Beas, Chenab, and Ravi. Satluj basin alone covers 45% of total geographical area of the state (923645 Sq. Km). The basin is very active and experiences regular floods causing widespread damage in the down valleys. Agriculture, horticulture and animal husbandry are the mainstay of 60-70% of the population in the hills despite very small area under irrigation (Partap and Partap, 2002). Due to global climate fluctuations the water resources of the river basin are going to be altered over time. Hence a systematic study of water resources in the basin is pre-requisite for embarking on development plans. Keeping these facts in view the present study on inventory of glaciers and glacial lakes in Satluj basin was undertaken to estimate the total water reserves in the basin.

Materials and Methods

Study Area

The study area of the Satluj river basin lies between 30°22' to 32°42' N Longitude and 75°57' to 78°51' East Latitude in Himachal Pradesh. The basin constitutes parts of the districts of Lahaul & Spiti, Kinnaur, Shimla, Kullu, Mandi, Bilaspur, Solan, Sirmour and Una. The basin exists in the topographic maps published by the Survey of India (SOI) vide numbers 53A, 53E, 52H, 52L, 53I, and 53F published in the 1960's-1970's on the scale of 1:50,000.

Data Base Development of Water Resources

The digital database for the various biophysical characteristics of the basin has been generated and thematic maps prepared on GIS platform using ArcView software. Mapping of various water resources, glaciers, glacier lakes, drainage maps have been done using satellite imagery of Indian Remote sensing Satellite Series 1 D (IRSID) Linear Imaging and Self Scanning Sensor (LISS) 3.

Glacier Inventory

To create a comprehensive inventory and GIS database of glaciers present in the state, a digital database of glaciers was developed for the Satluj basin. Major glaciers were digitized on satellite imagery using software IL WIS 3.1. The methodology for the mapping and inventory of glaciers was adopted from Mool *et al.* (2001a and b). The inventory of glaciers has been based on topographic maps and satellite images. Glaciers were digitized on the satellite image and their identification, classification, and stages of glaciers was accomplished by referring to the topographic maps of the glaciated regions of Himachal Pradesh. The spatial inventory is based entirely on topographic maps on a scale of 1:50,000 published in the 1960s to 1970s by the Survey of India. All the projection parameters of the topographic maps are incorporated in the images to make the prints compatible with the topographic maps. The geographic extension of the glaciers was found with the help of geographic information system (GIS). To estimate the ice reserves, mean thickness of the glaciers is required and since the mean glacier thickness data are not available, this was estimated using the equation developed for the Tianshan Mountains (Chaohai Liu and Liangfu 1986)

$$H = -11.32 + 53.21F^{0.3}$$

Where H = mean ice thickness (m) and F = area of glacier (km²)

The ice reserves were estimated by multiplying the mean thickness by the area of the glacier.

The other characteristics observed for the glaciers include, numbering area, length, mean width and elevation as followed by Mool *et al.* (2001a and b).

Glacial Lake Inventory

The methodology for the inventory of glacial lakes is based on the procedure developed by the Lanzhou Institute of Glaciology and Geocryology, the Water and Energy Commission Secretariat and the Nepal Electricity Authority (LIGG/WECS/NEA 1988). The methodology for the mapping and inventory of glaciers was adopted from Mool et al. (2001a and b). The inventory of lakes has been based on topographic maps and satellite images. The lakes were digitized on the satellite image, and the identification, classification, and determination of stages of glaciers was accomplished by referring topographic maps of the glaciated regions of Himachal Pradesh. Like glaciers the numbering of lakes, area, length, width, orientation and altitude was observed as followed by Mool et al. (2001a and b).

Water Reserves Scenario as Affected by Global Climate Change in Satluj Basin

To assess the effect of changing climate on the water reserves of Satluj river basin, trend analysis of temperature, rainfall, and snowfall and water inflow in Bakhra dam were carried out. The average snowfall of the basin is 4685.0mm. The surface runoff was calculated as below.

Surface runoff = Rainfall - Potential evaporation - Available water content of soil.

The potential evaporation was taken as 0.70 of the pan evaporation as the major part of the Satluj basin area fall under dry temperate climate. The average evaporation of the basin was 1095.9 mm. The available water content of soil was taken as 200 mm as the majority soils are sandy soils (Mandal et al., 1999), and available water content of 200 mm was taken for calculation. The rainfall was converted into depth of water (million acre feet (MAF) by multiplying with area of the basin. Similar water volume from average snowfall was also calculated. The area under snow was worked out from glaciers and glacial lakes. The runoff water flow was compared with water inflow into the Bakhra Dam which is the only outlet of the entire Satluj river basin.

Results and Discussion

The north-eastern part of the Satluj river basin is mountainous, while the south-western part encounters gently sloping lands. The altitude of basin from 1000 m to 6770 m. The climate of upper part of Satluj river basin is characterized by absence of heavy monsoon rains. Instead the upper part of the Satluj river basin receives easy precipitation of snowfall. The major glaciers and glacial lakes are also found in the upper Satluj catchment. The rainfall of the basin recorded from 28 weather stations located in basin varies from 384 mm to 2683 mm annually.

The average annual snowfall in the basin is 4685 mm (18 years average). Eighty five percent of total snowfall is received during December to March. Snowfall above 3000 m is fairly uniform throughout the year. The Satluj river basin temperatures ranged from freezing to above normal. Minimum and maximum temperatures of the basin ranges from 0.7° C to 17° C and 19° C to 31° C respectively (based on data from eight weather stations). The upper part of the basin has low temperatures and lower part of the basin has comparatively higher temperature. This most of the water reserves are in the form of ice that rests in the upper part of the basin located within the districts of Shimla, Kinnaur & Lahaul and Spiti. Since most of the area is inaccessible due to hilly terrain and unstable geology. Remote sensing technique has been applied effectively and efficiently for inventory of glaciers and glacial lakes in the basin.

Glaciers in Satluj Basin

The study indicated that eighty percent of Satluj river catchment is snow fed. The glaciers were found to be mostly distributed in the north eastern part of the basin. There were altogether 945 glaciers with a cumulative area of 1217.70 sq. km and an estimated ice reserve of 94.45 km³ within the basin area.

The aspect of the glaciers in the Satluj basin was randomly distributed in all directions. The glaciers with north, northwest or northeast aspect are generally large in number and extensive. They constitute more than 50 per cent in number and

Table 1. Summary of glaciers in Satluj basin with respect to aspect

Aspect	E	N	NE	NW	S	SE	SW	W
Number of glacier	59	143	195	155	114	150	83	46
Area (km ²)	46.38	299.86	314.22	230.08	89.83	123.19	62.22	51.92
Area (%)	3.8	24.6	25.8	18.9	7.4	10.1	5.1	4.3
Maximum area (km ²)	9.77	39.26	25.14	63.79	12.3	16.24	9.41	17.42
Minimum area (km ²)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Maximum length (m)	6975.9	20218.2	11005	19181.9	7311.6	7592.6	7084.7	7452
Minimum length (m)	377.9	267.9	251.9	213.3	133.8	223.8	232.1	354.7
Ice reserve (km ³)	2.66	25.40	24.84	21.31	4.94	7.84	3.49	3.97

Table 2. Distribution of glaciers by type in Satluj basin

Glacier type	Number		Area				Ice reserve	
	Count	%	km ²	%	of largest glacier	of smallest glacier	km ³	%
Cirque	65	6.9	9.6	0.8	0.49	0.03	0.21	0.2
Ice Apron	82	8.7	43.1	3.5	9.77	0.03	2.14	2.3
Ice Cap	57	6	12.86	1.1	1.12	0.20	0.37	0.4
Mountain	260	27.5	173.44	14.2	6.84	0.06	8.17	8.7
Mountain basin	416	44	697.51	57.3	17.42	0.06	47.26	50
Niche	52	5.5	8.43	0.7	0.84	0.02	0.19	0.2
Valley glacier	13	1.4	272.76	22.4	63.79	7.88	36.11	38.2

cover 69.3 per cent of the area occupied by total glaciers in the basin (Table 1). The distribution of glaciers in southern aspect covers about 37 per cent of the total number of the glaciers. Eastern and western aspects contain only 5 and 6 per cent of the total number of glaciers. As a general rule, the west aspect is much warmer than the east aspect and is expected so in the number and area of glaciers, but in the Satluj basin study area not much difference was observed. The glaciers were classified into Seven types i.e. cirque, ice apron, ice cap, mountain, mountain basin, niche and valley glaciers. Out of these, mountains basin glaciers are dominant in terms of their number. There are 416 mountain basin glaciers, 260 mountain glaciers and 13 valley glaciers (Table 2). Areas occupied by these glaciers are 697.51, 173.44 and 272.76 sq. km, respectively. Out of the total ice reserves in the basin, the mountain basin and valley glaciers contain 50.0 and 38.2 per cent, respectively (Table 2). The maximum length of the glaciers was 2.02 km and the minimum length is about 0.1782 km. Mountain basin and valley glaciers occupy most of the area and encompass greater ice reserves. The head

water region of the valley glaciers is classified as a mountain glacier, while the adjoining mountain glacier with a valley glacier is considered to be valley glacier. The other types of glaciers such as ice caps, cirques and niches have a very thin ice sheet or ice thickness and small spatial extension.

The glaciers on mountain slopes with the forms of miscellaneous, simple basin, compound basin are also included in mountain basins. Hence the area occupied by other types of glaciers is generally low (less than 10%) in comparison to mountain and valley glaciers. Valley glaciers, (13 in number) in the basin were found to be settled in 22.4 per cent of the area. The area occupied by valley glaciers is quite high due to the addition of adjoining parts of the mountain glaciers. The largest glacier in Satluj basin which lies in the extreme south eastern corner of the state border, occupies an area of 63.79 sq. km and ice reserve of 11.04 km³. Randhawa, et al. (2001), using remote sensing techniques indicated the presence of total 334 glaciers and 1987 snow field in the entire satluj basin covering an area of 2697 sq. km. Srivastava, (2003) reported that Satluj basin has 926 glaciers covering an area of 1252 km².

Glacial Lakes in Satluj Basin

The Satluj river basin is largest river basin in Himachal Pradesh in terms of spatial extension. A total of 40 lakes were identified in this basin with an area of 136.46 sq km. Most of the lakes were found to be small in size with area less than 0.06 sq km, the aerial extent of the lakes varied from 0.017 to 0.058 sq. km. in the basin. About 35 lakes were found to be directly associated with glaciers. There were maximum number of moraine dammed lakes (20), followed by supra-glacial (6), valley lakes (95), erosion (4) blocked (3) and cirque (2). Moraine dammed lakes dominate in number, however, valley lakes constitutes 99.5 per cent of the area covered by the lakes. The Gobind Sagar (man made) lake, which is a water reservoir, alone covers 135.8 sq km area and 77 km in length (Table 3)

Water Reserve Scenario as Affected by Global Climate Change in Satluj Basin

The total area of the basin is 5842388.762 acres (Table 4). The basin receives on an average annual rainfall of 1181.7 mm which is equivalent to 23.02 million acre feet of water in the entire basin. The average annual pan evaporation of the basin is 1095.9 mm. The potential evaporation of the area is considered to be 70% of the pan evaporation as major area is dry temperate region. The water loss through potential evaporation is worked out to be 737.2 mm. The water surplus (Rainfall – Potential evaporation – Available water content of soil) from the entire basin is 214.50 mm. This water depth is equivalent to 3.89 million acre feet of water volume. The basin receives average snowfall of 4685 mm, and has approximately 1217.7 sq km area under snow and

Table 3. Type of lakes in Satluj basin

Type	Number		Area (m ²)		Area of largest lake
	Number	%	Area	%	
Blocked	3	7.50	24507.74	0.02	12422.25
Cirque	2	5.00	14562.32	0.01	10073.39
Erosion	4	10.00	120440.70	0.09	52705.76
Moraine dammed	20	50.00	390791.49	0.29	58659.48
Supraglacial	6	15.00	50267.80	0.04	16936.49
Valley	5	12.50	135870426.26	99.56	135794074.50

Table 4. Water budget of Satluj Basin

Average annual rainfall based on 28 meteorological stations	=	1187.7mm
Average annual evaporation 70% of Pan evaporation	=	767.2mm
Available water content (AWC) of soils of region		200mm
Water depth available (Rainfall-potential evaporation-AWC of soils)	=	1181.7-767.2-200mm= 214.5
Water depth available for entire region		214.5mm
Area of Basin	=	23643.8234 sq km
Area of Acres	=	5842388.8 acres
Water volume available in MAF (million acre foot)	=	5842388 x 21.45/30 3.89 million acre feet
Average snowfall in Satluj Basin	=	4685 mm
Area under snow	=	1217.7 acre
Total area under snow	=	300893.67 acre
Total volume of water available from snow	=	0.49 million acre feet
Total water volume from precipitation (rain+snow)	=	4.38 million acre feet
Contribution of snow in inflow of Satluj river		11%

Table 5. Decreasing trends of rainfall, snow and water inflows in Satluj basin

S.No.	Parameters	Decreasing rate (million feet per annum)
1.	Rainfall	0.331263 (17.01 mm)
2.	Snowfall	0.096633 (82.7 mm)
3.	Water inflows	0.0339

water. The water available through snow is 0.49 million acre feet. The total volume of water surplus or available from the entire basin is 4.38 million acre feet (Table 4).

Trend analysis of rainfall for four meteorological stations of upper catchment of Satluj basin (Fig 1 to 4) indicated average decreasing rate of rainfall to the tune of 17.01 mm annually. This decreasing rate is equivalent to 0.331263 million acre feet annually (Table 5). Similarly, a trend analysis of snowfall indicated 82.7 mm snowfall rate of decrease annually (Fig. 5), which is equivalent to 0.096633 million acre feet. The total rate of decrease in Satluj basin was 0.427896 million acre feet from rainfall and snow. The data of Bhakhra Beas Management Board (BBMB) on inflow of water in the Gobind sagar Bhakra dam also showed decreasing trend in the accumulation of water in the reservoir. The rate of decrease was 0.0339 million acre feet (Figure. 6) which is 12 times less than the rate of decrease of total precipitation annually in the upper catchment. This clearly indicates that excess water is actually coming from glaciers and glacial lakes reserves. Hence it can be concluded that water reserves present in the form of glaciers reserves are depleting at approximately 12 times faster than decreasing rate of precipitation. These data primarily based on average values, present an alarming situation of depletion of Satluj glaciers and glacial lakes. The glaciers mass balance estimation using accumulation area ratio during 2001 and 2002 for 19 glaciers Baspa river basin suggested a loss of 0.2347 km³ glacial ice in the last two years (Kulkarni et al., 2004). Srivastava, (2003) also studied the other Satluj basin glaciers Gara, gor Garang, Shaune Garang, Nagpo Tokpo in details and observed an average retreat of 4.22-6.8 m/year in all these glaciers.

The data in Table 4 indicates that snow contributed 11. the contributed of snow to the

runoff of major rivers in the eastern Himalayas is about 10% (Sharma, 1993) and more than 60% in the Western Himalayas (Vohra, 1981). Singh and Jain (2002) reported that the average contribution of snow and glacier melt runoff in the annual flow of the Satluj River at Bhakra Dam was about 59 percent while the remaining 41 percent is a contribution from rain.

Conclusion

The study revealed that there were 945 glaciers inventoried with a cumulative area of 1217.70 sq. km. and estimated ice reserve of 94.45 kms and 40 lakes identified in this basin with an area of 136.4 sq. km. Trend analysis of rainfall and snow indicated decreasing trends to the tune of 17.01 mm and 82.7 mm respectively. Trend analysis of the water inflows in Bhakra dam recorded 12 times less rate of decrease than precipitation annually in the Satluj basin. Hence it can be concluded that water reserves present in the form of glacier reserves in the satluj are depleting at approximately 12 times faster rate than decreasing rate of precipitation. The data also indicated that snow contributed 11 percent towards the total inflow of Satluj River alone.

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