Impacts of climate change on Cryosphere and hydrological Regimes of Upper Jhelum River Basin of North-western Himalayas

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1. Abstract

The critical significance of keeping the current information about the extent and dynamics of the cryosphere in the Himalayas cannot be underlined. The climate of the Himalayas is vulnerable and interlinked with global-scale climate changes, and the hydrology of the region mainly depends on the cryosphere. This is the first study that has created glacier, and glacier lake inventory that links the impact of cryosphere on streamflow to land system dynamic changes under changing climate of Upper Jhelum River Basin (UJRB) in Kashmir Himalayan region. This study uses series of satellite data (1980–2016) to understand depletion of Snow Cover Area (SCA), deglaciation and dynamics of glacial lakes. Besides, observational long-term hydrometeorological data were used to understand the variability in temperature, precipitation and track changes of land system dynamics under depletion of streamflow. This analysis suggested an overall rise in temperature (T_{Max}=0.05ºC a^{-1}; T_{Min}=0.02ºC a^{-1}; T_{avg}=0.06ºC a^{-1}) and a decrease in precipitation (2.9 mm a^{-1}) between 1980 and 2016 with a significant increase in annual average temperature and decrease in annual precipitation at stations located at higher altitudes. The Snow Cover Area (SCA) is showing a significantly decreasing ($p<0.01$) trend in the glacierized sub-basins with an annual rate of decrease is -0.78% a^{-1}, -0.15% a^{-1}, -0.03% a^{-1} -0.90% a^{-1} for Lidder, Sindh, Vishow, and Rambiara sub-basins, respectively. Inventory data show that the basin has 229 glaciers in 1980 with deglaciation (72.08±0.48 km^2) and disintegration of glaciers between 1980 to 2016 with rapid rate of deglaciation observed between 2010-2016 (18.34±0.14 Km^2), followed between 1992-2000 (15.61±0.13 Km^2). The average rate of retreat was observed to be 6.81± 1.5m a^{-1} with an average total retreat of 267±80m during 1980-2016, which is higher than reported from surrounding mountain ranges in the Himalayas. The mapped 244 glacial and high-altitude lake inventory is covering a total surface area of around 15 Km^2, with 5.87 Km^2 (40%) being covered by 25 bedrock dammed lakes. The glacial expansion and creation of new lakes are observed to be because of increasing glacial and snow melting between 1980 to 2016, which increases the risk of GLOF events in the future. The annual average discharge in UJRB significantly increased from 1991 to 1998 and was observed to be higher than the annual average of the respected gauge stations but shows significant depletion from 1998 onwards. The streamflow depletion under climate changes is one of the reasons for land system dynamics in UJRB. The area under agriculture has decreased up to 63% with a massive expansion of Built-up (399%), Aqua vegetation (523%), and Plantation (765%) between 1980-2015.

2. Study area

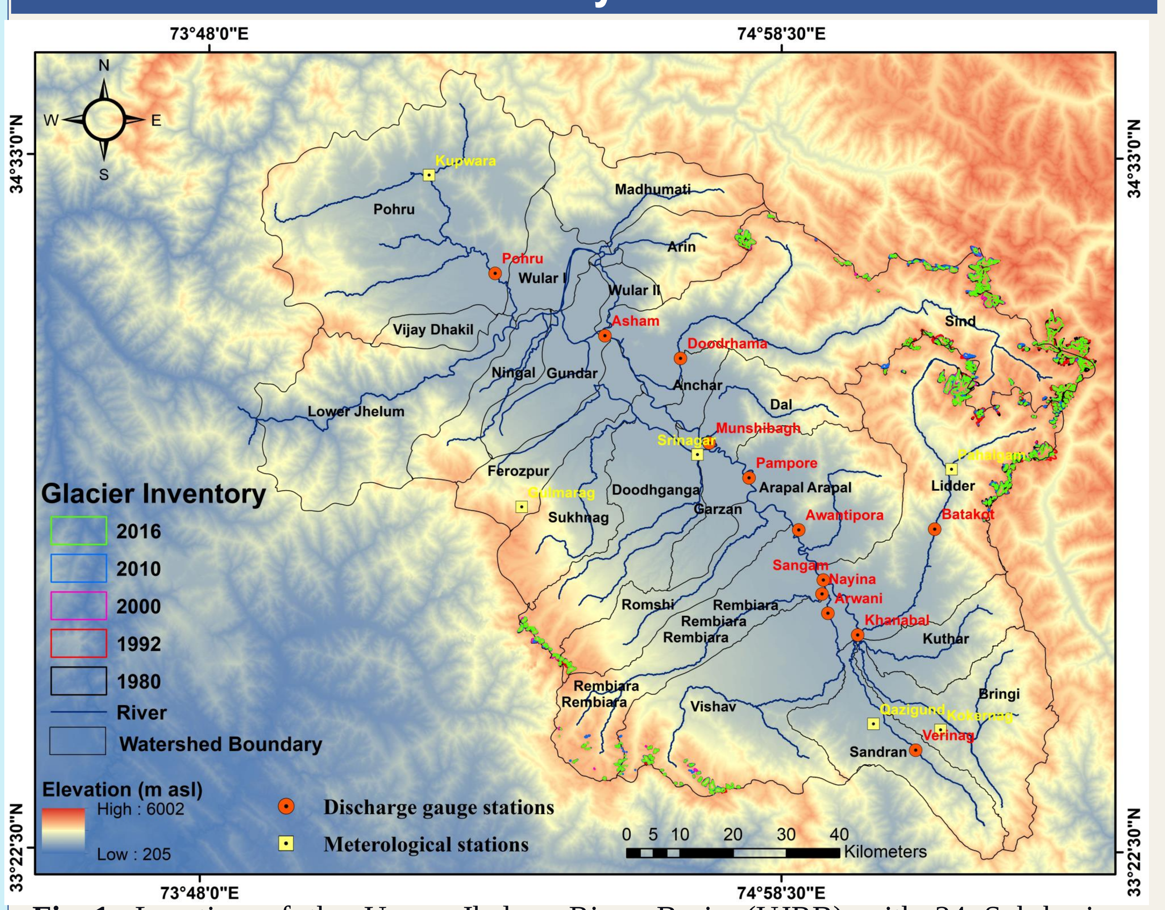

Fig 1. Location of the Upper Jhelum River Basin (UJRB) with 24 Sub-basins, Drainage network, meteorological stations, and discharge gauging stations. Temporal Glacier Inventory (1980-2016) in UJRB extracted from LANDSAT data are studied for their response towards the climatic conditions. SRTM DEM (30m) is used as the background.

3. Methodology

3.1 Hydro-meteorological data

3.2 Cryosphere dataset

$$\mathrm{NDSI} = \frac{Green-SWIR}{Green+SWIR} \qquad \text{(Eq. 1)}$$

3.3 Land use Land cover (LULC) changes

•The following formula was used to get the overall accuracy and land use-wise accuracy.

$$\rho = \frac{n}{N} \times 100 \text{.................................(Eq. 2)}$$

•where ρ is accuracy, n is the number of correctly classified samples, and N is the total samples taken into consideration (field points).

Table 1. Details of dataset used in the present study.

Sensor/Image/Maps	Resolution/Scale	Path/Row	Acquisition date	Source
Landsat MSS	30m	161/36	22-Oct-80	USGS
Landsat 5 (TM)	30m	150/36	18-Oct-92	USGS
Landsat 7 ETM+	30m	92/46	26-Sep-00	USGS
Landsat 7 ETM+	30m	92/47	23-Oct-10	USGS
Landsat OLI	30m	149/36	25-Oct-15	USGS
Landsat OLI	30m	149/36	26-Oct-16	USGS
SRTM DEM	30m		2018	USGS
MOD10A2	30m		2013-2019	(http://modis-snow-ice.gsfc.nasa.gov
Randolph Glacier Inventory (RGI 6.0)				http://www.glims.org/RGI/index.html
Temperature and precipitation	Daily		1980-2017	IMD, Srinagar
Discharge data	Daily		1980-2018	IFCD, Srinagar

4. Results and Discussion

4. 1 Hydrometeorological changes

Table 2. Annual and seasonal temperature trends of meteorological parameters over the UJRB from 1980–2016.

Stations	Temperature (°C) & Precipitation (mm)	Z-Statistics	Sen's slope	Trend & p-value
Qazigund	T_{Max}	2.03	0.05	No-trend (0.01*)
	T_{Min}	0.39	0.04	No-trend (0.69)
	T_{Avg}	-0.22	0.04	No-trend (0.01*)
	P	-1.01	-4.85	No-trend (0.31)
Kokernag	T_{Max}	2.68	0.05	Increasing (0.01*)
	T_{Min}	2.18	0.02	Increasing (0.03*)
	T_{Avg}	1.84	0.04	No-trend (0.01*)
	P	-0.72	-2.76	No-trend (0.47)
Pahalgam	T_{Max}	3.15	0.05	No-trend (0.0*)
	T_{Min}	4.26	0.04	Increasing (0.02*)
	T_{Avg}	1.72	0.05	No-trend (0.03*)
	P	-0.61	-2.73	No-trend (0.54)
Srinagar	T_{Max}	2.75	0.06	No-trend (0.01*)
	T_{Min}	0.51	0.01	No-trend (0.61)
	T_{Avg}	1.96	0.04	No-trend (0.01*)
	P	-0.95	-3.57	No-trend (0.34)
Gulmarg	T_{Max}	1.29	0.03	No-trend (0.02*)
	T_{Min}	4.2	0.08	Increasing (0.0*)
	T_{Avg}	1.32	0.05	No-trend (0.01*)
	P	-0.92	-9.08	No-trend (0.36)
Kupwara	T_{Max}	2.27	0.07	Increasing (0.02*)
	T_{Min}	1.82	0.02	No-trend (0.07)
	T_{Avg}	1.64	0.04	No-trend (0.03*)
	P	-2.38	-12.4	Decreasing (0.02*)
UJRB	T_{Max}	1.05	0.05	Increasing (0.02*)
	T_{Min}	2.77	0.02	Increasing (0.01*)
	T_{Avg}	1.24	0.06	No-trend (0.01*)
	P	-0.8	-2.9	Decreasing (0.01*)

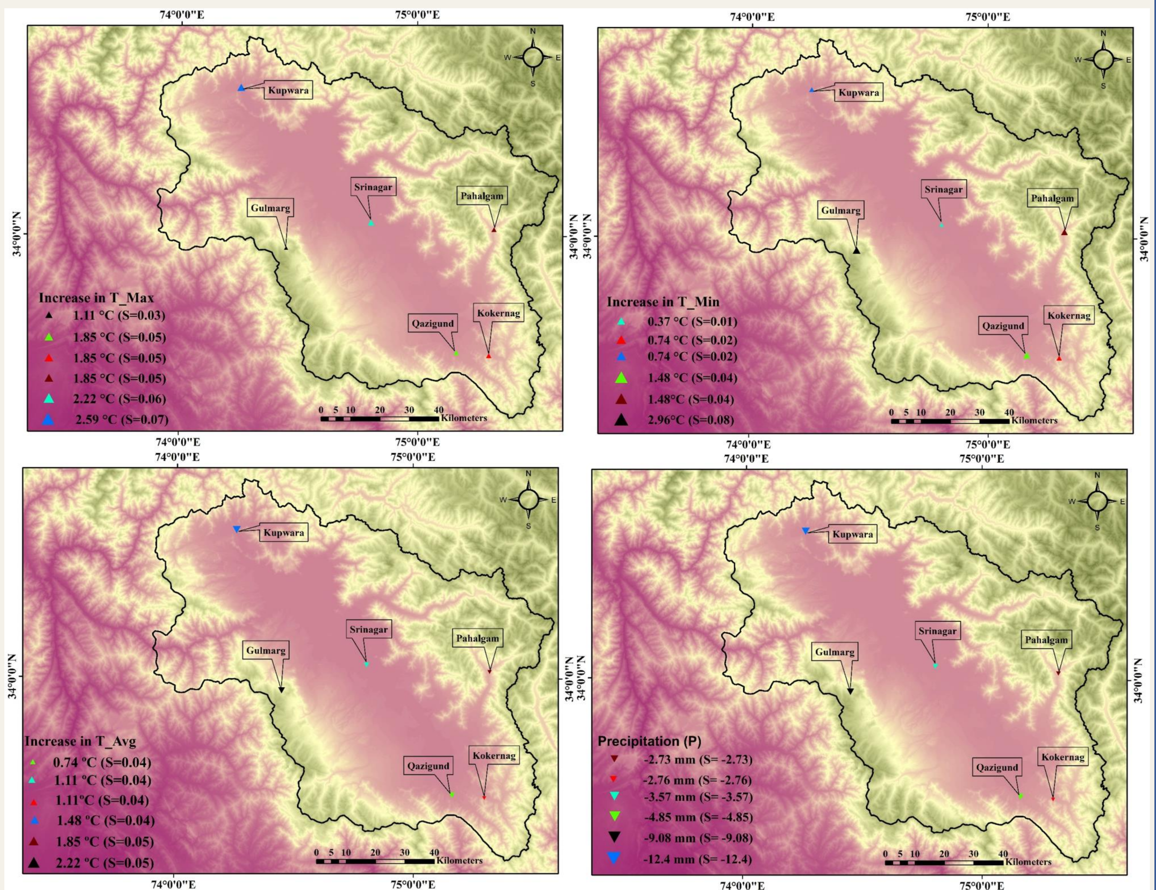

Fig 2. Trends in temperature and precipitation at the six meteorological stations of the UJRB (a) maximum temperature (T_{Max}) (b) minimum temperature (T_{Min}) (c) annual average temperature (T_{Avg}) (d) annual average precipitation (P). Increase in temperature/precipitation is indicated by pointing upward of triangle and decrease by pointing downward of triangle.

4. 2 Snow Cover Area (SCA) changes

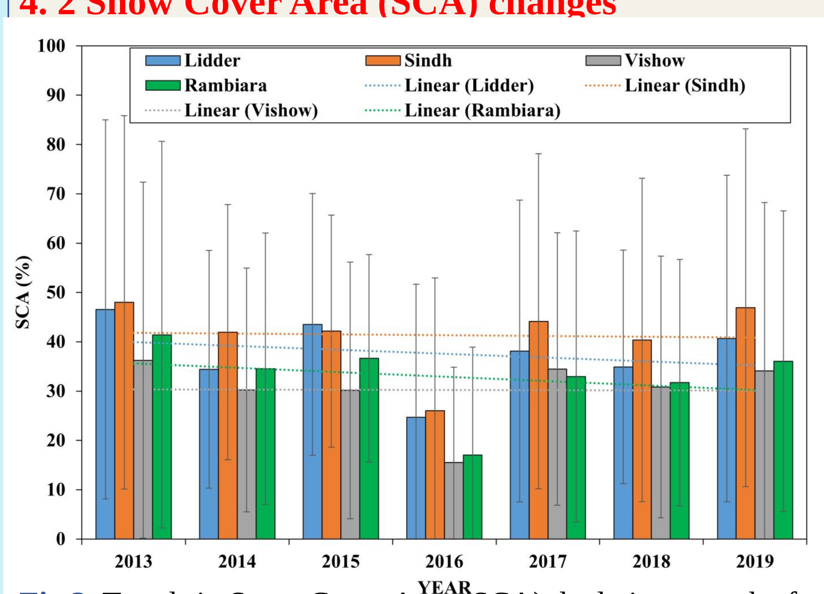

Fig 3. Trends in Snow Cover Area (SCA) depletion over the four sub-basins of UJRB during 2013-2019.

4. 3 Recent glacier retreat and lake expansion

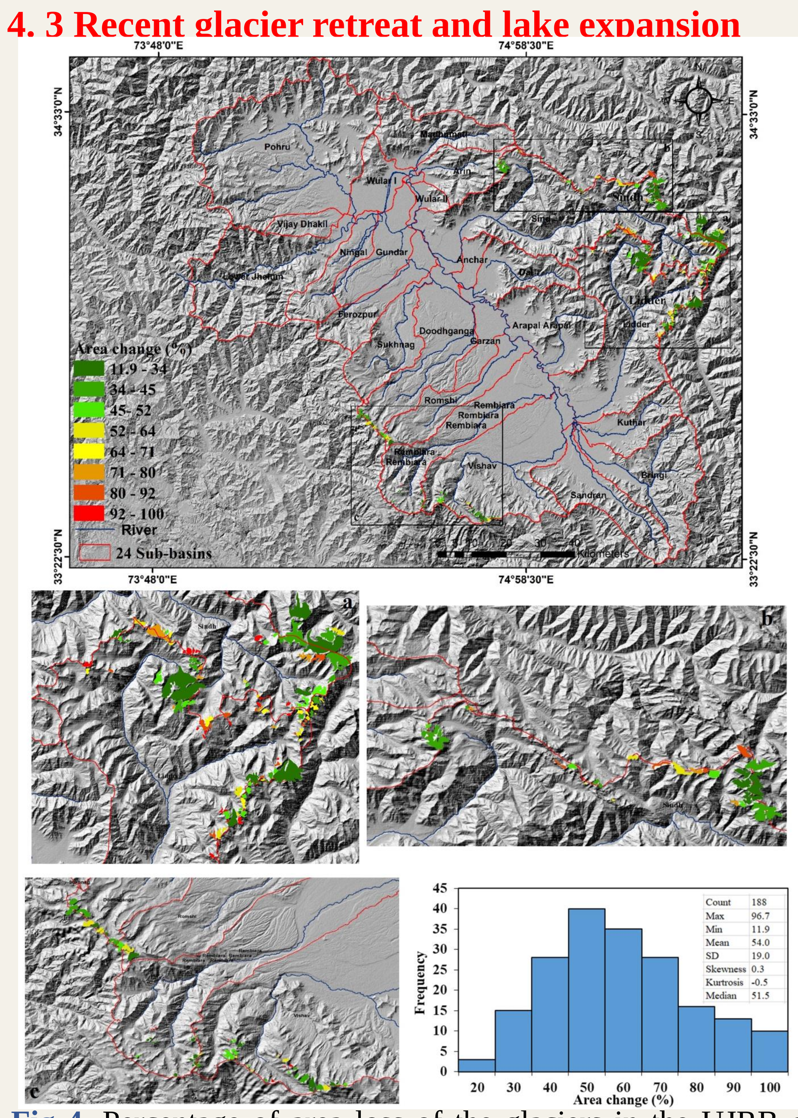

Fig 4. Percentage of area loss of the glaciers in the UJRB during the period 1980–2016. Frequency distribution histogram depicting that most of the glaciers have undergone an area loss in the range of 40–60%.

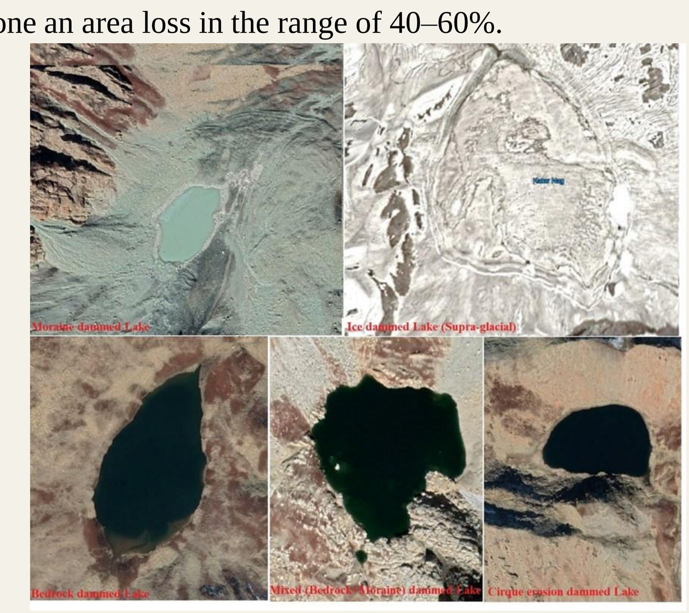

Fig. 5. Types of glacial lakes identified in UJRB.

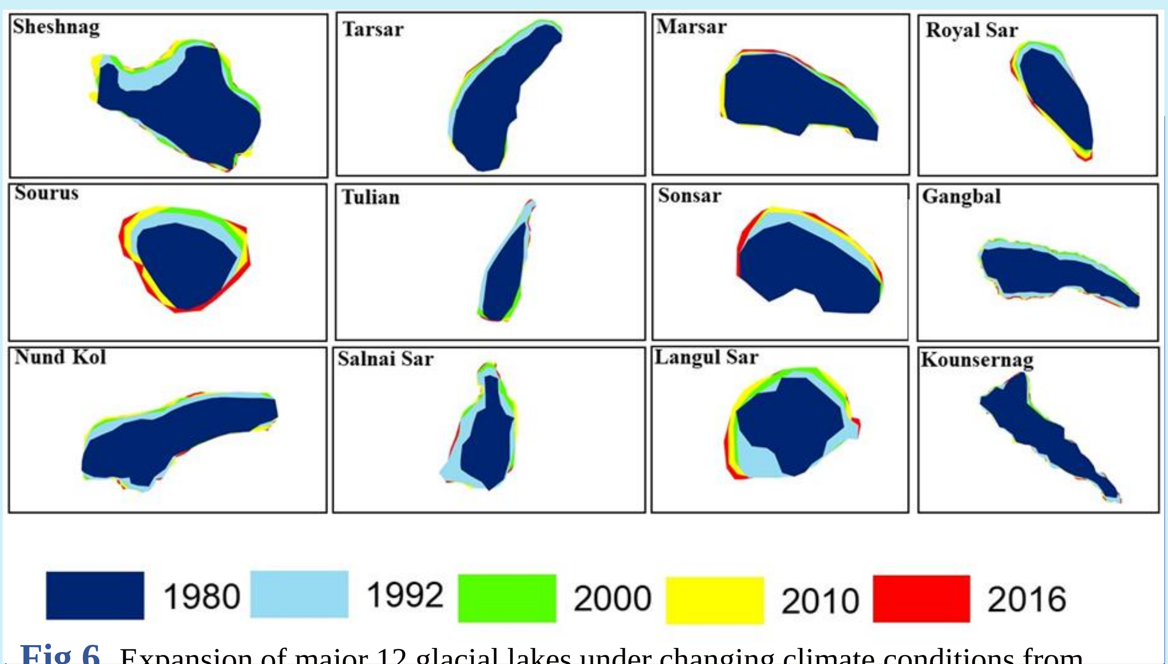

Fig 6. Expansion of major 12 glacial lakes under changing climate conditions from 1980s to 2016 in UJRB.

Table 3. Decadal growth of selected studied lakes.

		Area (Km^2)				
Lake ID	Lake name	1980	1992	2000	2010	2016
BD_2	Salnai Sar	0.22	0.33	0.35	0.36	0.37
BD_3	Gangbal	1.29	1.61	1.68	1.72	1.76
BD_4	Nund kol	0.32	0.38	0.39	0.41	0.42
BD_8	Tulian	0.20	0.24	0.27	0.28	0.29
MD_9	Sheshnag	0.48	0.55	0.59	0.61	0.63
MD_17	kounsernag	1.28	1.35	1.38	1.42	1.44
MD_47	Marsar	0.42	0.44	0.45	0.47	0.48
MD_48	Sonsar	0.08	0.10	0.10	0.10	0.11
MD_53	Royal Sar	0.17	0.19	0.20	0.22	0.23
CE_2	Longul Sar	0.12	0.16	0.17	0.19	0.19
CE_4	Sourus	0.16	0.20	0.22	0.25	0.27
MO_93	Tarsar	0.81	0.92	0.95	0.97	0.97

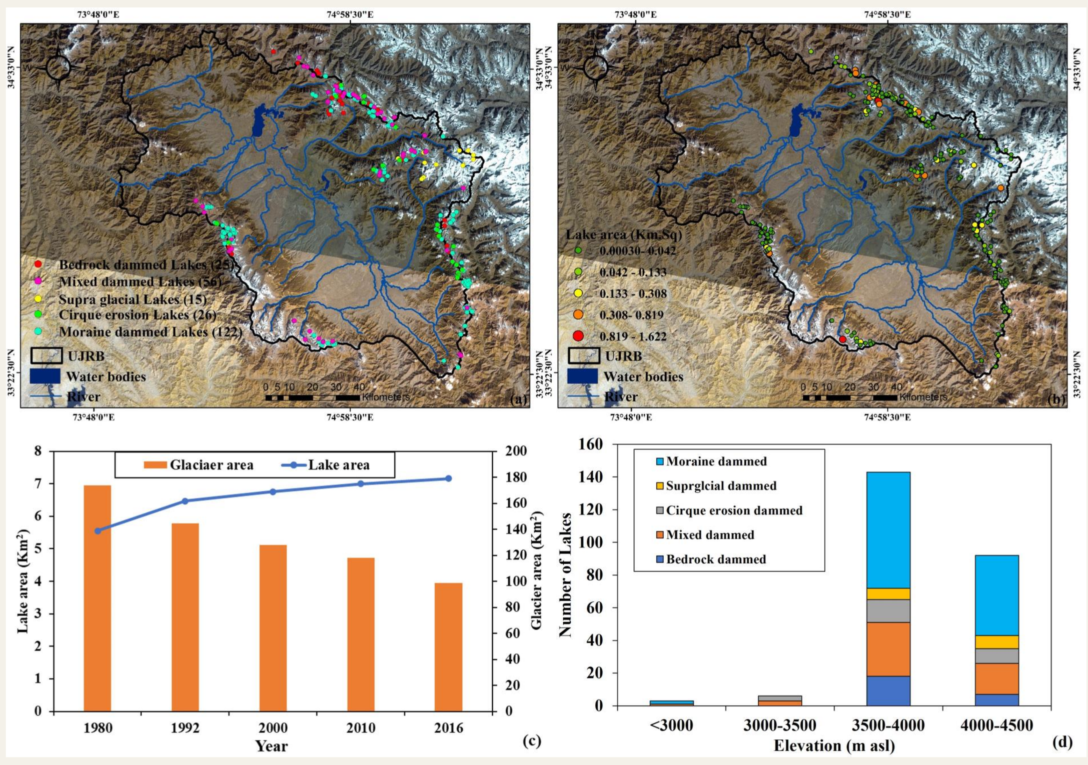

Fig 7. (a) Spatial patterns and type of glacial lakes, (b)spatial variability of lake area (c) deglaciation and evolution of lakes from 1980-2016 (d) lake type hypsometry in study area.

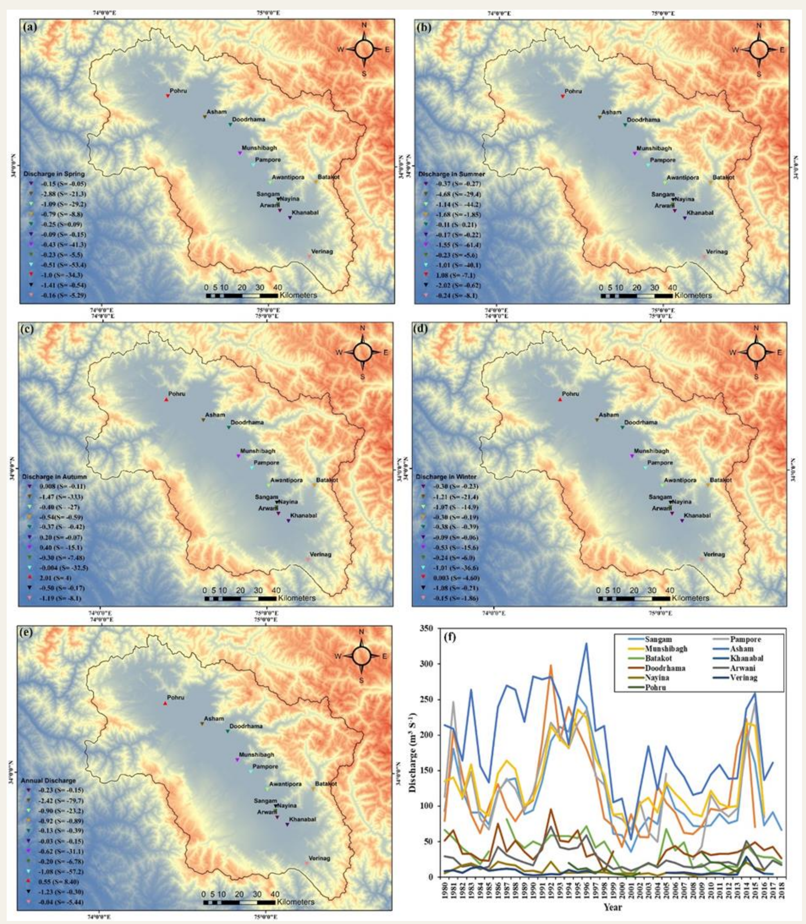

Fig 8. Spatial distribution of trends for annual and seasonal streamflow of river Jhelum and its tributaries, (a) spring (b) summer (c) autumn (d) winter (e) annual and (f) Hydrograph of respective gauges. Increase in discharge is indicated by pointing upward of triangle and decrease by pointing downward of triangle.

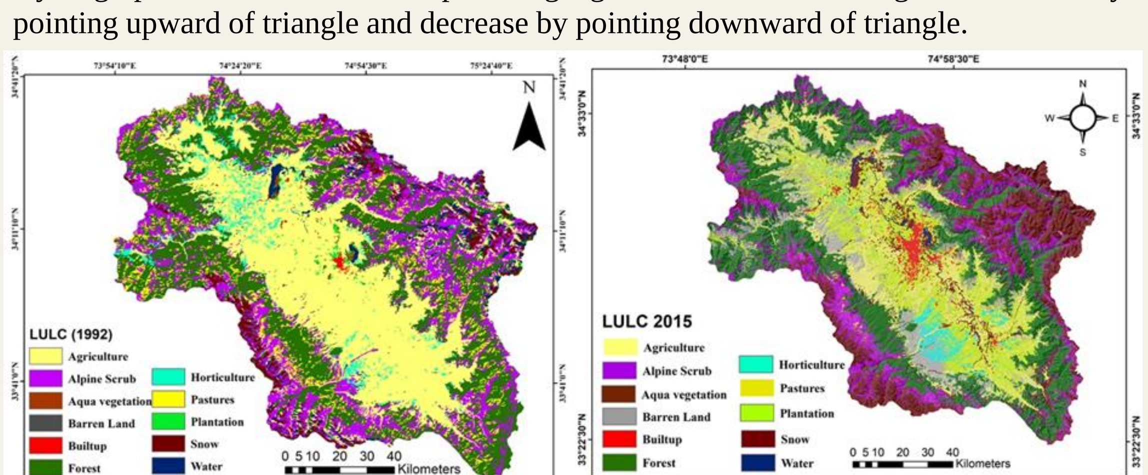

Fig 9. Land use Land Cover (LULC) changes in UJRB between 1980 and 2016.

5. Conclusion

1. Long-term meteorological data indicate an overall rise in temperature (TMax=0.05ºC a-1; TMin=0.02ºC a-1; Tavg=0.06ºC a-1) and decrease in precipitation (2.9mm a-1) trends in UJRB between 1980 and 2016 with a significant increase in annual average temperature and decrease in annual precipitation at stations located at higher altitudes.
2. The SCA is showing a significantly decreasing ($p<0.01$) trend in the glacierized sub-basins. The annual rate of decrease is -0.78% a-1, -0.15% a-1, -0.03% a-1 -0.90% a-1 for Lidder, Sindh, Vishow, and Rambiara sub-basins, respectively. Decreasing trends were more pronounced and very significant for the winter and summer seasons.
3. The UJRB comprised 229 glaciers ranging in size from <0.02 to 16.46 Km2. The study region shows deglaciation (72.08 ± 1.39 km2) and disintegration of glaciers between 1980 to 2016, most with the rapid rate of deglaciation observed between 2010-2016 (2.6 ± 0.05 Km2 a-1), followed between 1992-2000 (1.4±0.06 Km2 a-1). The slow rate of deglaciation was observed between 2000-2010 (0.9±0.001Km2 a-1). The average rate of the retreat was observed to be 6.81± 1.5m a−1, with an average total retreat of 267 ± 80 m during 1980-2016, which is higher than reported from surrounding mountain ranges in the Himalayas.
4. This is the first study in UJRB that mapped the 244 glacial and high-altitude lakes covering a total surface area of around 15 Km2, with 5.87 Km2 (40%) covered by 25 bedrock dammed lakes. The glacial expansion and creation of new lakes resulting from increasing glacial and snow melting between 1980 to 2016, increases the risk of GLOF events in the future.
5. The inherent local climate variability has influenced the behaviour of the hydrological regimes of the basin and resulted in overall streamflow depletion. The annual average discharge of all stations in UJRB significantly increased from 1991 to 1998 and was observed to be higher than the annual average of the respected gauge station but shows significant depletion from 1998 onwards. The streamflow depletion under climate changes is one of the reasons for land system dynamics in UJRB. The area under agriculture has decreased up to 63% with a massive expansion of Built-up (399%), Aqua vegetation (523%), and Plantation (765%) between 1980-2015.