Impacts of Spatio-Temporal Changes of Glaciers on the water resources of Hindukush-Karakoram-Himalaya region

Attaullah Shah[1]*, Irfan U. Jan[2]

[1]Karakoram International University, Gilgit, Gilgit-Baltistan, Pakistan
[2]Humaif Geosciences Consulting Inc, Canada
*Email: drshah965@gmail.com

Abstract

Global warming and subsequent climate changes have adversely affected the glacial mass balance in the Hindukush-Karakoram-Himalaya (HKH) region. The glacial melting and formation of new glacial lakes have increased over time. The impacts of temporal and spatial changes of glaciers on water resources show a high degree of variability, depicting periodic oversupply and shortages in the next century. Uncertainties in the physical and social systems of the region further complicate the situation. Some of the challenges for sustainable water supply include forecasting the water supply and demand under various climate scenarios and developing appropriate response strategies in terms of availability of water, its conservation, governance, capacity of the relevant stakeholders and their involvement. Based on the literature review, the changes in the glaciers of the HKH region and their impacts on the water supply have been studied. Recommendations have been made for sustainable water supply in the short term and long term.

Keywords: HKH, glaciers, glacial lakes, water resources.

1. Introduction

The water from the Upper Indus Basis (UIB) accounts for 44% of the requirements of irrigation in Pakistan (Immerzeel et al., 2010, Khan et al., 2015). More than 50% of the water resources of UIB are fed by the melting of the glaciers in the Hindukush-Karakoram-Himalaya (HKH) region (Ali and De Boer, 2007). These glaciers constitute the third largest ice mass on the earth's surface after the Polar regions, estimated at about 2700 km^3. These glaciers show spatial and temporal variations, exhibiting retreat, advances and stable status in various places (Scherler et al., 2011). The ten important basins of the HKH region are shown in Fig. 1.

Jan, M.Q., Shafique, M., Raynolds, R.G., Jan, I.U., Ghani, M. (Eds.) Indus Water System. National Centre of Excellence in Geology, University of Peshawar & Pakistan Academy of Sciences, Islamabad, Pakistan (2024) weblink: http://nceg.uop.edu.pk/books/IWS.html

2. Glaciers dynamics in the HKH Region

2.1. Glaciers dynamics and Glacial lakes formation in the Karakoram Hindukush region

In the Central Karakorum National Park (CKNP), 608 glaciers, with an area of 3680 ± 61 km^2, and 202 glacial lakes are reported as given in Table 1, however, very little information is available about the nature of these lakes (Arendt et al., 2017). The glaciers of Hunza valley in the Central Karakorum region, have receded from 4.11% to 10.63% during 1977-2014.

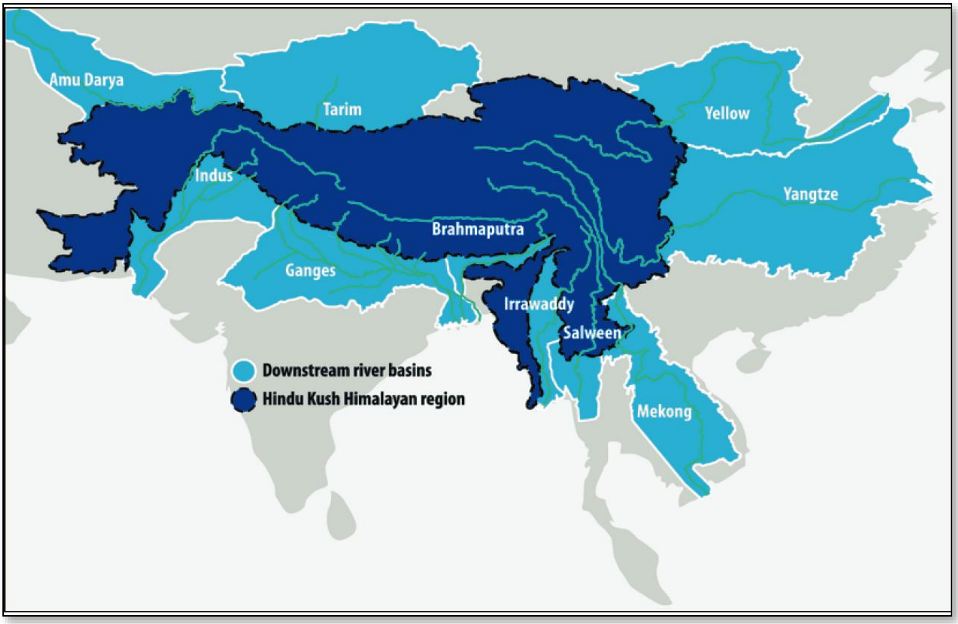

Figure 1. Three mighty mountain ranges of HKH and ten basins (Molden and Sharma, 2013).

Similarly, about 2420 glacial lakes have been reported in the Hindukush-Karakorum-Himalayan region, out of which 52 were declared to be prone to GLOF threats (Ashraf et al., 2012) (Table 2). The Pamir-Hindu Kush-Karakoram-Himalaya and the Tibetan Plateau showed an increase in the formation of glacial lakes ($\geq$0.003 km^2) from 4602 to 4981 and 5701 in 1990, 2000, and 2010, respectively (Zhang et al., 2015). More frequent changes were witnessed in the higher altitudes, which is alarming. The International Centre for Integrated Mountain Development (ICIMOD) studied changes in the glaciers and glacial lakes in Pakistan, India and Tibetan region from 2002 to 2015. About 165 lakes have been reported to be highly vulnerable, including 52 in Pakistan. Some of these lakes have already experienced GLOFs during the last few years. Similarly, the temperature increase in the glacial region of Pakistan has forced the snowline to shift to higher altitudes, thereby creating supra and subglacial lakes, which are more vulnerable to outbursts.

Table1. Various types of glaciers, glacial lakes and their cumulative area cover in the CKNP (Senese et al., 2018).

Lake Type	Number	Number (% with respect to the	Cumulative area	Area (% with respect to the	Area (km^2) of the
Lake type	(Value)	CKNP total)	(km^2)	CKNP total)	largest lake
Glacial Erosion	2	0.99%	0.01	0.40%	0.01
Cirque	1	0.50%	0.06	1.76%	0.06
Trough Valley	2	0.99%	0.02	0.46%	0.01
Supraglacial	140	69.31%	2.04	57.21%	0.26
Lateral Moraine	3	1.49%	0.05	1.51%	0.02
End Moraine	13	6.44%	0.22	6.12%	0.06
Dammed					
Blocked	41	20.30%	1.16	32.55%	0.17
CKNP total	202	100.00	3.56	100.00	0.26

Table 2. Distribution of glaciers, glacial lakes in Pakistan, India and Tibetan autonomous region (after Campbell and Pradesh, 2005).

Region/Country	Total glaciers	Total covered area (Km2)	Glacial Lakes	Vulnerable Lakes
Pakistan	5218	15040	2420	52
Indian Himalayas				
i.Tista River Basin	285	576	266	14
ii. Himachal Pardesh	2554	4160	229	22
iii. Uttaranchal	1439	4060	127	0
Tibetan autonomous area of PR China	1578	2864	824	77
Total	11074	26700	3866	165

2.2. Glaciers dynamics and Glacial formation in the Himalayan Region

The Himalayan region’s glaciers are experiencing retreat in various basins like the Dhauliganga basin and Chandra basins in the north-western Himalayas. The four decadal changes in the glacial lakes in the Himalayan region are given in

Table 3, which also shows a substantial increase in their number during 1977-2017. The increase in the number of glacial lakes is more pronounced in the two major basins of Gandaki and Karnali. The majority of the lakes in the north-western Himalayan region are fed by glaciers (75%) and exhibited significant temporal expansion as compared to non-glacial-fed lakes. A total of 251 (>0.01 km^2) glacial lakes exist in the Indian Himalayan region, of which 45 lakes are not classifiable due to poor image resolutions. About 12 lakes were considered critical by them and suggested further investigation. Some 93 lakes were reported as potentially critical and 101 were deemed to have no GLOF threats (Worni et al., 2013).

Table 3. Total number of glacial lakes by type between 1977 and 2017 with total decadal and overall change (%). The values in parentheses indicate the total surface area in km^2 (Khadka et al., 2018).

Lake type		1977	1987	1997	2007	2017	Overall change (%) (1987-2017)
Glacier fed	Supraglacial	21 (0.88)	98 (2.21)	101 (2.25)	158 (2.35)	166 (2.33)	69 (6)
	Paraglacial	87 (13.59)	124 (16.77)	170 (19.42)	275 (24.76)	349 (30.52)	181(82)
	Unconnected	252 (26.71)	445 (29.37)	476 (30.20)	540 (30.72)	549 (31.84)	23 (8)
Non-glacier-fed		246 (14.37)	470 (16.01)	481 (16.94)	516 (16.36)	477 (16.24)	1(1)
	Total	606	1137	1228	1489	1541	36 (25)
		(55.53 +16.52)	(64.56 +11.64)	(68.8 + 12.18)	(74.2+ 14.22)	(80.95+ 15.25)	
Total decadal changes			87.62 (16.3)	8 (6.68)	21.25 (7.74)	3.49 (9.1)	

3. Impacts of glacial change and global warming on water resources in the KHK region

The ten river systems of the HKH region provide water resources to about 1.3 billion people in eight countries i.e. Afghanistan, Bhutan, Bangladesh, China, India, Myanmar, Nepal and Pakistan. Most of the water in these basins comes from glacier melts with different proportions, ranging from 13% in the upper Brahmaputra, 16% in the Ganges to 41% in the Indus basin (Immerzeel et al., 2010). Lack of understanding about the interaction between glacial retreat and groundwater recharge, as well as the transboundary issues for shared water management are some of the major issues for effective water management in the region (Prakash and Molden, 2020). Rigorous research and climate modeling are also recommended in the upper reaches of the HKH region to quantify the impacts of glacial retreat on the variability of water in the basins (Miller et al., 2012). There is a need to analyze, the hydro climate variables, for future planning of the water availability to the millions of people in the Upper Indus Basin (UIB) (Khan and Adams, 2019) (Fig. 2).

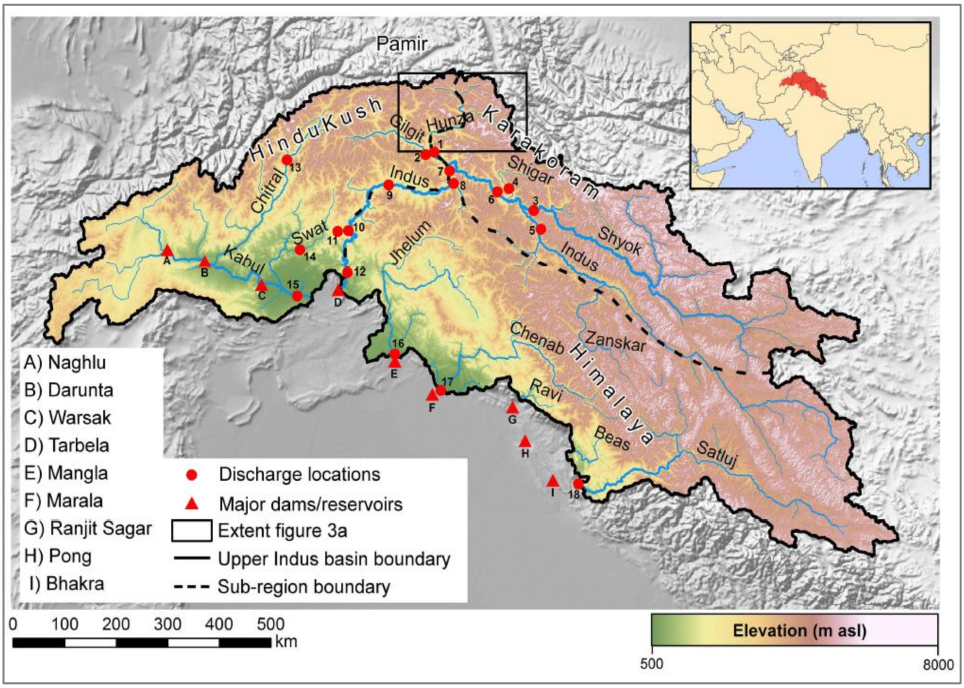

Figure 2. Map of the upper Indus Basin, showing the main rivers, mountain ranges, digital elevation model and locations of the main dams (Farr et al., 2007).

The increased melting of glaciers in the HKH region in recent years led to rising river flows in the Shigar and Ghizer rivers (Mukhopadhyay and Khan, 2014). In the subsequent years, episodes of high floods have been witnessed in these rivers, leading to the inundation of irrigated fertile lands. The hydrological projections for the sub-basins of UIB reveal an increase in the flow for at least the first half of the 21st century, based on the assumptions relating to the reference climate dataset being used, the future climate forcing and downscaling method, the type and complexity of the hydrological model, the treatment of glacier evolution in the future and the calibration and validation strategy. In the Gilgit River Basin (GRB), about 62% of the water is contributed by snowmelt followed by 28 % due to glacial melt (Latif et al., 2020). Similarly, the six glaciers in the Chitral River Basin (CRB) in the Hindukush region are showing retreat and increased melting due to climate changes (Gul et al., 2020, Khan et al., 2020). Under the climate change and expected rise in temperature from 0.7 to 2.6 C° during 2039–2070, flooding will increase in CRB but in the long run, the water resources may decline due to the melting of snow and glaciers. Based on the use of a variety of climate prediction techniques under various scenarios, a flood with a return period of 10 years or even lower has been projected with high intensity in the future in UIB (Khan et al., 2020). Climate change and its impact on the variability of water supply in the downstream end of the UIB shows both shortages and oversupply for the next century, which will require to construction of larger reservoirs for water storage (Khan et al., 2015). Significant variability in the hydrology, climate, glacier behavior, demographic and water use patterns have been identified in the HKH region. The uncertainties in the physical and social system of the region will also continue to exist, which would require improved monitoring. Water management and hazard mitigation systems are the most compelling needs in this context (Council, 2012).

4. Adaptability measures to the changes in climate, hydrology and water availability

For better adaption to the changing scenario, robust monitoring through extending the programs for data collection will be required about important parameters, like hydro-meteorological; measurements of glacial mass balances; seasonal snow cover; black carbon on snow and ice; assessment of GLOF risks; streamflow (i.e., discharge); water quality; and demographic patterns of water use. On the supply-side strategies, there is a need to improve the storage capacity at the downstream end. This will need to improve the water supply forecasting and enhance dams and catchment systems. In this context, the construction of small dams and catchment systems may prove more useful, as the construction of large water reservoirs involves many national and international challenges.

On the demand side, water conservation strategies in the major agricultural sector, particularly the water use in the production of rice, cotton and sugarcane in the Indus River basis can improve water efficiency. More efficient irrigation systems, like a sprinkler system, drip irrigation and close conduit system can save waste water. Another option can be changing the land use patterns, which may involve changing the crop patterns and shifting from water-intensive crops to rain-fed (less water-intensive) crops. At the basin management level, the concept of Environmental Flow (EF) must be taken into account. EF considers the water system in terms of quantity, timing and quality to maintain the surrounding environment system and human livelihood (Smakhtin et al., 2006). For poverty alleviation in the HKH region, effective water use has been recommended with the help of policy and institutional framework which require enhanced focus on the SDGs and regional cooperation (Koirala et al., 2020). The climate water governance issues in Pakistan include river basin and watershed management, agriculture and irrigation management, urban and domestic water issues, floods, droughts and disaster management, groundwater management, and transboundary management. In urban areas, water extraction from the ground has further worsened the situation and availability of water (Yasin et al., 2021).

There is no consensus-based regional governance framework for water in the HKH region, as most of the water has been initialized by the countries in the region and they have established their sovereignty on the water, though some of the countries have undertaken bilateral treaties. The key features of water governance include a hybrid formal-informal regime with a balance of power with the non-formal sector. For larger nation-states, there is a mismatch between local, regional and national water governance institutions. A larger synergy is required between the informal sector and States for water management (Dong et al., 2017). With the increase in the population of the HKH region, the existing spring water is becoming insufficient for the communities and in many towns, groundwater is extracted through boreholes and pumping. This has lowered the aquifer and, in the absence of recharge ponds, the water level is going down. The fast urbanization in the HKH region, together with changing climates, increase in population, and pressure of tourism and developmental activities are further jeopardizing urban water security.

It is important to understand the urban water dynamics and water-related hazards in urban areas of the HKH region (Romero-Lankao and Gnatz, 2016). Some of the important measures for creating urban water resilience include mapping water sources, assessment of water demand and supply with future projections, developing a deeper understanding of recharge zones and their protection, and documentation of climate-induced water issues in the wake of increased population and urbanization. Legislation and policy formulation about water conservation, protection of recharge zones, restriction of groundwater extraction and conservation of catchment areas will be required to create urban water resilience in the KHK region (Singh and Pandey, 2020).

To deal with the future water scarcity issues in the KHK region due to climate changes, it is recommended to bridge the water demand and supply by augmenting the supply side and rationalizing the demand side. The governance system of water supply across the region needs to be strengthened with the help of community involvement. In this context, the rural water supply projects under the Water and

Sanitation Extension Program (WASEP) of Aga Khan Agency for Habitat (AKAH) in the Gilgit-Baltistan and Chitral (GBC) in northern Pakistan remained a success story in providing water to about 700 villages. Similarly, urban water resilience must be created for their future water needs through better planning, monitoring and adaptation. The overexploitation of groundwater for domestic and commercial uses needs to be discouraged through water metering and rationing. Water governance at the village, town and city levels needs to be improved through better policy-making and strengthening of the institutional capacity of the related organizations (Virk et al., 2020).

5. Conclusions and Recommendations

Based on the review of earlier research on the inventory of glaciers, and glacial lakes and the latest GLOF events in the region, the following major conclusions are made:

i. The surface area of the glaciers in the HKH region is reducing due to climate change and global warming impacts. At the same time, the area and number of glacial lakes is increasing. The majority (62%) of these lakes are end moraine lakes posing high threats of outburst flooding. The recent GLOF events have further verified it.

ii. This glacial lake formation is more pronounced in the Himalayan region, where 25-36% increase in the formation of glacial lakes has been observed in some of the basins.

iii. The cryosphere of the HKH region provides water to eight countries and ten river systems. The increased melting of these glaciers and the formation of glacial lakes have seriously threatened the water resources and communities of the region. Due to a lack of coherent data, transboundary issues of shared waters, and lack of coordinated research on the water variability and seasonality, the water availability cannot be estimated. For the understanding of the water issues, there is a need to analyze the hydro-climatical variables for future planning of the water availability.

iv. The forecasting of water availability under various climate change scenarios reveals initial high flooding in the next 50-100 years due to increased melting of glaciers under increased temperature, followed by a decline of water in different basins. In the long run, both surface and groundwater will be depleted. This would require specific water conservation and adaptability measures.

v. For water conservation, the construction of large water reservoirs at the downstream end of the basins is required. The policy-making and institutional capacities at the village, town, city, national and regional levels have to be developed for better governance of the water. For such policy making the community and women's involvement is very important to create ownership.

vi. To make resilient cities for urban water needs, the supply side must be augmented with water harvesting and securing the water recharge areas. On the demand side, rationalization strategies including awareness, water metering and water rationing can be employed.

vii. To strengthen the research culture in the HKH region, the existing research data need to be properly documented and validated. The research findings must be effectively communicated for policy-making and research must be packaged under specific themes linked to the challenges faced by the region.

Acknowledgment: The authors are highly indebted to anonymous reviewers for the review of the paper and the financiers for publishing this review paper as part of the book. The author is also grateful to Prof. M. Qasim Jan for his support in publishing this paper.

References

Ali, K.F., de Boer, D.H., 2007. Spatial patterns and variation of suspended sediment yield in the upper Indus River basin, northern Pakistan. Journal of Hydrology, 334, 368–387.

Anjal, P., David, M., 2020. Mapping challenges for adaptive water management in Himalayan towns. Editorial Water Policy, 22, 1–8.

Antonella, S., Davide, M., Davide, F., Andrea, S., Carlo, D.A., et al., 2018. Inventory of glaciers and glacial lakes of the Central Karakoram National Park (CKNP – Pakistan). Journal of Maps, 14(2), 189–198.

Arendt, A., Bliss, A., Bolch, T., Cogley, J.G., Gardner, A.S., Hagen, J.O., Zheltyhina, N., 2017. Randolph Glacier Inventory – a dataset of global Glacier outlines: version 4.0. Global Land Ice Measurements from Space, Boulder Colorado, USA. Digital Media

Arshad, A., Rozina, N., Rakhshan, R., 2012. Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis, Geomatics, Natural Hazards and Risk, 3(2), 113–132.

Asim, J.K., Manfred, K., Adnan, A.T., 2020. Impacts of Climate Change on the Water Availability, Seasonality and Extremes in the Upper Indus Basin (UIB). Sustainability, 12, 1283.

Dong, S., Bandyopadhyay, J., Chaturvedi, S., 2017. Environmental Sustainability from the Himalayas to the Oceans, Springer.

Farr, T.G., Rosen, P.A., Caro, E., Crippen. R., Duren. R., Hensley, S., et al., 2007. The Shuttle Radar Topography Mission. Rev. Geophysics, 4, 1–33.

Guoqing, Z., Tandong, Y., Hongjie, X., Weicai, W., Wei, Y., 2015. An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. Global and Planetary Change, 131, 148–157.

Gul, J., Muhammad, S., Liu, S.Y., et al., 2020. Spatio-temporal changes in the six major glaciers of the Chitral River basin (Hindukush Region of Pakistan) between 2001 and 2018. Journal of Mountain Science, 17(3), 572–587.

Hafiz, Q., Jessica, B., Muhammad, N.T., 2020. Climate-water governance: a systematic analysis of the water sector resilience and adaptation to combat climate change in Pakistan. Water Policy, 23(3), 1–35.

ICIMOD, 2005. Inventory of Glaciers, Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of India, Pakistan and China/Tibet Autonomous Region- Final report for APN project 2004-03-CMY

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. Science 2, 328, 138223(3), 1-35–1385

Khan, F., Pilz, J., Amjad, M., Wiberg, D.A., 2015. Climate variability and its impacts on water resources in the Upper Indus Basin under IPCC climate change scenarios. International Journal of Global Warming, 8, 4623(3), 1-3569.

Khan, S.I., Adams, T.E., 2019. Introduction of Indus River Basin: Water Security and Sustainability. In Indus River Basin, 1st ed.; Khan, S.I. (Ed.) Elsevier Cambridge, MA, USA, 3–16.

Koirala, M., Khadka, U.R., Thakuri, S., Deshar, R., 2020. Designing Water Resource Use for Poverty Reduction in the HKH Region: Institutional and Policy Perspectives. In: Shang, Z., Degen, A., Rafiq, M., Squires, V. (Ed.) Carbon Management for Promoting Local Livelihood in the Hindu Kush Himalayan (HKH) Region. Springer, Cham.

Miller, J.D., Immerzeel, W.W., Rees, G., 2012. Climate Change Impacts on Glacier Hydrology and River Discharge in the Hindu Kush–Himalayas. Mountain Research and Development, 7, 461-467.

Molden, D., Sharma, E., 2013. ICIMOD’s strategy for delivering high-quality research and achieving impact for sustainable mountain development. Mountain Research and Development, 33, 179-183.

Mukhopadhyay,. B, Khan, A., 2014. Rising river flows and glacial mass balance in central Karakoram. Journal of Hydrology, 513, 192–203.

National Research Council (NRC), 2012. Himalayan Glaciers: Climate Change, Water Resources, and Water Security. Washington, DC: The National Academies Press. https://doi.org/10.17226/1344

Nitesh, K., Guoqing, Z., Sudeep, T., 2018. Glacial Lakes in the Nepal Himalaya: Inventory and Decadal Dynamics (1977–2017), Remote Sensing (MDPI), 10, 1913 (19 pages).

Raphael, W., Christian, H., Markus, S., 2013. Glacial lakes in the Indian Himalayas — From an area-wide glacial lake inventory to on-site and modelling based risk assessment of critical glacial lakes. Science of the Total Environment, 468–469, S71–S84.

Romero, L.P., Gnatz, D.M., 2016. Conceptualizing urban water security in an urbanizing world. Current Opinion in Environmental Sustainability, 21, 45–51.

Scherler, D., Bookhagen, B., Strecker, M.R., 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience, 4, 56–59.

Singh, V., Pandey, A., 2020.Urban water resilience in Hindu Kush Himalaya: issues, challenges and way forward” Water Policy, 22 (S1), 33–45.

Smakhtin, V., Shilpakar, R.L., Hughes, D.A., 2006. Hydrology-based assessment of environmental flows: An example from Nepal. Hydrological Sciences Journal, 51(2), 207-222.

Virk, Z.T., Khalid, B., Hussain, A., Ahmad, B., Dogar, S.S., Raza, N., Iqbal, B., 2020. Water availability, consumption and sufficiency in Himalayan towns: a case of Murree and Havellian towns from Indus River Basin. Pakistan Water Policy, 22(S1), 46–64.

Yasir, L., Yaoming, M.,Weiqiang, M., Sher, M., Muhammad, A., Muhammad, Y., Rowan, F., 2020. Differentiating Snow and Glacier Melt Contribution to Runoff in the Gilgit River Basin via Degree-Day Modelling Approach. Atmosphere, 11, 1023.