



FOUR DECADES OF GLACIER RELATED RESEARCH IN THE HINDU KUSH HIMALAYA (HKH): A BIBLIOMETRIC ANALYSIS AND NETWORK VISUALIZATION USING PYTHON

Sundaram¹, Saqib Iqbal Raina¹, Mohd Ramiz², Priti Deo³, Sakshi Mankotia⁴, Durgesh Dwivedi¹, Umar Faruque¹, Sidra¹, Hasan Raja Naqvi¹, Lubna Siddiqui¹, Masood Ahsan Siddiqui¹

¹ Department of Geography, Jamia Millia Islamia, New Delhi, India

² ICAR-Indian Institute of Farming Systems Research (IIFSR), Modipuram, Meerut, India.

³ School of Planning and Architecture, New Delhi, India.

⁴ Western Himalayan Regional Centre, National Institute of Hydrology, Roorkee, Uttarakhand, India.

Corresponding Author: Sundaram <sundarambohemia8272@gmail.com >

ABSTRACT: Glaciers of the Hindu Kush Himalaya (HKH) are critical to regional hydrology and climate systems, yet the rapidly expanding body of related research lacks a comprehensive bibliometric synthesis. This study systematically analyses glacier-related publications from 1980 to 2020 using the Scopus database with 24,086 articles examined through advanced bibliometric and network visualization techniques implemented in Python. Results indicate a pronounced and sustained growth in scientific output, with a compound annual growth rate of 13.98%, accelerating markedly after the mid-1990s in response to advances in remote sensing and geospatial technologies. The analysis reveals a strong dominance of Chinese institutions and authors, alongside key publication outlets such as *Geomorphology* and *Earth and Planetary Science Letters*. Keyword co-occurrence patterns identify "climate change," "Tibetan Plateau," and "remote sensing" as central research themes, reflecting the interdisciplinary evolution of HKH cryospheric studies. Collaboration networks further highlight clustered research communities and limited cross-group integration. By synthesizing four decades of scientific output, this study provides critical insights into research trajectories, dominant contributors, and emerging gaps, offering a robust foundation for future investigations and policy frameworks in high mountain cryosphere research.

Keywords: Hindu Kush Himalaya, cryospheric studies, network visualization.

1. INTRODUCTION

Glaciers serve as natural archives for paleoclimatologists to study past climate and atmospheric conditions as they preserve information in the form of trapped air bubbles and fossil records (Petit et al., 1999; Raynaud et al., 2005). Such studies provide crucial insights into the geological past and long-term environmental changes, and they contribute to improving predictions of future climate scenarios (Braconnot et al., 2012; Otto-Bliesner et al., 2016). Additionally, Glaciers share a direct relationship with climatic variables such as precipitation and temperature, making them reliable indicators for assessing regional and global climatic trend (Braithwaite, 2002; Zemp et al., 2015). Frozen glacier ice constitutes approximately three-fourth of the Earth's freshwater and is directly linked to eustatic sea-level changes, making it critically important for global freshwater resources (Vaughan et al., 2014). About 800 million people in Indo-Gangetic plain depend on freshwater from the perennial Indus, Ganga and Brahmaputra rivers, which originate from glaciers (Azam et al., 2024; Kulkarni et al., 2021; Thanveer et al., 2024) Further-

more, the water supplied by these rivers play a vital role in sustaining agricultural irrigation and supporting hydro-power generation (Kumar & Vijay, 2026).

Nearly 76 % of the global glacierised area is located in the polar regions (RGI Consortium, 2017), while the remaining is distributed across various mountain ranges in different continents. Outside the polar region, the Hindu Kush Himalaya (HKH) region hosts numerous glaciers and snowpacks and is therefore referred to as the "Water Tower of Asia" (Immerzeel et al., 2010; Wester et al., 2019). Compared with little ice age at its maximum, glacier cover has reduced to approximately one third, accounting for about 10 % of the total land surface (Grove, 2013; Benn & Evans, 2013; Solomina et al., 2015). The 21st century has witnessed widespread negative glacier mass balance (Zemp et al., 2015), accelerated glacier retreat (Intergovernmental Panel on Climate Change (IPCC, 2023), and an increase in glacier lake outburst flood (GLOF) hazards and impacts (Carrivick & Tweed, 2016) across most major glacierized regions outside the polar areas. A similar trend is observed in parts of the Hindu Kush Himalaya (HKH) region, indicating the impacts of regional warming (Bolch et al., 2012;

Kääb et al., 2012). The Hindu Kush Himalayan region is highly vulnerable to climate change, posing a significant threat to the water supply of millions of people (Immerzeel et al., 2010). Therefore, glaciers are not only indicators of climate change but are also critical components of regional water security, particularly by regulating seasonal streamflow and buffering drought impacts (Pritchard, 2019). Thus, glacier studies not only enhance understanding of climatic impacts in high mountain regions but also have important implications for the livelihoods and sustainability of downstream populations dependent on glacier-fed water resources (Hock et al., 2019).

Mountain glaciers were the first to receive the attention of glaciologists, primarily due to the relative feasibility of conducting field surveys compared to the logistical challenges of working in Antarctica or Greenland. In the 20th century, glacier research advanced significantly with the development of remote sensing technologies and the availability of well-characterized satellite products (Kääb et al., 2005; Paul et al., 2002; Pfeffer et al., 2014). In addition, improved logistics and modern scientific instruments have enabled more accurate field measurements on mountain glaciers, facilitating robust verification and validation of remote-sensing-based observations (Cuffey & Paterson, 2010; Haeberli et al., 2007; Zemp et al., 2013). As a result, the last four decades have produced extensive literature on glacier related studies in the HKH region (Azam et al., 2018; Bolch et al., 2012). Assessments of glacier dynamics including glacier retreat (Bolch et al., 2012; Oerlemans, 2005) area change (Bhambri et al., 2011; Paul et al., 2004), and mass balance (Zemp et al., 2015) and associated hazards such as snow avalanches and glacier lake outburst floods (GLOFs) have been conducted using remote sensing datasets (Bhattacharya et al., 2016; Kääb et al., 2012), geodetic approaches (Brun et al., 2017), and numerical models (Farinotti et al., 2020), supported by field observations (Wagnon et al., 2013), across varying spatiotemporal scales. In addition, paleo glacial reconstruction and modelling studies have gained considerable attention among glaciologist worldwide. (Joughin et al., 2010; Pollard & DeConto, 2009). These advances in Himalayan glacier research indicate a growing focus on the Himalayan cryosphere. However, despite the increase in glacier-related studies, the existing literature remains fragmented and poorly organized (Bolch et al., 2019).

Although bibliometric approaches have been applied to literature reviews in polar regions, such applications remain limited outside these areas. For instance, (Dastidar & Ramachandran, 2008; Qu et al., 2014) employed bibliometric methods to examine the growth of Antarctic research in terms of national and subject-wise

outputs, international collaborations, study mapping, and temporal evolution. Similarly, (Liang et al., 2018) used a bibliometric approach to assess progress in polar studies between 1987 and 2016. In addition, (Fu & Ho, 2016) analysed trends in Antarctic field research from 1900 to 2012 using citation and keyword analyses. However, beyond the polar regions, numerous reviews of glacier studies in the Himalaya and other parts of the world have been conducted using approaches other than bibliometrics (Benn et al., 2007; Eyles, 1993; Hodson et al., 2008; Lambeck & Chappell, 2001; Sigman et al., 2010). To the best of our knowledge, no bibliometric-based review of glacier studies currently exists for the Hindu Kush Himalayan (HKH) region.

Consequently, the present study aims to fill this research gap by organising and presenting the extensive glacier related literature in HKH region using bibliometric approach. Primarily, bibliometrics methods provide an effective way to organize and analyse both quantitative (e.g., annual output, top journals, authors keywords, top contributor) and qualitative (e.g., research hotspots and future methodological directions) developments in the literature (Fu et al., 2013; Li et al., 2011). The present review employs conventional bibliometric methods to assess glacier-related studies in the HKH region published between 1980 to 2020 based on documents retrieved from the Scopus database (Pati et al., 2025). This review provides a comprehensive overview of the temporal evolution and research contributions in HKH glacier studies. By synthesizing quantitative bibliometric indicators, this review identifies annual scientific output, leading authors and institutional contributions, top journals by research publication, and the most cited articles, thereby providing a structured and robust foundation for guiding future glacier research in the region.

2. STUDY AREA

From Afghanistan in the west and Myanmar in the east, Hindu Kush Himalaya (HKH) stretches across 3,441,719 square kilometres in terms of area encompassing parts of eight countries. Namely, India, Pakistan, Nepal, China, Bhutan, Bangladesh, Myanmar and Afghanistan. Region hosts around 54000 thousand of glaciers covering an area of 60000 square kilometres with seasonal snow and other part of the cryospheric component (Bajracharya & Shrestha, 2011; Wester et al., 2019). Geographically, HKH stretches from 15° 57' 00" N to 39° 18' 36" N and 60° 51' 00" E to 105° 02' 24" E longitude (Fig. 1). Due to varying gradient and geographical extent, HKH comes under a spatially varying climate and precipitation. HKH also hosts most of the tallest mountain peaks in the world. Climatically, the HKH is influenced by both the Indian summer monsoon

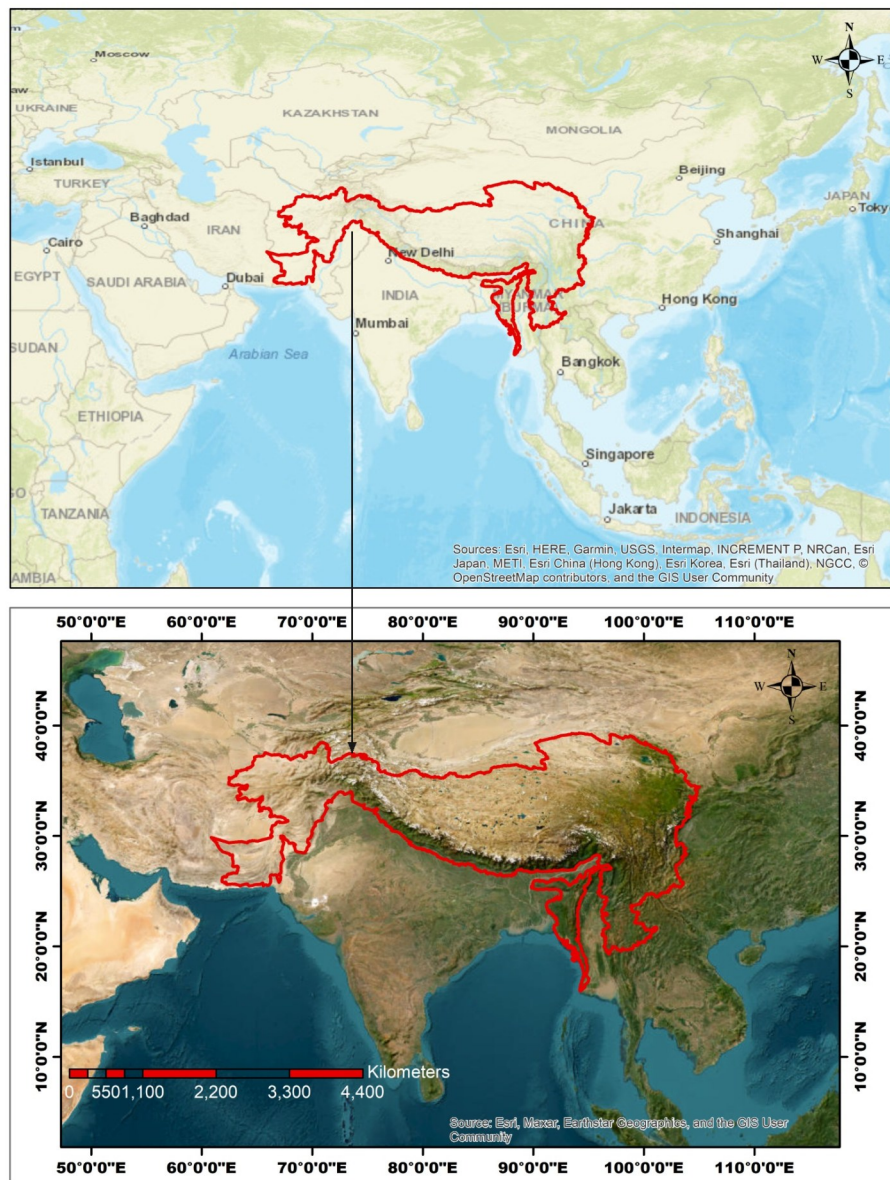


Fig. 1 - Locational map of the Hindu Kush Himalaya (HKH).

and mid-latitude westerlies. Eastern and central Himalaya receive their annual precipitation during summer monsoon whereas western region is mainly feed by westerly system (Miller et al., 2012). These geographical, topographic and climatic contrasts contribute to considerable spatial variability in glacier characteristics and behaviour.

3. DATA SOURCE AND METHODOLOGY

3.1. Data Source

For this review, Scopus database was utilised as it supports broader journal coverage, comprehensive citation indexing, and high-quality bibliographic metadata. Additionally, Scopus is highly regarded for its robust

statistical and literature-organization feature (Singh et al., 2021) making it more reliable and organised source of literature available on Internet. The study was confined between January 1980 to January 2020, including all days of the selected month to maintain consistency of study period window at the decadal level.

3.2. Search Strategy

The search query used in the study was developed after a carefully reading on past reviews related with glacier and ice sheet studies. Furthermore, multiple pilot searches employed with keywords suggested by Glacier scientists, furnished by relevancy with the field of Glaciology to retrieve the maximum literature for screening. Apart from keywords selection, Boolean op-

erators e.g. "OR", "AND" and star marking with quotation mark helped search query to avoid irrelevancy of the keywords. Star marking retrieves all the related variants of the word on which it is used while "OR" and "AND" refined synonyms, combined keywords with the study region. Another significant filter used to ensure all the glacier related literature retrieval was title, abstract and keywords (TITLE-ABS-KEY). This filter in Scopus is primarily used to restrict the word refinement within the title, abstract and keywords, avoiding full text where the words could have been written accidentally for some other context. Final keywords used in search bar of the Scopus are ("glacier*" OR "glaci*" OR "ice mass*" OR "ice sheet*" OR "cryosphere" OR "snow cover" OR "snowmelt" OR "permafrost" OR "supraglacial" OR "subglacial" OR "glacial lake" OR "GLOF" OR "debris-covered glacier" OR "glaciology") AND ("Himalaya*" OR "Hindu Kush" OR "Karakoram" OR "Trans-Himalaya*" OR "Indus Basin" OR "Ganga Basin" OR "Brahmaputra Basin" OR "Spiti" OR "Zaskar" OR "Garhwal" OR "Kumaon" OR "Ladakh" OR "Sikkim" OR "Nepal Himalaya" OR "Eastern Himalaya" OR "Western Himalaya" OR "Central Himalaya").

3.3. Literature Screening and Data cleaning

As the literature search was conducted using selected keywords, multiple records flashed both related and not related with our analysis (Tab. 1), manual inclusion exclusion criteria applied on filter interface to get the relevant documents for our bibliometric purpose (Tab. 2). Even after downloading the filtered documents, further screening done in MS Excel to remove blank entry, duplicity and irrelevant documents in the datasheet (Fig. 2).

In the first search we got a total of 32514 documents between 1980 to 2020. After applying language filter of 'English' only, the number reduced to 31246. Of these 31246 documents, 25502 were original articles and only these original articles were considered for further analysis. Rest of the document type and number are mentioned in Table number 1. 1416 articles removed on the basis of blank entry, Keyword normalization, Institution name cleaning, Author name cleaning, irrelevancy or not related with HKH in terms of glacier studies and missing value in data. finally, 24086 documents shortlisted for visualisation and further processing after a manual review of all the documents in MS Excel.

3.4. Bibliometric Analysis

Following Literature Screening and Data cleaning, the screened glacier-related literature was systematically analysed to identify key research themes. This thematic analysis was conducted to synthesize the existing body of knowledge and to understand the major direc-

Article	25502
Book chapter	1842
Review	1683
Conference paper	1157
Book	705
Note	112
Editorial	95
Letter	72
Short survey	40
Erratum	21
Retracted	10
Data paper	6
Conference review	1

Tab. 1 - Number and type of Documents.

Criterion	Included	Excluded
Language	English only	Other language
Document type	Original article	All other type
Study area	HKH	Outside HKH
Time period	1980-2020	Outside period

Tab. 2 - Inclusion and exclusion criteria.

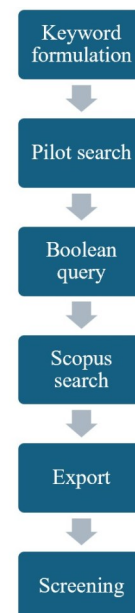


Fig. 2 - Pilot search for screening.

tions of glacier research in the HKH region. Accordingly, the selected literature was examined under the following themes.

Annual Scientific production
Top Authors
Top Journals
Top Institution
Most cited articles
Keyword analysis
Keyword cooccurrence network

In Annual scientific production theme, Compound Annual Growth Rate (CAGR) and Growth Rate (GR) were calculated using Python coding in Jupyter notebook. CAGR explains the mean annual growth in numbers of any quantity (Niu et al., 2014) (Equation-1), whereas GR explains the actual annual growth of any unit (Equation-2).

$$CAGR = \left(\frac{v_f}{v_i} \right)^{\frac{1}{n}} - 1$$

Equation-1

$$GR = \frac{v_f - v_i}{v_i} \times 100$$

Equation-2

Where,

v_f = final value

v_i = initial value

n = number of years

Academic influence of the journals was also calculated using p-index. The p-index is a composite bibliometric indicator proposed by (Prathap, 2014) to measure a researcher's overall research performance by combining:

Quantity of publications

Quality / impact (citations)

Consistency of performance

It was also calculated in Jupyter notebook using the formula:

$$p = \left(\frac{TC^2}{TP} \right)^{\frac{1}{3}}$$

Equation-3

Where,

TP = total number of publications in a journal

TC = total number of citations to articles in a given journal

Core authors were identified according to Lotka's Law, using number of publications and citations using the following formula (Ding et al., 1993):

$$(Mp) = 0.749 \times \sqrt{N_{max}}$$

Equation-4

$$(Mc) = 0.749 \times \sqrt{C_{max}}$$

Equation-5

While N_{max} and C_{max} are number of publications by most productive author and number of citations of most cited one. Purpose of these metrics also explained in Table 3.

Top institution, country, keyword frequency, author

Metric	Purpose
GR	Annual Publication Growth
CAGR	Long Term Growth Trend
P-index	Journal Influence
Lotka's Law	Author Productivity
Citation analysis	Scientific Impact

Tab. 3 - Metric and their purpose.

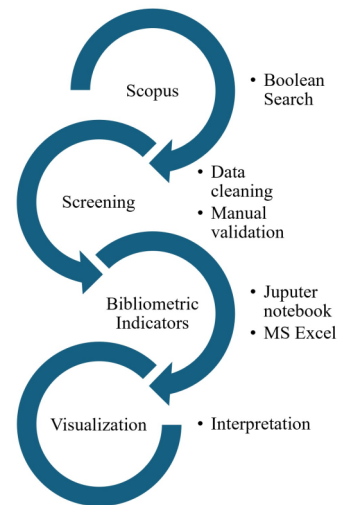


Fig. 3 - Research Framework.

collaboration and keyword co-occurrence network, all were calculated and visualized using Python programming in Jupyter notebook after a manual check in MS Excel. (Fig. 3)

3.5. Network Analysis and Software Settings

Authors and Keyword network analysis was done to visualise the major hotspots of authors and keywords used in Glacier related studies in HKH. Metadata downloaded from Scopus was pre-processed in Excel and Python to extract top authors and frequently used keywords for the construction of network graph. The basic idea behind network construction is that if two entities of Authors or Keywords appear in a publication, they can be visualised with an edge (connecting Line) while entity itself is visualised with a circle or node. Higher the collaboration between authors thicker the edge. Similarly higher the repeatability of the two keywords in a publication thicker the edge connecting them.

All bibliometric analyses were performed using Python in the Jupyter Notebook environment. Data pre-processing and calculations were carried out using the Pandas and NumPy libraries, network construction and analysis were performed using NetworkX, and graphical visualizations were generated using Matplotlib (Tab. 4).

Software	Purpose
Python	Data analysis
Jupyter Notebook	Coding environment
Pandas	Data cleaning
NumPy	Numerical calculations
NetworkX	Network construction and analysis
Matplotlib	Visualization

Tab. 4 - Software and their tasks.

4. RESULTS AND DISCUSSION

4.1. Annual Scientific Production

Temporal distribution of the glacier related literature in the Hindu Kush Himalayan (HKH) is presented in Figure 4. A statistically sound trend observed in the annual publication count. Though not uniform, from 16 in 1980 to 3157 in 2020, a big jump in annual production. Lenier regression of annual publication output against publication year yielded a positive slope of 56.06 publication per year with $R^2=0.685$ and $r=0.828$ ($p<0.001$), signaling a statistically sound long-term growth in scientific production. Spearman rank correlation was also calculated as the growth in publication following an accelerated trend ($\rho=0.994$, $p<0.001$). from the beginning and the end of the study period a 13.98 % CAGR (compound annual growth rate) validates a sustained long-term expansion in HKH glacier related research.

Temporal distribution highlights that this growth in publication is more visible after 2000. If we look at the decadal growth, the growth in publication surged from 297 in 1980-1989 to 934 in 1990-1999, 3748 in 2000-2009. The largest number of articles (15782) published in 2010-2019 accounting 65.98 % of the total publication output between 1980-2020. Alone 2020 witnessed 3157 publications related to HKH glacier studies. Scientific output in this forty year is not only influenced by number of publication but the exponential growth of recent years publication.

This growth pattern of publication also reflects feasibility of assessment of the remote terrain of HKH. Early research was mainly constrained by limited data and field visits, while later on development of computer processing, satellite observation and remote sensing products made the assessment possible over broader terrain.

4.2. Top authors

The leading authors in the field were identified based on their individual publication output during the period 1980–2020. Table 5 presents the most productive authors, together with their respective author IDs, which were included to distinguish between researchers with identical or similar names. The corresponding results are also presented graphically in Figure 5, which was generated in Jupyter Notebook using Equations 4 and 5.

The results indicate a marked concentration of publication output among a small number of highly productive researchers. Shichang Kang ranked first, with 324 publications, followed by Tandong Yao and Lewis A. Owen, with 226 and 106 publications, respectively. The remaining authors listed in Table 5 also demonstrated substantial research productivity, with each contributing

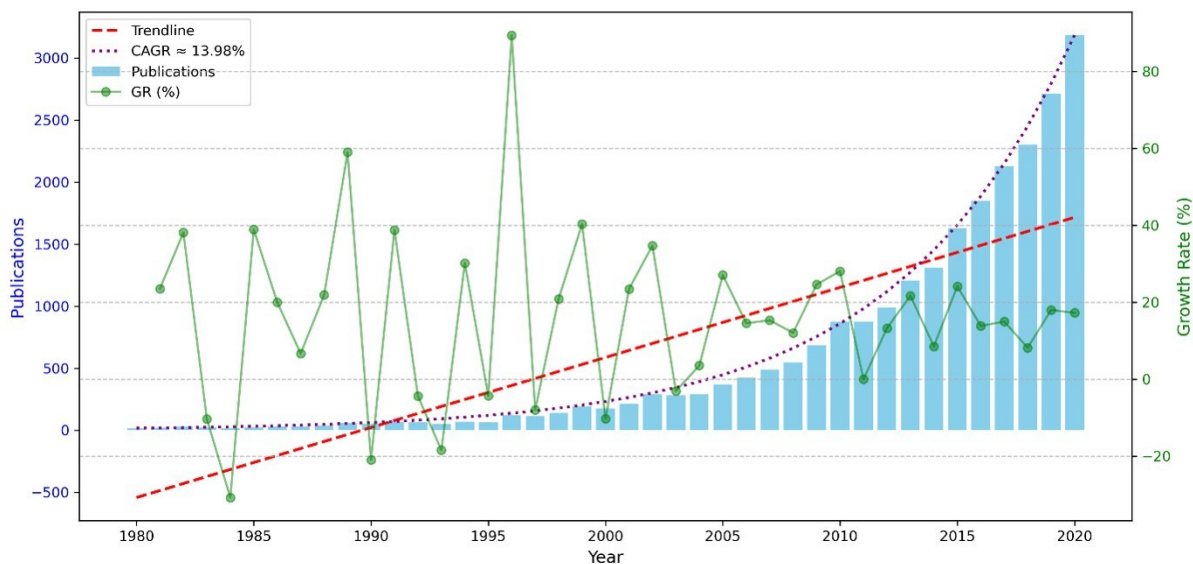


Fig. 4 - Annual scientific publications with GR and CAGR (1980-2020).

Author full name	Author's ID	Publication
Shichang Change Kang	57203321797	324
Tandong Dong Yao	55664151400	226
Lewis A. Owen	57203106423	106
Shiyin Liu	7409462943	100
Lide Tian	7202296460	98
Dahe Qin	55664298600	97
Xiaomin Fang	7401433183	95
Peter D. Clift	7004449923	92
Baiqing Qing Xu	7404588800	92
Marc W. Caffee	7005913149	77
Zhongqin Li	7409078608	75
Bodo Bookhagen	6603446872	74
Shugui Hou	57678404600	73
Qiangong Zhang	15849804700	71
Walter Willem Immerzeel	23090602200	71
Tobias Bolch	55901447400	70
Kouji Fujita	34974040400	69
Paul Andrew Mayewski	7006033826	66
Zhisheng An	57196890224	65
Robert C. Finkel	34869459600	64

Tab. 5 - Top authors by Publication count with author's ID

more than 50 publications to the field during the study period. Robert C. Finkel, with 64 publications, ranked lowest among the authors included in the table. Overall, the distribution highlights the contribution of a relatively small group of prolific researchers to the development of glacier-related research in the Hindu Kush Himalaya

during 1980–2020.

4.3. Top Journals

Based upon the data downloaded from Scopus, we got the source journal of all the articles. firstly, we arranged articles with groups to categorized them with same journal name then a python code formulated to get the top 20 performing journal within the study period. Results are displayed in Figure 6. Journal 'Geomorphology' emerged as the most publication in it related with HKH glacier related research with 605 articles. Though journal 'Earth and Planetary Science Letters' is not far behind with 504 articles followed by journal 'Palaeogeography, Palaeoclimatology, Palaeoecology' with 473 articles. Other most productive journals are 'Quaternary International' with 418, 'Quaternary Science Reviews' with 371 articles. The figure portrays the diversity of the subject contribution in HKH glacier related research ranging from Hydrology, Geology, Ecology, Glaciology, Paleontology, remote sensing and environment science.

In Figure 6, top 3 journals with publication count of 605, 504, 473 have a reason to win this figure. Obviously, glacier studies are geomorphological to its origin so as can be seen in the figure 6 as Journal "Geomorphology" placed 1st. HKH region has been categorized as third pole so the study of this region becomes by default planetary importance again explained by the journal "Earth and Planetary Science Letters" placed on second number. If we go down in this figure, we find journals like "Remote Sensing" "Cryosphere" and other core subjects of Geosciences.

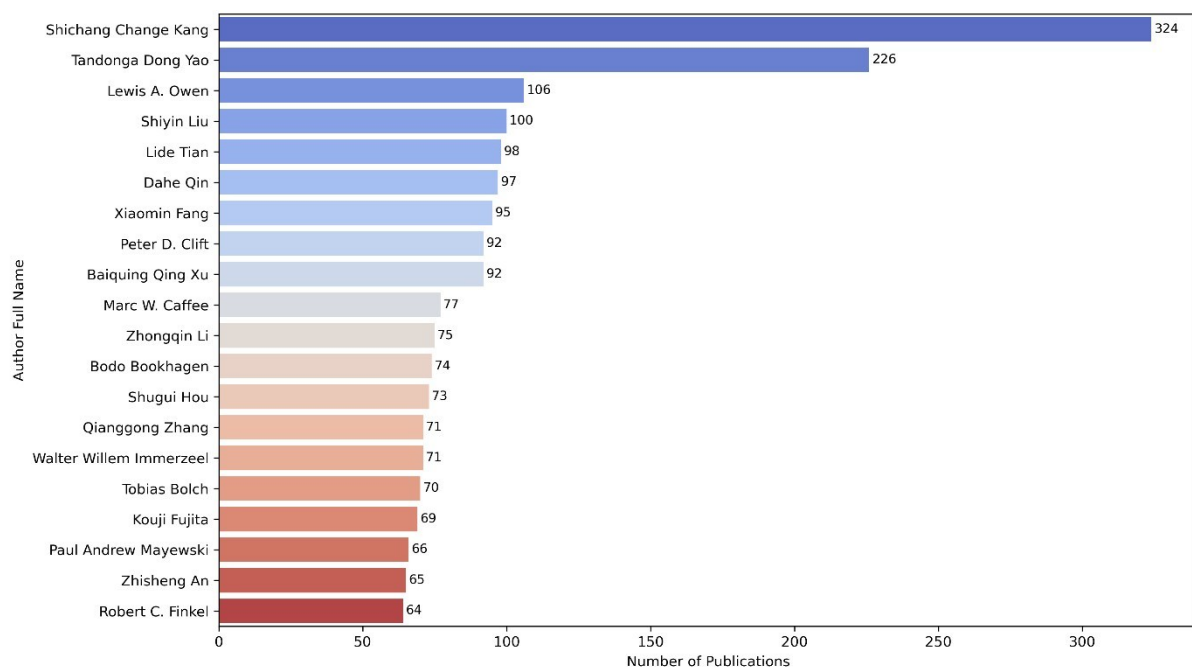


Fig. 5 - Top Authors by Publication count (1980-2020).

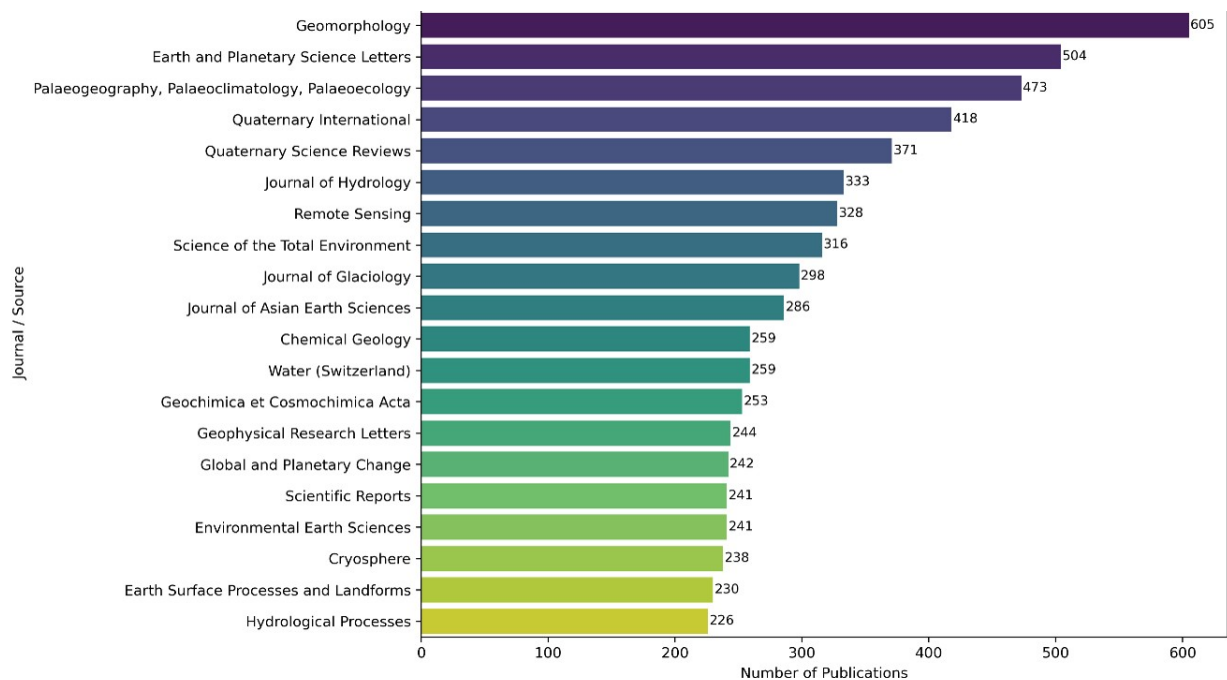


Fig. 6 - Top Journals by Publication count (1980-2020).

4.4. Top Institutions

For this section we analysed our csv file again in Jupyter notebook to retrieve number of publications from all the institution during study period. After then a little change done in the code to get the top 20 institution with their country name and institution name. Chinese Academy of Sciences has shown one-sided win for this section as the most publication (4498) between

for this section as the most publication (4498) between 1980-2020. China is clearly dominating the HKH in terms of Cryosphere related research with 12 institutions in top 20 list as clearly seen in this data Figure 7.

University of Chinese academy of sciences with 1513 publication is the second most productive institute in terms of publication count between 1980 to 2020 followed by CNRS Centre national de la Recherche Scien-

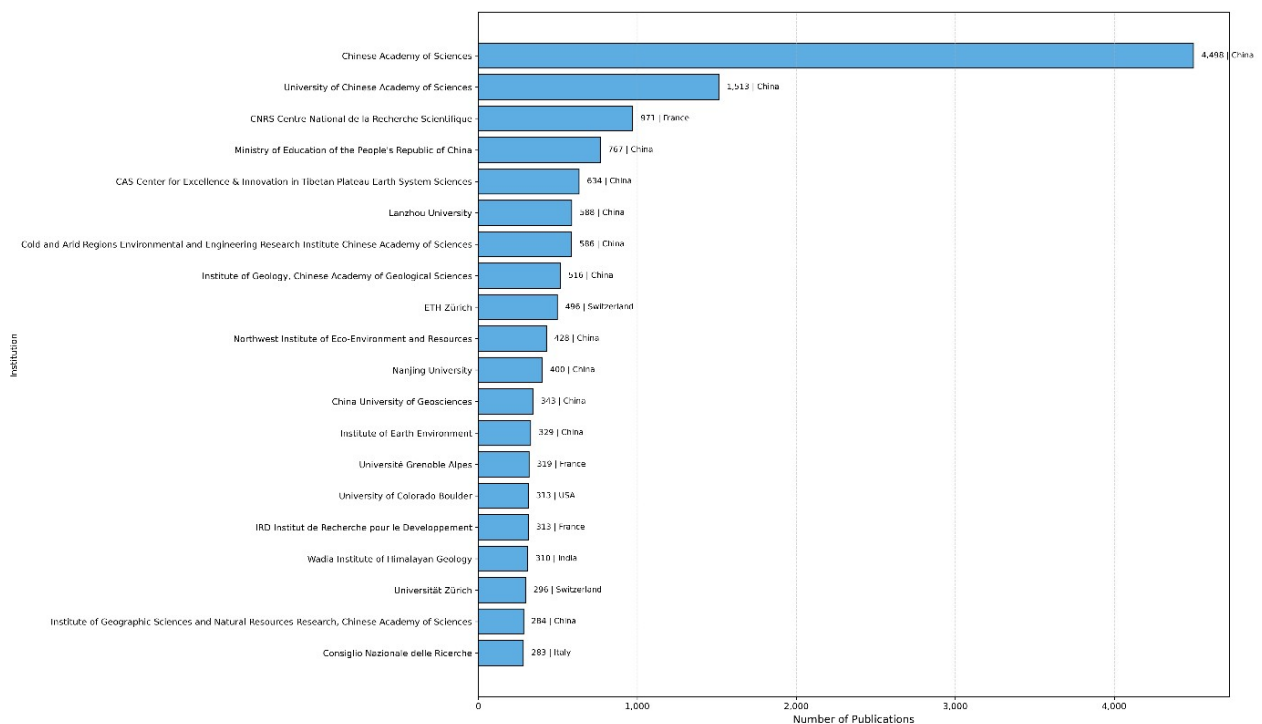


Fig. 7 - Top 20 Institutions publishing glacier related research in HKH region (1980-2020).

lowed by CNRS Centre national de la Recherche Scientifique of France with 971 publications and Ministry of Education of Peoples Republic of China with 767 publications. Other countries working in the region are Switzerland, USA, Italy, India. India's Wadia institute of Himalayan Geology has secured 17th place in this top 20 list with 310 articles between 1980-2020. It is to be considered that study period is 1980 to 2020 and since early researches were started in the region by China that's why Chinese institutions are dominating this list.

4.5. Top 20 Most cited articles

Though early researches in the HKH region were mainly field based but after the advancements in remote sensing technology glacier related research was mainly dominated by remote sensing technology. New satellites helped researchers to map remotest part of the HKH which was unreachable without it. We sorted our csv file for citation column to get the top 20 most cited articles between 1980-2020. Results are tabled in Table 6 along with citation count title name, doi, publication year and journal name.

If look closely at these top 20 articles, it can be observed that these articles are related with burning issues of the time when published. The studies are mainly dominated with climate change, geology, Meteorology and Remote sensing application. In the table 6, article "The shuttle radar topography mission" has been placed on first position with 6648 citations from 2012 (the year of publication) to 2020. Reason of it is explained by the title itself as being a remote sensing field article SRTM to be specific. It is to be noticed here that SRTM, itself is not an original article in fact it's a data set reference for majority of the glacier related articles in HKH after 2000. That explains why it has so many citations. But here it is referred because the base data source of our study 'Scopus' has put it in Articles category. In all top 20 most cited articles 9 of them are focused on evolutionary geology and paleo sciences related with HKH, 5 are focusing on climatology, 3 on remote sensing, 2 on glaciology and hydrology as core and one on ecological distribution.

4.6. Keyword analysis

Keyword analysis provides an overview of the principal thematic areas represented in the HKH glacier-related literature. A total of 95,543 keyword occurrences were extracted from the Scopus records after standardization and normalization. The 20 most frequently occurring keywords are presented in Figure 8. "Climate change" was the most frequently occurring keyword, appearing 1,382 times, followed by "Tibetan Plateau" (823), "remote sensing" (532), "Himalaya" (453), and "precipitation" (348). The prominence of climate

change indicates that changes in the cryosphere and their climatic controls constitute a major component of HKH glacier research. The high frequency of "Tibetan Plateau" also reflects the importance of the broader high-elevation Asian cryosphere as a geographical and environmental context for glacier-related investigations. Similarly, the frequent occurrence of "remote sensing" demonstrates the importance of satellite-based and geospatial approaches in investigating glacierized terrain, particularly where field observations are spatially constrained. Other frequently occurring terms, including "glacier", "climate", "Holocene", "paleoclimate", "weathering", "erosion", and "snow", indicate that HKH glacier research extends beyond contemporary glacier change and encompasses interactions among climate, geomorphology, palaeoenvironmental reconstruction, and Earth-surface processes. The frequency distribution therefore suggests that HKH glacier research has developed as an interdisciplinary field rather than being restricted to glacier monitoring alone.

4.7. Keyword Co-occurrence Network

Keyword co-occurrence analysis was conducted to identify the major thematic relationships and research orientations within glacier-related studies in the Hindu Kush Himalaya (HKH). Before constructing the network, keywords were standardized by converting them to a common case, removing unnecessary spaces and harmonizing obvious lexical variants. For example, singular and plural forms such as glacier/glaciers and Himalaya/Himalayas were treated as equivalent, while alternative expressions of Geographic Information Systems were standardized as GIS. This normalization was necessary to avoid artificially separating semantically identical terms in the network. The co-occurrence network was generated in Python using the Pandas, NumPy, itertools, NetworkX and Matplotlib libraries within the Jupyter Notebook environment. Each unique keyword was represented as a node, and an edge was created when two keywords occurred in the same publication. The frequency of a keyword determined its prominence in the network, whereas the strength of an edge represented the number of publications in which the corresponding pair of keywords occurred together. Thus, a large and highly connected node represents a frequently used and thematically well-connected research concept, while a strong connection between two nodes indicates that the two concepts are frequently investigated together. To improve visual clarity, only the most highly connected and frequently occurring keywords were retained for the final visualization. The resulting network is presented in Figure 9. The network shows a strongly interconnected structure centred mainly on climate change, glacier, Himalaya, Tibetan Plateau and remote sensing.

S. N.	Article title	Publication year	Cited by	Journal	doi
1	The shuttle radar topography mission	2012	6648	Reviews of Geophysics	10.1029/2005RG000183
2	Bounding the role of black carbon in the climate system: A scientific assessment	2003	4943	Journal of Geophysical Research: Atmospheres	10.1002/jgrd.50171
3	'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications	2005	3336	Geomorphology	10.1016/j.geomorph.2012.08.021
4	Assembly, configuration, and break-up history of Rodinia: A synthesis	2011	3314	Precambrian Research	10.1016/j.precamres.2007.04.021
5	Climate change will affect the asian water towers	2009	3290	Science	10.1126/science.1183188
6	Global silicate weathering and CO ₂ consumption rates deduced from the chemistry of large rivers	2014	2870	Chemical Geology	10.1016/S0009-2541(99)00031-5
7	⁸⁷ Sr/ ⁸⁶ Sr, δ ¹³ C and δ ¹⁸ O evolution of Phanerozoic seawater	2014	2701	Chemical Geology	10.1016/S0009-2541(99)00081-9
8	Evolution of Asian monsoons and phased uplift of the Himalaya - Tibetan plateau since Late Miocene times	2013	2633	Nature	10.1038/35075035
9	Monsoons: processes, predictability, and the prospects for prediction	2014	2621	Journal of Geophysical Research: Oceans	10.1029/97jc02719
10	Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings	2006	2510	Nature Climate Change	10.1038/nclimate1580
11	Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations	2013	2430	Journal of Asian Earth Sciences	10.1016/S1367-9120(01)00069-4
12	Landsat-8: Science and product vision for terrestrial global change research	1994	2018	Remote Sensing of Environment	10.1016/j.rse.2014.02.001
13	Evidence for intensification of the global water cycle: Review and synthesis	2012	1922	Journal of Hydrology	10.1016/j.jhydrol.2005.07.003
14	Monsoon and Enso : Selectively Interactive Systems	2014	1774	Quarterly Journal of the Royal Meteorological Society	10.1002/qj.49711850705
15	Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China	2013	1746	Nature	10.1038/416159a
16	Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and fore-land sedimentation	2012	1720	Earth-Science Reviews	10.1016/j.earscirev.2005.05.004
17	Terrestrial in situ cosmogenic nuclides: Theory and application	2013	1715	Quaternary Science Reviews	10.1016/S0277-3791(00)00171-2
18	The tortoise and the hare II: Relative utility of 21 noncoding chloroplast DNA sequences for phylogenetic analysis	2013	1714	American Journal of Botany	10.3732/ajb.92.1.142
19	Global fatal landslide occurrence from 2004 to 2016	2017	1547	Natural Hazards and Earth System Sciences	10.5194/nhess-18-2161-2018
20	The origin and pre-Cenozoic evolution of the Tibetan Plateau	2005	1459	Gondwana Research	10.1016/j.gr.2012.02.002

Tab. 6 - Top 20 most cited articles along with their doi, publication year and journal name.

Among the standardized keywords, climate change was the most frequently occurring term, followed by Tibetan Plateau, Himalaya, remote sensing, glacier and precipitation. The strong position of these keywords indicates

tation. The strong position of these keywords indicates that climate variability and its effects on the cryosphere constitute a major research focus within the HKH literature.

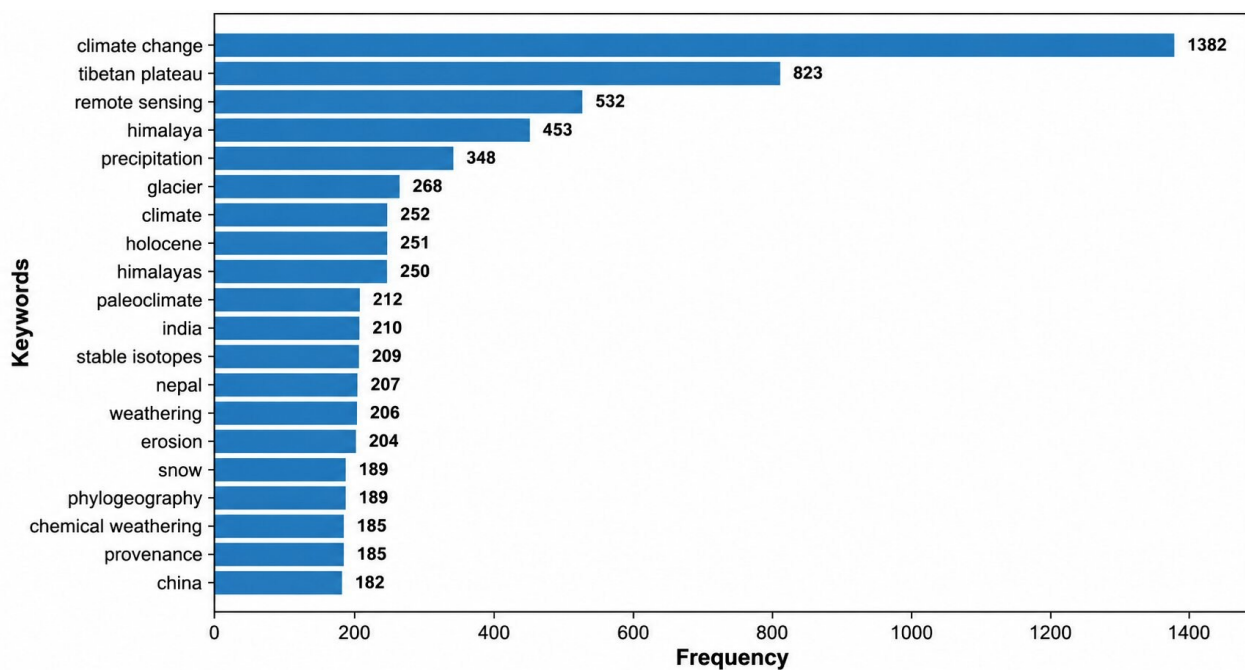


Fig. 8 - Top 20 most repeated keywords with their frequency.

ture.

The central position of climate change is particularly evident from its strong associations with several major research themes. It co-occurred frequently with Tibetan Plateau, glacier, Himalaya, remote sensing, water resources, Nepal, precipitation and temperature. This pattern demonstrates that climate change research in the HKH is not confined to glacier response alone but is closely connected with regional climate processes, hydrological systems, water availability and spatial observation of environmental change. A prominent glacier-climate-remote sensing grouping is visible in the network. Keywords such as glacier, glacier mapping, glacier mass balance, remote sensing, GIS, snow, and cryosphere are closely interconnected. The strong association between GIS and remote sensing further demonstrates the importance of geospatial and satellite-based techniques in monitoring glaciers and associated cryospheric processes. The occurrence of MODIS with snow cover also reflects the use of satellite observations for monitoring snow and glacier-related environmental changes.

Another important component of the network is the hydrology and water-resources theme, represented by keywords including precipitation, temperature, hydrology, runoff, streamflow, watershed, water resources, irrigation, SWAT and hydrologic modelling. The particularly strong relationship between precipitation and temperature indicates that climatic variables are frequently investigated together in studies of hydrological variability. Their connections with runoff, snow cover and water resources demonstrate the importance of glacier and

snow dynamics for understanding downstream hydrological processes in the HKH.

The palaeoclimate and monsoon component forms another clearly recognizable thematic group. Tibetan Plateau, Holocene, paleoclimate, stable isotopes, monsoon, pollen and paleoenvironment are closely associated within the network. The prominent position of the Tibetan Plateau and its connections with Holocene and palaeoclimate research indicate that the HKH literature also places substantial emphasis on reconstructing past climatic and environmental variability. The presence of monsoon-related keywords highlights the importance of South Asian and Asian monsoon systems in interpreting climatic and cryospheric changes across the region.

A separate geomorphology and geological processes grouping are represented by geomorphology, erosion, weathering, chemical weathering, geochemistry, provenance, sediment, tectonics and Quaternary. The relationship between geochemistry and provenance, together with the links among erosion, weathering and geomorphology, indicates that glacier-related research in the HKH is closely associated with landscape evolution and sedimentary processes. This component illustrates that the scientific literature extends beyond contemporary glacier monitoring to investigate the geological and geomorphological processes responsible for shaping the high-mountain environment. The network also contains a recognizable biodiversity and conservation component involving keywords such as biodiversity, phylogeography, biogeography, phylogeny, genetic diversity and conservation. Although these key-

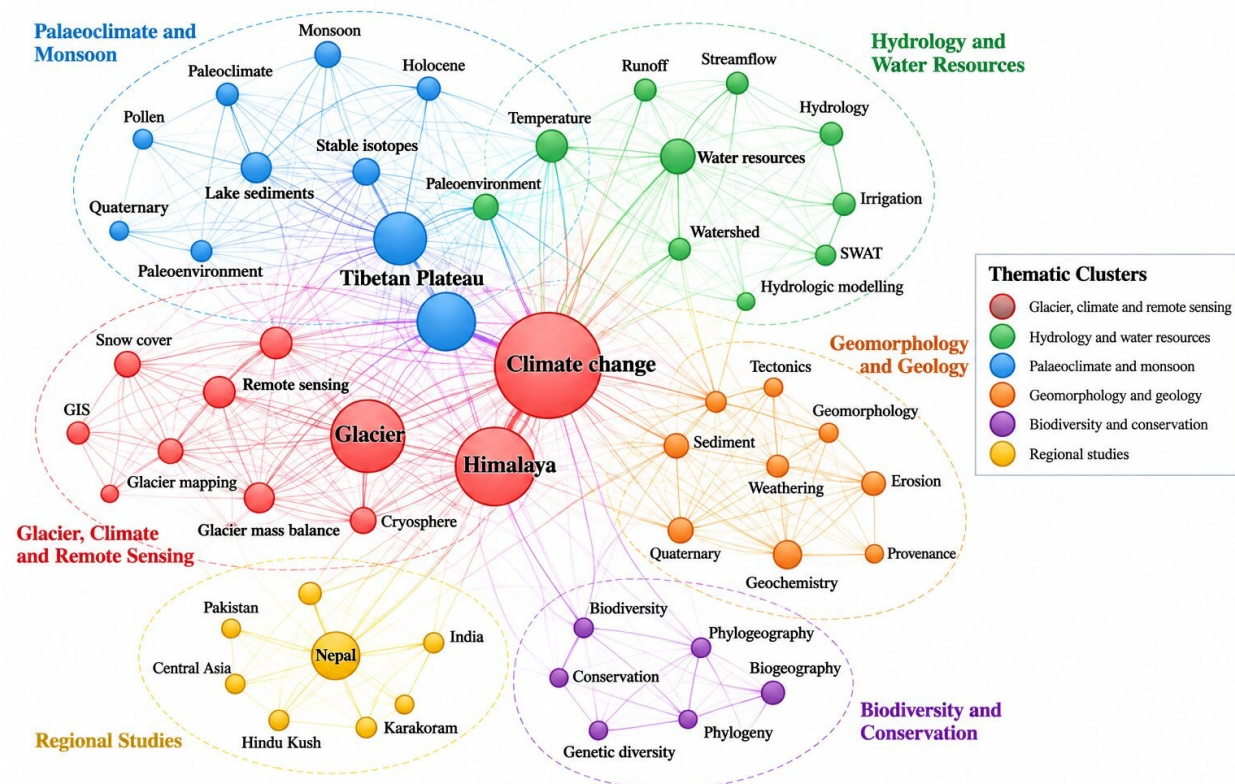


Fig. 9 - Keyword Co-occurrence network.

words are less directly connected to glacier dynamics than the climate and hydrological groups, their presence demonstrates the interdisciplinary nature of HKH mountain research. Glacier and climate-related environmental changes are studied alongside ecological, evolutionary and biodiversity-related processes.

The keyword co-occurrence network demonstrates that HKH glacier research has evolved into a highly interdisciplinary research domain. The network is not dominated by glacier studies alone; instead, glacier-related research is strongly embedded within the broader interactions among climate change, cryosphere, hydrology, remote sensing, palaeoclimate, geomorphology, geology and biodiversity. The central position of climate change and its extensive connections with glacier, Himalaya, Tibetan Plateau, precipitation, remote sensing and water resources particularly indicate that the contemporary research agenda is increasingly focused on understanding glacier change within the wider climate-cryosphere-hydrological system.

4.8. Author collaboration network

Author collaboration analysis (Fig. 10) was carried out to examine the pattern of co-authorship among researchers involved in glacier-related studies in the HKH region. The Authors column of the scopus dataset was used to construct the network in Jupyter Notebook using

Pandas, NumPy, itertools, NetworkX and Matplotlib. The author collaboration network illustrates the major groups of researchers and their collaborative relationships in glacier-related research. Each node represents an author, with larger nodes indicating authors with a greater number of collaborative connections, while connecting lines represent co-authorship links. The network shows eight major collaboration groups, including the Central Collaboration Network, European, Chinese, Indian, North American, Nepalese, Pakistani, and Multidisciplinary research groups.

The Central Collaboration Network forms the largest and most interconnected component, with authors such as Molg T., Chen J., Sakai A., Zhang G., Fujita H., and Shrestha A.B. occupying prominent positions. The European Research Group is strongly centred around Bolch T., with Käab A., Immerzeel W.W., Farinotti D., Berthier E., and Hugonnet R. showing close collaboration. Similarly, the Chinese Research Group is dominated by Yao T., with strong connections involving Shen Y., Li Z., Zhang Y., Wang Y., and Qin Y. The Indian Research Group is mainly centred around Rana P., while Shrestha A.B. represents an important node within the Nepalese group. Other relatively distinct clusters are observed for North American, Pakistani, and multidisciplinary research groups.

Overall, the network indicates that glacier research

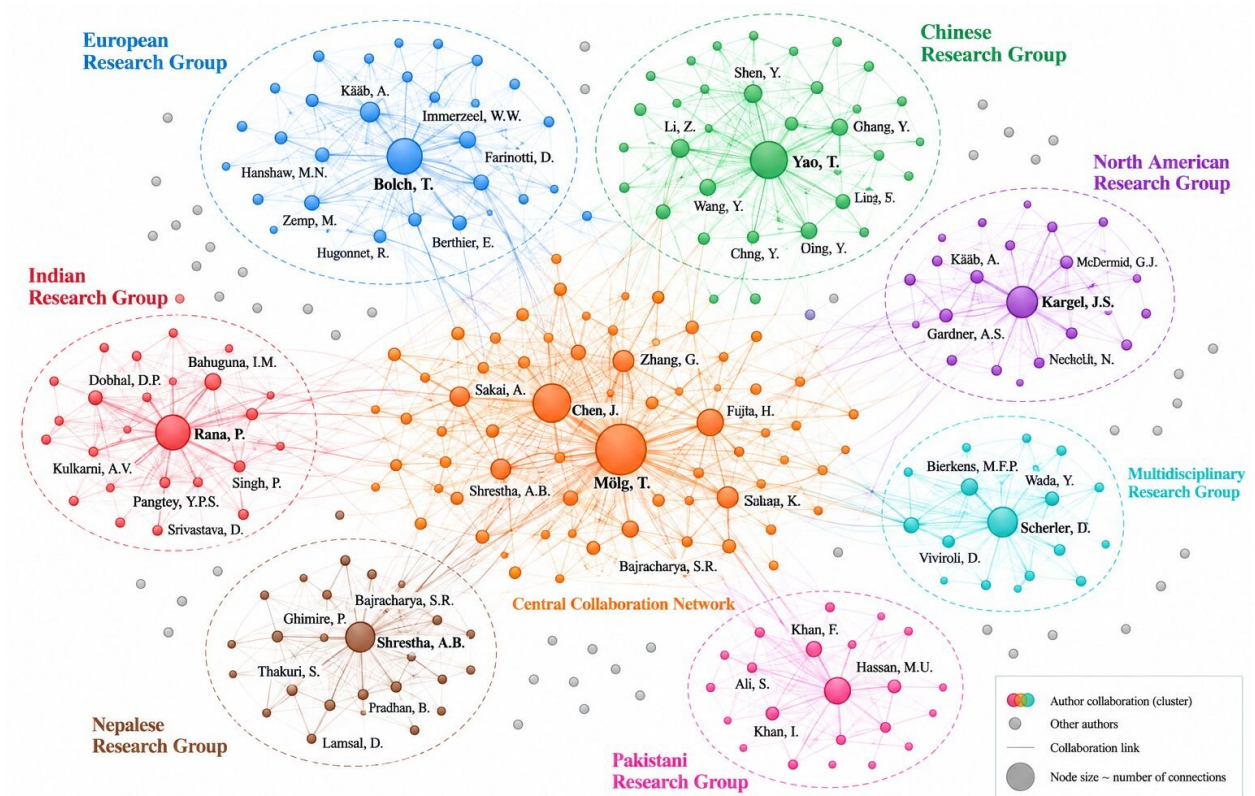


Fig. 10 - Author collaboration network.

is characterized by strong regional collaboration as well as substantial international linkages. The large central cluster and several highly connected authors suggest that a relatively small number of researchers play an important role in linking different research groups. At the same time, the presence of separate regional clusters indicates that collaboration remains partly geographically structured. This pattern highlights the development of an increasingly interconnected international research community in glacier studies.

5. CONCLUSION

This study provides a bibliometric assessment of glacier-related research in the Hindu Kush Himalaya (HKH) region and examines the major patterns in scientific production, collaboration, and research themes over the period 1980–2020. The results indicate a substantial increase in scientific production during the study period. During the earlier period (1980–1995), glacier-related research was comparatively limited and was primarily associated with field-based observations and empirical modelling. With the increasing availability of satellite observations and advances in remote-sensing and geospatial technologies, the scope of glacier research subsequently expanded, particularly after the mid-1990s. This development enabled more extensive investigation

of glacier dynamics and environmental changes across the geographically complex and relatively inaccessible HKH region.

The bibliometric analysis also indicates a strong contribution from Chinese researchers and institutions. More than half of the 20 most productive authors identified in the analysis were affiliated with China, while Chinese institutions also occupied a substantial proportion of the leading institutional positions. The author collaboration network further indicates the presence of distinct collaborative clusters, suggesting that research collaboration within the HKH glacier research community is structured around several groups of researchers. These patterns highlight the geographical and institutional concentration of research activity within the literature analysed in this study. The increasing role of remote sensing represents an important methodological development in HKH glacier research. The availability of satellite observations has facilitated regional-scale assessment of glacier extent, surface characteristics, elevation changes, and other cryospheric parameters that are difficult to investigate through field observations alone. The increasing use of these datasets has therefore contributed to the expansion of spatial and temporal coverage in glacier-related research across the HKH.

Overall, the findings demonstrate that HKH glacier research has undergone substantial expansion and

methodological development over the past four decades, accompanied by increasing use of remote-sensing technologies and strong contributions from institutions in several countries. The bibliometric patterns identified in this study provide an overview of the development and structure of the research field and may help identify areas for further investigation, particularly regarding interdisciplinary collaboration, regional representation, and the interaction between glacier dynamics and multiple climatic drivers.

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Code and data can be provided of all the graphs generated by python on request if asked.

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