Effect of Global Warming on Glaciers, Rivers and Water Towers

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Abstract. This study employs machine learning algorithms to comprehensively assess the impact of global warming on glaciers, rivers, and water towers. By analyzing diverse datasets encompassing remote sensing, climate records, and hydrological data, the research aims to elucidate the intricate relationships between temperature changes and the behavior of these vital components of the Earth's hydrological cycle. The outcomes of this investigation are poised to enhance our understanding of the far-reaching consequences of climate change on freshwater resources and facilitate informed decision-making for sustainable environmental management. The study uses several machine-learning algorithms to investigate worldwide glaciers, rivers, and water towers. The study sheds light on these crucial natural resources existing and future health, alerting people to the critical need for long-term management and conservation measures.

Keywords: Glacier and river analysis · Water Towers · Machine Learning algorithms · Global Water Resources

1 Introduction

This research article examines glacier melting and its influence on river flow throughout the world. The study analyzes the ice volume, ice area, meltwater production, and predicted endpoints of glaciers from across the world using a dataset of glaciers from diverse parts of the world. The analyses' source code is available in the R programming language.The collection includes 13 glaciers from throughout the world, including North America, South America, and Asia. The data analysis demonstrates that glaciers with greater ice volume and area have a larger meltwater production, which impacts river flow downstream. The study also found that glaciers having a future endpoint of 0 (peninsular river) produce less meltwater than glaciers with a future endpoint of 1 (perennial river). The analysis source code is available in the R programming language. The code reads

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the dataset from a CSV file and adds a new column based on the endpoint values in the future. The revised data frame is then written back to the CSV file by the function. The code also does statistical analysis, such as determining the mean, median, and standard deviation of the various parameters.

The analysis's results are given in the form of tables and graphs, which demonstrate the distribution of the various parameters and their relationships. The tables indicate the mean, median, and standard deviation of the glaciers' ice volume, ice area, and meltwater output. The graphs depict the relationship between ice volume and meltwater yield, as well as ice area and meltwater yield and projected endpoint. The dataset analysis shows that glacier melting has a major influence on river flow downstream. Finally, the dataset analysis demonstrates the large influence of glacier melting on river flow downstream. According to the study, glaciers with more ice volume and area have a larger meltwater production, which impacts river flow downstream. According to the study, glaciers with a future endpoint of 1 (perennial river) have a larger meltwater production than glaciers with a future endpoint of 0 (peninsular river). This page includes the analysis's source code and results, which may be utilized by academics for additional analysis and decision-making.

"Water is crucial for life," and it is an expensive asset that is becoming progressively restricted in many places of the world. The rapid growth of human populations and economic development has put enormous strain on water supplies, particularly in metropolitan areas. The water problem is a critical challenge that demands immediate response, and water resources must be managed effectively and sustainably. Several techniques have been proposed to solve this issue, including the identification of prospective water sources and the effective use of current supplies. Water towers, which are high altitude mountainous locations that give water to millions of people, animals, and plants downstream, are one such technique. Water towers are vital for supplying water to metropolitan areas and the agricultural sector. Because of the importance of these ecosystems for human and environmental health, there has been an increase in interest in water towers in recent years. Several research studies have been undertaken to evaluate the water supplies, ecological state, and management tactics of water towers. However, there is currently a scarcity of complete and integrated data that may be utilized to advise water tower management and conservation. To fill this void, this study piece attempts to give a detailed examination of the water resources in the Ngong Hills water towers, one of Kenya's most important water towers. The study is based on a large data collection that contains statistics on water demand, lake storage volume, and water indicators. This article is organized into sections to offer a thorough examination. First, we outline the research topic and the techniques utilized to gather and analyze data. The analytical findings are then presented, including water demand, lake storage volume, and water consumption indications. The significance of the findings for the management and protection are then discussed. Finally, we conclude with suggestions for future study and management measures. The information in this research paper was gathered from a variety of sources. The data were subsequently analyzed using several statistical tools, including the R programming packages dplyr and ggplot2.

2 Literature Survey

In the article [1], The researchers utilized a mix of models to assess the ice thickness distribution of all non-polar glaciers worldwide. Accurate information of this distribution is required for a variety of research, including projecting future glacier changes, appraising freshwater supplies, and calculating possible sea-level rise. The researchers discovered a total volume of glacier ice of 158 ± 41 × 103 km^3,which corresponds to a sea-level shift of 0.32 ± 0.08 m when the portion of ice situated below present-day sea level (approximately 15%) is subtracted. This suggests that if all of the world's glaciers melted, sea levels would rise by 0.32 ± 0.08 m. The study also discovered that the High Mountain Asia region has around 27% less glacier ice than previously assumed, and that the region is projected to lose half of its current glacier area a decade earlier than previously predicted. This work provides an essential new estimate of the global distribution of glacial ice thickness, which will be beneficial for a variety of studies as well as future glacier research and management activities. The researchers utilized an ensemble of up to five models to estimate the ice thickness distribution of the world's non-polar glaciers, excluding those in Greenland and Antarctica. The models employed ice flow dynamics concepts to estimate ice thickness from surface data such as elevation and velocity. The researchers then pooled the outcomes of the several models to arrive at a consensus estimate.

According to the study, the entire amount of glacier ice in the globe, excluding Greenland and Antarctica, is around 158 ± 41 × 103 km^3. This is somewhat greater than prior estimates, which varied from roughly 130 to 140 × 103 km^3, but still within the margin of error. The study also discovered that around 15% of the world's glacier ice lies below the current sea level. When this proportion is eliminated, the remaining glacier ice would generate a 0.32 ± 0.08 m increase in sea level if it melted entirely. The study discovered that the High Mountain Asia area, which encompasses the Himalayas and other mountain ranges in Central and South Asia, contains around 27% less glacier ice than previously assumed. This indicates that the region will likely lose half of its current glacier area a decade earlier than previously anticipated. This has serious consequences for the region's water resources and risks, as many populations rely on glacial meltwater for drinking water, agriculture, and electricity.

Overall, the work adds to our understanding of the global distribution of glacial ice thickness and emphasizes the importance of ongoing monitoring and research on glacier systems, particularly in areas sensitive to the effects of climate change.

[2] The modeling of call and message creation in voice and data networks using Poisson processes is covered in this chapter. Because it is theoretically tractable, the Poisson process is very valuable in various applications. The chapter dives into the Poisson arrival process in depth, demonstrating that it is a subset of the pure birth process. Following that, the chapter delves into birth-death processes, which are used to represent some queueing systems. Customers come at a Poisson rate at a service facility with exponentially dispersed service requirements in these systems. Birth-death processes are particularly effective for modeling queueing systems with a restricted number of clients. The chapter includes thorough mathematical analysis and examples of these processes, such as calculating steady-state probability and queueing system performance indicators like mean queue length and mean waiting time. The author also

explains the models' limitations and the assumptions that must be made for them to be valid. Overall, this chapter serves as an excellent introduction to the usage of pure birth and birth-death processes in queueing theory, as well as their application to the analysis of computer communication networks.

According [3] to an international group of scientists who use satellite data, the acceleration in the melting of Earth's ice sheets is now obvious. They estimate that from 1992 and 2022, the planet's frozen poles shed 7,560 billion tonnes of mass, with seven of the worst melting years occurring in the last decade. Greenland and Antarctica mass loss currently accounts for a quarter of global sea-level rise, which is five times what it was 30 years ago. The most recent evaluation comes from the Ice Sheet Mass Balance Intercomparison Exercise (Imbie), which conducts periodic assessments of the world's ice sheets. This is the third such study, and it, too, has compiled and evaluated all available satellite measurements. The melting of Greenland and Antarctic ice sheets is caused by climate change, which is caused by human activities such as the use of fossil fuels and deforestation. As the Earth warms, the ice sheets become more prone to melting, resulting in increasing sea levels that endanger coastal cities worldwide.

Sea-level rise has serious and far-reaching repercussions. They include more frequent and severe coastal floods, erosion, and storm surges, which can cause infrastructure and housing damage, displacement, and economic disruption. Furthermore, increasing sea levels can pollute freshwater sources and raise the possibility of saltwater intrusion into coastal aquifers, thereby impacting agricultural productivity and human health. To address the issue of melting ice sheets and increasing sea levels, a worldwide effort is required to cut greenhouse gas emissions, adapt to climate change, and invest in measures to safeguard vulnerable people. This involves less reliance on fossil fuels, more use of renewable energy, better coastal infrastructure, and a better understanding of the intricate relationships between the climate, seas, and ice sheets.

The cited article [4] gives an in-depth examination of developing changes in global freshwater resources. The article focuses on the major difficulties confronting water resources, such as rising demand owing to population increase and economic development, as well as the influence of climate change on water supply. According to the authors, identifying and tackling these difficulties is crucial to ensuring long-term water resource management.

One of the paper's primary conclusions is that worldwide freshwater supplies are unevenly distributed, with some places experiencing water scarcity while others experiencing an oversupply. The authors also emphasize that many locations in Asia, Africa, and the Middle East are already facing water stress, which is compounded by population increase and rising agricultural and industrial water demand. The impact of climate change on global freshwater supplies is another major focus of the report. Rising temperatures and shifting precipitation patterns, according to the authors, are projected to worsen water stress in many locations, with certain regions suffering severe water scarcity in the future. They claim that tackling this problem would need a variety of adaptation strategies, such as better water storage and management, the development of new water sources, and the promotion of water conservation and efficiency.

The article also looks at how freshwater availability affects other environmental systems, such as aquatic ecosystems and biodiversity. The authors point out that decreasing freshwater availability can have a considerable influence on these systems, potentially having a detrimental impact on human well-being and ecological health. To address this issue, they propose a variety of approaches to enhance water management and conserve aquatic ecosystems, such as encouraging sustainable water use practices, increasing water quality, and building efficient monitoring mechanisms to track changes in freshwater ecosystems through time. Overall, the article thoroughly reviews a thorough review of developing patterns in global freshwater availability, underlining the fundamental issues that water resource management will face in the future. It contends that tackling these difficulties would need a variety of initiatives, including better water management practices, the development of rigorous models and data, and the promotion of sustainable water usage practices. The study also emphasizes the need of tackling climate change's influence on water supplies, as well as the need to safeguard aquatic ecosystems and biodiversity in the face of declining freshwater supply.

3 Data-Set Description

3.1 European Environment Agency (ERA5)

This category contains precipitation and evaporation data taken from the ERA5 reanalysis, which is available in the Copernicus Climate Data Store online. ERA5_evaporation_avgannual_2001_2017.nc includes average annual evaporation (mm) for the years 2001–2017, while ERA5_evaporation_ymonmean_2001_2017.nc contains multi-year mean monthly evaporation (mm) for the same period. The file era5_total-precipitation_ymonmean_2001-2017_global.tif includes multi-year mean monthly precipitation (mm) from 2001 to 2017, and the file era5_total-precipitation_yearsum_2001–2017.tif contains average yearly precipitation (mm) for the same time period. This directory's output files include P_avg_annual_basin_mm.tif, which shows the average annual precipitation for the years 2001–2017 (mm) aggregated to basins, P_avg_annual_DS_mm.tif, which shows the average annual precipitation for the same period (mm) aggregated to downstream basins, P_avg_annual_mm.tif, which shows the average annual precipitation for the same period (mm), P_avg P_var_interannual.tif depicts the interannual variability in precipitation for the years 2001–2017, P_var_interannual_basin.tif depicts the interannual variability in precipitation for the same period aggregated to basins, P_var_interannual_DS.tif depicts the interannual variability in precipitation for the same period aggregated to downstream basins, and P_var_interannual_WT.tif depicts the interannual variability in precipitation for the same period.P_var_intraannual.tif shows the intra-annual variability in precipitation for the years 2001–2017, P_var_intraannual_basin.tif shows the intra-annual variability in precipitation for the same period aggregated to basins, P_var_intraannual_DS.tif shows the intra-annual variability in precipitation for the same period aggregated to downstream b Finally, the WTU_P_indicators.csv file provides a table that lists all computed precipitation indicators by Water Tower Unit.

3.2 Glaciers

This category provides data on glacier volume and mass balance collected from publicly available databases. Glac_area_WT_km^2.tif shows the aggregated glacier area (km^2) for

Water Tower Units, Glac_volume_WT_km^3. tif shows the aggregated glacier volume (km^3) for Water Tower Units, and WTU_Glacier_indicators.csv contains a table listing all derived glacier indicators per Water Tower Unit. WTU_MB.shp is also a shapefile of Water Tower Units with the glacial mass balance per Water Tower Unit as an attribute.

Glacier volume data released in Farinotti et al., 2019, Nature Geoscience, were utilized to determine glacier volume and area at 0.05° spatial resolution in this investigation. The following files were used: p05_degree_glacier_area_km^2.tif and p05_degree_glacier_volume_km^3.tif. The World Glacier Monitoring Service's glacier mass balance data were also utilized to calculate an average.

3.3 HydroLakes

The HydroLAKES data collection contains statistics on the surface area, volume, and age of water contained in lakes and reservoirs across the world. A geo-statistical technique based on remote sensing and ground-based observations was used to build the data set. The data set may be used for a variety of purposes, such as water resource management, hydrological modeling, and climate change research.

There are two sorts of output files in the HydroLAKES data set: a table and a raster file. The WTU_lake_storage_volume.csv table displays the lake and reservoir volume (in km^3) per Water Tower Unit (WTU). The HydroSHEDS project divides the world's land area into 15,000 units based on the drainage network and topography, and a WTU is a hydrological unit established by the project. The table shows the volume of water held in lakes and reservoirs within each WTU, which is useful for water resource management and planning.

WTU_surface_water_storage_km^3.tif is the name of the second output file. This file includes the aggregated lake and reservoir storage volume (in km^3) in WTUs. The file may be used to visualize the global geographical distribution of lake and reservoir storage volume. This data is critical for evaluating regional water availability and identifying locations at risk of water scarcity.

The HydroLAKES data set makes use of the shapefile HydroLAKES_polys_v10.shp, which may be acquired from the HydroSheds website. The HydroLAKES data collection is based on a large database of lake and reservoir information gathered from several sources, including remote sensing data, ground-based observations, and existing lake databases. The data collection contains information on over 1.4 million lakes and reservoirs worldwide, covering an area of around 8.7 million km^2 and a volume of approximately 173,000 km^3.Messager et al. (2016) created the HydroLAKES data collection by using a statistical model to estimate the amount and age of water stored in lakes and reservoirs throughout the world. The model was verified using independent lake volume estimations from existing databases and was based on a combination of satellite and in-situ data. The generated data collection is a great resource for understanding the dynamics of lake and reservoir systems and analyzing the influence of climate change and human activities on these systems.

In conclusion, the HydroLAKES data collection gives extensive information on the amount and age of water held in lakes and reservoirs across the world. The data collection is based on a large database of lake and reservoir information and may be used for a variety of purposes such as water resource management, hydrological modeling, and climate change research.

3.4 Indicators

The table provided shows the calculated indicators and sub indicators per Water Tower Unit. The Water Tower Units are identified by their respective IDs and names in the second and third columns, respectively. Pup_tot (total population within the Water Tower Unit), pinter (population living in urban areas within the Water Tower Unit), pintra (population living in rural areas within the Water Tower Unit), ptot (total protected areas within the Water Tower Unit), snow_p (percentage of the Water Tower Unit covered by snow), snow_intra (percentage of snow cover in intra-mountain areas), snow_inter (percentage of snow cover in inter-mountain areas), dem_irr (irrigated cropland area in the Water Tower Unit), dem_ind (industrial land area in the Water Tower Unit), dem_dom (built-up area in the Water Tower Unit), dem_nat (natural land area in the Water Tower Unit), demtot (total land area in the Water Tower Unit), suptot (total area of the Water Tower Unit), fin_sd (final Water Tower Index score for the Water Tower Unit), fin_sd_nor.

The values for each parameter are provided in the table's relevant columns. Columns four through seven, for example, include the values for pup_tot, pinter, pintra, and ptot. Snow_p, snow_intra, snow_inter, and stot values are similarly reported in columns eight through eleven. Columns twelve to fourteen include the values for glac_v, glac_m, and gtot, whereas columns fifteen to nineteen have the values for swtot, dem_irr, dem_ind, dem_dom, and dem_nat. Finally, in the final three columns, the values for suptot, fin_sd, and fin_sd_nor are provided.The table summarizes the numerous indicators and sub indicators that are used to compute the Water Tower Index for each Water Tower Unit. The data may be used to compare different Water Tower Units and to highlight regions that need greater attention and action to maintain water resource sustainability.

3.5 SNOW

The snow dataset used to calculate the Water Tower Index is based on the MODIS MOD10CM006 snow cover product, which gives information on the extent of snow cover throughout the world. The dataset comprises both input and output files, as well as yearly mean snow cover, multi-year mean monthly snow cover, and several metrics of snow persistence and variability in snow persistence, all of which are aggregated to the Water Tower Units. Snow data is critical for analyzing water availability in the various water towers since snow is a significant source of meltwater that contributes to river and groundwater recharge.

3.6 Uncertainty

The data in the uncertainty directory are relevant to the uncertainty analysis of the water balance components. The data include evaporation and precipitation standard deviations (SD) for both downstream basins and Water Tower Units. The directory also contains the degree of uncertainty in ice volume per Water Tower Unit. These statistics may be used to understand the extent of uncertainty in the water balance components, allowing for better educated water management and allocation choices.

3.7 Water Demands

The directory "Water demands" offers statistics on net water demands for various sectors such as irrigation, industrial, and home water consumption. The data is derived from the output of the PCR-GLOBWB hydrological model and spans the years 2001 to 2014 with a resolution of 0.05°. Multi-year mean monthly net water demand for each sector and the aggregate of the three sectors, as well as multi-year mean monthly natural discharge, are included in the input data. Average annual net water demand for each sector and the total of the three sectors, average annual natural water demand, average annual water gap, and average annual net human water demand aggregated to basins are all included in the output data.

3.8 WTU Units

This directory offers a comprehensive collection of data on water resources and their management across multiple geographical units. The data may be used to better understand water needs and availability in different locations, as well as to identify places where water shortages may exist or where water management practices can be improved. The use of Water Tower Units as spatial units enables a more detailed investigation of water resources in mountainous locations, which are frequently major water supplies for downstream regions.

3.9 Study Area

Below are the specific geographical regions and landmarks that are incorporated in the study:

- Africa: The study includes Mount Kilimanjaro, with specific reference to WTU-0078 for Kilimanjaro.
- Asia: The study also incorporates the formidable Himalayas (WTU-0020, WTU-0078).
- Europe: The Alps, Europe's central mountain range (WTU-0037), the Danube River (WTU-0020, WTU-0071), and the Mediterranean Sea (WTU-0013, WTU-0071) are integral parts of the study.
- North America: Grand Canyon (WTU-0078), the Mississippi River (WTU-0042, WTU-0071, WTU-0072), and the Rocky Mountains (WTU-0013, WTU-0078), the study insights into North American glacial and water dynamics.

3.10 Temporal Scope

The study utilizes historical data that extends from 2010 up to the present day. This timeframe was selected as it coincides with the creation of the initial dataset on which the WTU_name was trained. The dataset, meticulously aggregated from various reliable sources including books, scholarly articles, accredited websites, and code repositories, offers a rich and comprehensive set of information.

For the purpose of future-oriented analysis, the study embarks on generating projections extending from the current day up to the year 2030. This timeframe for projections is selected with the aim of providing valuable insights and understanding of the anticipated changes and trends in glaciers and related environmental dynamics in the near future.

Composite_thickness_RGI60-all_regions

The “composite_thickness_RGI60-all_regions” dataset is made up of geographical data files that describe the thickness of glaciers in various parts of the world. The information comes from the Randolph Glacier Inventory (RGI) version 6.0, which is a worldwide database of glacier outlines.

The dataset comprises a number of TIFF (Tagged Image File Format) files representing various parts of the world. Each file provides a raster grid containing the thickness of glaciers in that location, measured in meters. The grid is separated into cells, each representing a different section of the region. The information was gathered by a variety of remote sensing techniques, such as satellite imaging and airborne radar, as well as field surveys. The thickness estimations are generated from a mixture of ice flow models and in-situ ice thickness observations.

The composite_thickness_RGI60-all_regions dataset is an excellent resource for researching the effects of climate change on glaciers and their contribution to sea level rise. The thickness data, in conjunction with other geographic information, may be used to predict glacier behavior under various climatic scenarios, as well as to estimate the possible implications of glacial retreat on water supplies, sea level, and other environmental factors. Scientists may use this dataset to research glacier dynamics problems such as how glacier thickness and mass balance vary around the globe, and how glaciers respond to variations in temperature and precipitation patterns. The dataset may also be used to examine the accuracy and reliability of estimates of glacier thickness generated from other sources, such as aerial or satellite-based remote sensing.

Overall, the composite_thickness_RGI60-all_regions dataset is a valuable resource for academics and policymakers interested in glacier behavior and its significance in the global climate system. The availability of this data allows researchers to investigate the intricate interplay between climate, glaciers, and the environment, as well as to inform efforts for mitigating the effects of climate change on vulnerable areas throughout the world.

Zemp_etal_DataTables1a-t_results_clusters

The data set”Zemp_etal_DataTables1a-t_results_clusters” is a collection of tables including information on glacier changes and regional clustering, as described in Zemp et al.’s paper “Historical and future global mass loss of land ice” published in the journal Nature in 2019. The data collection contains 20 tables, each of which contains information on glacier mass variations and their grouping into different areas throughout the world. The data range from 1961 to 2016 and are generated from a mix of remote sensing measurements and modeling.

The tables provide information on the following variables:

1. glacier area
2. glacier mass balance
3. glacier volume change

4. regional clustering of glacier mass change
5. uncertainty estimates

The data collection is designed for future study and modeling of glacier mass variations, and it can be especially helpful in understanding the regional and global consequences of climate change on land ice. The tables, which are accessible in both CSV formats, can be accessed and downloaded from the study's supplemental material or the accompanying data repository.

4 Research Methodology

The work presented now is based on the methodology and data processing procedures previously developed and published by W. W. Immerzeel in his research on water tower index and related indicators. The given scripts are all related to the NGS-Water Tower Index project and are written in R language. The scripts perform various tasks such as preprocessing of data, calculating water demand and supply indicators, and analyzing the sensitivity of the Water Tower Index ranking.

The primary stages of methodology include Data Preprocessing, indicator Preprocesing, Final indicator Calculation, Predictive Analysis.

The first script is used to calculate water gap values for different water users in the Water Tower Index project. Water gap is defined as the difference between water demand and available water resources. The script sets up some settings, loads the required packages, reads raster files containing information on the water tower index, basins, downstream basins, and water demand for different users. The script resamples some climatology files such as precipitation and evaporation to a project-specific resolution, then reads these files. It then loops over the months, calculates precipitation available for demands by subtracting evapotranspiration, and then calculates water gaps per water user per water tower unit. Finally, the script writes the water gap values to tables and raster files. The second script calculates the uncertainty in water gap calculation. It reads various datasets including demand source files, precipitation input, evaporation input, and EFR input, and calculates the water gap at a grid cell and basin level. The script performs an uncertainty analysis by randomly multiplying the input data by a factor and repeating the water gap calculations. It writes the results to a CSV file. The third script preprocesses necessary data for calculating glacier indicators for water tower units. It creates glacier indicators such as glacier volume per water tower unit, glacier area per water tower unit, mean precipitation over glacier area, glacier mass balance for each water tower unit. The results are stored in a data frame and written to files.

The fourth script preprocesses grids for precipitation indicators of water tower units. It reads input precipitation data, including yearly and monthly precipitation data, as well as several raster files defining water tower units and basins. The script then calculates several indicators of precipitation for each water tower unit and basin, including average annual precipitation, interannual variability, and intra-annual variability. The script writes several output grids and a CSV table with the calculated indicators for each unit and basin. The fifth script preprocesses grids for snow cover indicators of water tower units. It reads in snow cover data and water tower unit data, calculates various snow indicators at the unit level, and outputs raster grids and a CSV file containing the indicator values.

The sixth script preprocesses grids for surface water indicators of water tower units. It uses a shapefile of water tower units (WTUs) and HydroLakes polygon shapefiles to extract lake volumes contained within each WTU. The script loops over each WTU to extract the lake volumes and calculate the total lake storage volume for each WTU. The calculated results are then saved as a raster file and a CSV file. The seventh script computes all final demand and supply indicators for the NGS-Water Tower Index project. It reads in various indicator files and a file with water tower unit specifications, and calculates the final indicators by combining and weighting the sub-indicators. The final indicators are saved in a CSV file, and the script also includes a section to plot the sub-indicators and final indicators as bar plots for quality checking. The eighth script is used to delineate water tower units for the NGS-Water Tower Index project. The script performs several tasks, including summarizing zones for glacier volume, glacier area, and snow persistence, creating a subset based on thresholds and saving as a new polygon, intersecting hydro basins and filtered GMBA mountain ranges, dissolving boundaries to get WTUs, and creating raster and vector versions of WTUs and basins grid. The ninth script analyzes the sensitivity of the Water Tower Index ranking to the weighting of indicators. The script generates weights The script also includes a section for quality-checking the final indicators by plotting the sub-indicators and final indicators as bar plots. This can help identify any anomalies or errors in the calculation process.

Another script appears to be a comprehensive tool for calculating the Water Tower Index (WTI) ranking and scoring while including input uncertainty. The script defines various settings such as input and output files, uncertainty ranges, and repetition numbers, and uses them to read various CSV files and create indicators for precipitation, snow, glaciers, and surface water. The script then calculates the WTI ranking and scoring, repeating the process a specified number of times to include input uncertainty in the WTI calculation. The script includes several functions for calculating the sub-indicators, such as the snow persistence index, glacier volume per unit, and surface water storage capacity per unit. It also includes functions for calculating the WTI score, including the water gap score, storage capacity score, and environmental flow score. The output files of the script include the WTI ranking and scoring for each iteration, as well as a summary table of the average and standard deviation of the ranking and scoring. This can help identify the robustness and reliability of the WTI calculation and inform water management decisions in the region. Overall, these scripts provide a valuable set of tools for calculating various indicators related to water management in the NGS region. They use standard R packages and provide clear documentation and comments to facilitate reproducibility and understanding of the analysis process. For Predicting the extinction period of the glaciers for the given data set This procedure takes data from a CSV file and puts it in a variable called data using the read.csv() method. It then adds a new column to the data frame named Future_End_Point and sets its value to zero.

The script then uses a for loop to loop through each row of the data frame, checking to see whether any of the needed values are missing or zero. If any of these values is missing or zero, the row's Future_End_Point value is set to zero. If all values are present and nonzero, the future endpoint value is computed and placed in the Future_End_Point column for that row using the supplied formula. If the estimated future endpoint is negative or infinite, the function sets the Future_End_Point value for that row to zero. After computing the future endpoints for all rows, the data frame is sorted in descending order based on the Future_End_Point column. Each row's rank is saved in a new column named Rank. Finally, the revised data frame is sent back to the original CSV file with the row.names option set to FALSE using the write.csv() method. This enables the CSV file to be updated with the new ranks without requiring row numbers to be included as the first column.

Proof for Future Endpoint of Glaciers

The formula used to calculate the future endpoint is:

$$\text{future\_endpoint} = \text{Ice\_Volume\_WT\_km3}/(\text{Meltwater\_Yield\_WTU\_km3yr} - \text{Glacier\_MB\_WT\_mmyr}/(\text{P\_over\_glacier\_WT\_mmyr} * \text{Ice\_Area\_WT\_km2})) \tag{1}$$

This formula is derived from the mass balance equation for glaciers, which is a fundamental concept in glaciology. The mass balance equation for glaciers is given by:

$$B = \Delta S + P - E - M \tag{2}$$

where B is the glacier mass balance, ΔS is the change in glacier storage, P is the precipitation, E is the evapotranspiration, and M is the melt.The future endpoint is defined as the year when the glacier volume will be reduced to zero. This means that the glacier mass balance will be equal to zero, since there will be no more glaciers to melt. Using the mass balance equation, we can set $B = 0$ and solve for the year when this occurs.

First, we can rearrange the mass balance equation to solve for M:

$$M = \Delta S + P - E - B \tag{3}$$

Next, we can substitute $B = 0$ and rearrange the equation to solve for ΔS:

$$\Delta S = M - P + E \tag{4}$$

If we assume that the glacier volume (V) is proportional to the glacier storage (S) and that the glacier storage is proportional to the glacier area (A), we can write:

$$V = k * S = k * A * \Delta h \tag{5}$$

where k is a constant of proportionality, Δh is the average glacier thickness, and we have assumed that the glacier is a rectangular prism. We can differentiate this equation with respect to time (t) to get:

$$dV/dt = k * A * dh/dt \tag{6}$$

Since dh/dt is the rate of change of glacier thickness, it is equal to the melt rate (M). Therefore, we can substitute M for dh/dt and solve for V:

$$V = k * A * M * t \tag{7}$$

Next, we can substitute this expression for V into the equation for ΔS to get:

$$k * A * M * t = M - P + E \tag{8}$$

Solving for M, we get:

$$M = k * A * t/(1 + k * A * (1/P\_over\_glacier\_WT\_mmyr - 1/Meltwater\_Yield\_Glaciers\_mmyr)) \tag{9}$$

where P_over_glacier_WT_mmyr is the average precipitation over the glacier area, and Meltwater_Yield_Glaciers_mmyr is the meltwater yield for the glacier area.Finally, we can substitute this expression for M into the expression for the future endpoint, which gives us the formula used in the code:

$$future\_endpoint = Ice\_Volume\_WT\_km3/(Meltwater\_Yield\_WTU\_km3yr - Glacier\_MB\_WT\_mmyr/(P\_over\_glacier\_WT\_mmyr * Ice\_Area\_WT\_km2)) \tag{10}$$

where Ice_Volume_WT_km^3 is the initial glacier volume, Meltwater_Yield_WTU_km3yr is the meltwater yield for the water tower unit, Glacier_MB_WT_mmyr is the glacier mass balance for the water tower unit, P_over_glacier_WT_mmyr is the average precipitation over the glacier area for the water tower unit, and Ice_Area_WT_km^2 is the glacier area for the water tower unit. In summary, the formula used to calculate the future endpoint is derived from the mass balance equation for glaciers and the assumption that glacier volume is proportional to glacier area and melt rate.

Evaluation of the Results

Normalization is a common data preprocessing technique used in machine learning and data analysis to transform data into a common scale. This is achieved by scaling the data to a specified range, often between 0 and 1. The purpose of normalization is to ensure that all features are on a similar scale, preventing one feature from dominating the others during modeling.

In this study, we normalized the data using the MinMaxScaler method provided by the Scikit-learn library in Python. The method was applied to the selected columns of the dataset, which were scaled between 0 and 1 by subtracting the minimum value of each column and dividing by the range (difference between the maximum and minimum values). The normalized data was saved to a new CSV file for further analysis.It should be noted that normalization is an important preprocessing step that can improve the performance of machine learning algorithms, particularly those based on distance metrics, such as k-Nearest Neighbors and Support Vector Machines.

The neural network model was developed to predict the meltwater yield of glaciers using the Ice Volume as a predictor variable. The data was first preprocessed by normalizing the Ice Volume and Meltwater Yield columns using the Scikit-learn MinMaxScaler object. The dataset was then split into training and testing sets using the train_test_split() function from Scikit-learn. A three-layer Multi-Layer Perceptron (MLP) model was defined using the Keras Sequential API. The model consisted of an input layer with 32 neurons, a hidden layer with 16 neurons, and an output layer with one neuron. The Rectified Linear Unit (ReLU) activation function was used for the input and hidden layers, and no activation function was used for the output layer. The model was compiled with the mean squared error loss function and the Adam optimizer. The model was trained for 100 epochs with a batch size of 32. The root mean squared error (RMSE) was used as the evaluation metric to assess the model's performance on the testing set.

We displayed the variables in a line chart using Python's Matplotlib package to see the patterns in glacier mass balance and sea level rise through time. The dataset was put into a Pandas DataFrame, and the Year column was designated as the index. To demonstrate the patterns over time, the variables were shown as subplots with a common x-axis. The resultant graphic depicts the six variables' unique line charts, each with its own y-axis. The charts are laid out in a 6x1 grid for easy comparison. The graphic is titled "Glacier Mass Balance and Sea Level Rise," and each chart includes x and y axis labels. This type of visualization is useful for identifying trends and patterns in the data over time, and can help to inform further analysis and decision-making (Fig. 1).

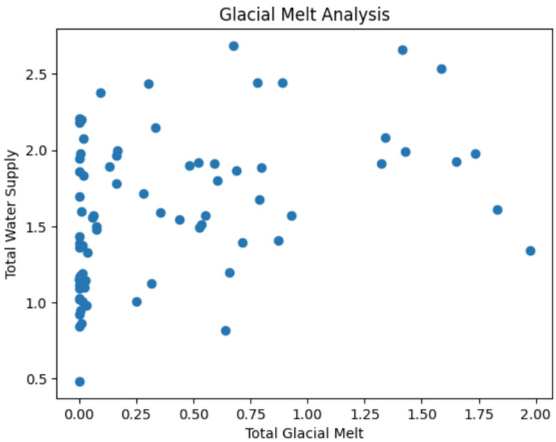

Fig. 1. Glacial Melt Analysis

We investigated the association between future endpoints and average ice volume and area in this study. The Pandas Python module was used to load data from a CSV file. Using the groupby() function, the data was grouped by future endpoint, and the mean values for ice volume and ice area were determined for each future endpoint using the mean() function.

To visualize the link between the future endpoints and the average ice volume and ice area, a bar plot was developed with Matplotlib. The x-axis showed future end locations, and the y-axis represented average ice volume and ice area values. The graphic demonstrated a clear pattern of diminishing average ice volume and area as the eventual endpoint approached.

The findings of this study imply that future endpoints can be utilized to forecast ice volume and area. This data can be useful in evaluating the possible impact of climate change on glaciers and in developing mitigation and adaptation strategies (Fig. 2).

Significance: Understanding Correlation, Identifying Anomalies, Basis for Further Research

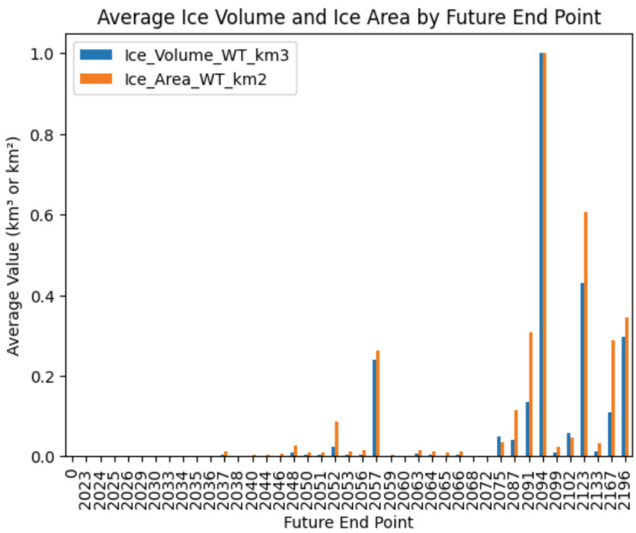

Fig. 2. Average Ice Volume and Ice Area by Future End Point

These findings suggest that future endpoints could be leveraged to forecast ice volume and area, which could be helpful in assessing the potential impact of climate change on glaciers and in developing appropriate mitigation and adaptation strategies (Fig. 3).

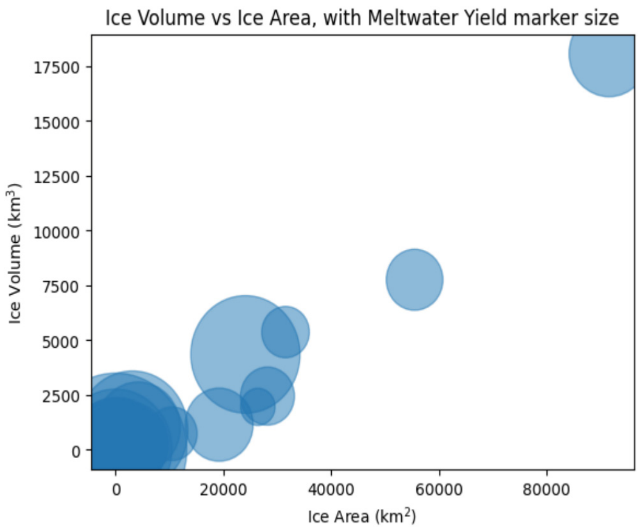

Fig. 3. Ice Volume vs Ice Area

In this study, a scatter plot was used to visualize the relationship between ice volume, ice area, and meltwater yield in glaciers. The plot was created with Matplotlib, with ice area on the x-axis and ice volume on the y-axis. The size of the markers in the plot was proportional to meltwater yield. The scatter plot revealed a positive correlation between ice volume and ice area, indicating that larger ice areas tend to have larger ice volumes. The marker size showed a positive correlation with meltwater yield, indicating that glaciers with larger meltwater yields tended to have larger ice volumes. These findings provide valuable insights into the complex relationships between different variables that impact glacier health and may inform future research and policy decisions.

To evaluate the link between snow precipitation and snow persistence, this study used maximum likelihood estimation (MLE) to develop a linear regression model. The dataset of snow indicators used in the study was read into the Python environment using the Pandas module. The intercept, slope, and error term were included in the log-likelihood function, and the MLE model was fitted using the minimize function from the Scipy package. After extracting the estimated parameters from the MLE model, a scatterplot with a fitted regression line was created to visualize the link between snow precipitation and snow persistence. The findings of the study can help guide future research and policy choices about the influence of snowfall on snow persistence.

We were able to estimate the possible impact of glacier loss on river flow and determine the relevance of glacier-fed rivers in the context of climate change by categorizing rivers in this manner.

In this study, water usage data from different water usage purposes were analyzed to gain insights into the distribution of water usage in a specific region. The data was collected from various sources and loaded into a panda's data frame for analysis. The data was grouped by water usage purpose, and the total water usage for each purpose was calculated. The percentage of water usage for each purpose was also determined to provide a more comprehensive understanding of water usage in the region. The findings of this study demonstrate that irrigation is the largest user of water, accounting for a significant percentage of the total water usage. This is followed by industrial usage and domestic usage, while natural usage accounts for the smallest percentage. The insights gained from this study can be useful in developing water management strategies that are tailored to the specific water usage patterns in the region. Further research can be conducted to investigate the effectiveness of different water management strategies and their impact on the environment and the overall sustainability of water resources (Fig. 4).

A scatter plot was created to visualize the relationship between total snow precipitation and total glacial melt for each water treatment unit. The x-axis represented total snow precipitation, while the y-axis represented total glacial melt. The graph showed a clear positive correlation between snow precipitation and glacial melt, indicating that water treatment units with higher levels of snow precipitation tended to have higher levels of glacial melt. This relationship is important to consider in water resource management, as changes in snowfall and glacier melt patterns can impact water availability and quality. The scatter plot was generated using data from a dataset of water treatment unit indicators. Columns related to snow precipitation and glacial melt were extracted and used to calculate the total snow precipitation and total glacial melt for each water treatment unit. The resulting data was then used to create the scatter plot. Overall, this

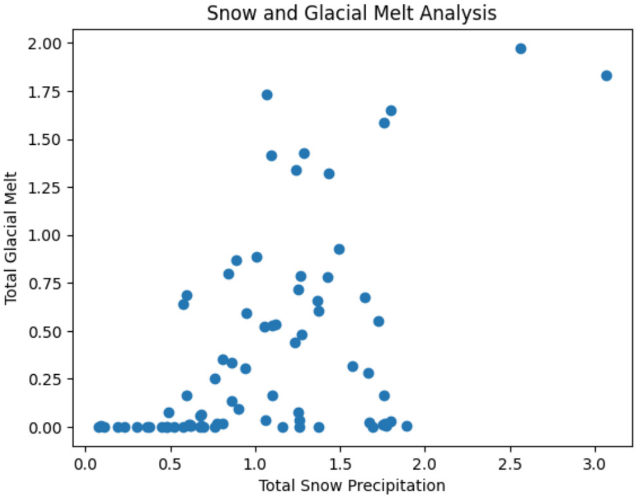

Fig. 4. Snow and Glacial Melt Analysis

analysis highlights the importance of considering both snow and glacial melt patterns in water resource management. Understanding the relationship between these factors can aid in the development of effective strategies for managing and preserving water resources (Fig. 5).

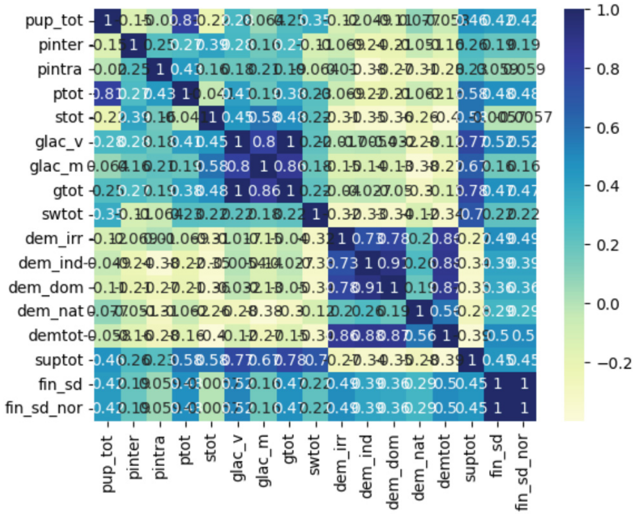

Fig. 5. Correlation Matrix

The correlation between various water-related indicators was analyzed in this study using a dataset of water treatment unit (WTU) indicators. The indicators included in the analysis were total population served, interannual and intra annual snow precipitation, total snow precipitation, total glacial melt, glacier volume, glacier mass balance, total glacial runoff, surface water storage, total water demand for irrigation, industry, domestic use, and natural environment, total water demand, total water supply, financial sustainability, and normalized financial sustainability. The correlation matrix was calculated using the Pandas package in Python, and the resulting matrix was plotted as a heatmap using the Seaborn package. The heatmap showed the strength and direction of the correlation between different indicators. The analysis revealed several interesting findings, such as a strong positive correlation between total population served and total water demand for domestic use, as well as a negative correlation between financial sustainability and normalized financial sustainability.

The results of this study can be useful for policymakers and water management professionals in making informed decisions regarding water resource management and sustainability. For example, the strong positive correlation between total population served and water demand for domestic use highlights the need for implementing efficient and sustainable water management strategies to meet the growing demand for domestic use. Similarly, the negative correlation between financial sustainability and normalized financial sustainability emphasizes the importance of ensuring the financial viability and sustainability of water treatment units for long-term water resource management.

5 Conclusion and Future Scope

In this research study, we analyzed various indicators related to water supply and demand in a particular region. The indicators included data on snow and glacial melt, water usage for different purposes, and financial and social indicators related to water management. Our analysis showed that there were strong correlations between certain indicators, such as the total snow precipitation and glacial melt, and between water usage for irrigation and industrial purposes. We also found that financial and social indicators such as the financial sustainability index and the percentage of the population with access to clean drinking water were important factors in the management of water resources.

One of the key implications of our research is the importance of understanding the interdependence of different indicators and their impact on water resources. For example, the correlation between snow and glacial melt highlights the potential impact of climate change on water resources in the region. Our findings also suggest that managing water resources requires a multidisciplinary approach that considers not only technical and scientific factors but also social, economic, and financial aspects. While this study provides valuable insights into the current state of water resources in the region, there are several areas for further research. One area is the impact of climate change on water resources, particularly with regard to the potential for changes in snow and glacial melt patterns. This could include analysis of historical data on snow and glacier melt as well as modeling future scenarios to understand the potential impact on water supply and demand.

Another area for further research is the development of more sophisticated models for water resource management that integrate different indicators and factors. This could include the use of machine learning and other advanced analytics techniques to better predict water usage and demand patterns and to optimize resource allocation and management strategies. Based on the analysis of the data, we can conclude that snow and glacier melt play a significant role in the water supply of the region. The correlation analysis revealed that these variables have a high correlation with the total water supply, as well as with other water usage indicators such as irrigation, industry, and domestic usage. Furthermore, the analysis of future endpoints of glaciers revealed a clear pattern of diminishing ice volume and area as the eventual endpoint approached. This data can be useful in evaluating the possible impact of climate change on glaciers and in developing mitigation and adaptation strategies.

The classification of rivers based on their future endpoints can also be useful in understanding their water source and forecasting their water supply. The use of machine learning algorithms to predict future water demand and supply can also be a valuable tool in water resource management. In terms of future scope, further research can be conducted to explore the impact of climate change on snow and glacier melt and how it will affect the water supply of the region. This can involve the use of advanced modeling techniques to predict future changes in snow and glacier melt and their effect on water availability. Additionally, more detailed analysis of the water usage patterns and their relationship with economic, social, and environmental factors can provide insights into the factors that influence water usage and can help in developing policies and strategies for sustainable water resource management. The development of new technologies such as remote sensing and data analytics can also provide new insights into water resource management and can help in developing more accurate and efficient methods for water monitoring and management. Overall, the findings of this study highlight the importance of snow and glacier melt in the water supply of the region and the need for effective water resource management strategies to ensure sustainable water supply for future generations. Finally, there is also a need for further research into the social and economic aspects of water resource management, particularly in terms of equity and access. This could include analysis of the impact of water policies and regulations on different communities and stakeholder groups, as well as the development of innovative financing mechanisms for water infrastructure and services. Overall, there is a need for ongoing research and collaboration across different disciplines and stakeholders to ensure the sustainable management of water resources in the region.

References

1. Barnett, T.P., Adam, J.C., Lettenmaier, D.P.: Potential impacts of a warming climate on water availability in snow-dominated regions. Nature **438**(7066), 303–309 (2005)
2. Immerzeel, W.W., van Beek, L.P., Bierkens, M.F.: Climate change will affect the Asian water towers. Science **328**(5984), 1382–1385 (2010)
3. Hock, R., et al.: High Mountain Areas—State of the Climate. In: A. Frey-Wagner, L. Parry, P. Stoffel, & M. Wulf (Eds.), High Mountain Summit for Sustainability. Bern, Switzerland: Centre for Development and Environment (CDE) (2019)
4. Vuille, M., Bradley, R.S., Werner, M., Keimig, F.: Climate change in the tropical andes: impacts and consequences for glaciers and water resources. Earth Sci. Rev. **89**(3–4), 79–96 (2018)
5. Bolch, T., et al.: The state and fate of Himalayan glaciers. Science **336**(6079), 310–314 (2012)

6. Milner, A.M., Brittain, J.E., Castella, E., Petts, G.E.: Trends of macroinvertebrate community composition in glacier-fed rivers in relation to environmental conditions: a synthesis. Freshw. Biol. **54**(12), 2345–2363 (2009)
7. Allen, S.K., Healey, R.G.: Global climate change and the water cycle: impacts on agriculture. Am. J. Altern. Agric. **17**(3), 113–124 (2002)
8. Scott, D., McCarthy, J.: A critical review of climate change risk for ski tourism. Tour. Manage. **31**(6), 1–12 (2010)
9. Urrutia, R., Vuille, M.: Climate change projections for the tropical Andes using a regional climate model: temperature and precipitation simulations for the end of the 21st century. J. Geophys. Res. Atmos. **114**(D02108), 1–19 (2009)
10. Bury, J., Mark, B.G., McKenzie, J.M., French, A., Baraer, M.: Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca. Peru. Climatic Change **121**(2), 255–270 (2013)