A dendrohydrological analysis for reconstructing river discharge to understand long-term hydrologic variability

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Abstract- Streamflow reconstruction using tree rings is crucial for understanding the long-term hydrological variability, particularly in data-scarce regions like the Upper Indus River Basin (UIRB), in northern Pakistan. This information is essential for managing water resources, assessing climate change impacts, and supporting hydropower generation. Instrumental streamflow records in this region are limited in length, thus emphasizing the need for alternative approaches like dendrohydrology. Besham Qila gauging station is a vital monitoring point of the River Indus as it represents 100% of the UIRB discharge. The objective of the current study was to reconstruct mean annual streamflow for the Besham Qila gauging station, located at the main Indus River, using the regional tree-ring chronologies as predictors in a step wise linear regression model. The analysis successfully explained 63% of the variance in the instrumental discharge. The reconstruction extended the streamflow record to four centuries from the year 1593-1993, and revealed range of hydrologic extremes, encompassing both high and low flow conditions. These findings may have important implications for water resource management of the region and predicting future changes in the river's flow. Future research will focus on integrating tree-ring data with other proxy records to enhance our understanding of hydrological variability and support informed decision-making for water resource management in the UIRB.

Keywords- tree ring chronology, Upper Indus Basin, streamflow reconstruction, Besham Qila

I. INTRODUCTION

Understanding of the long-term hydrologic variability is vital for formulating effective water management policies and mitigating risks associated with water scarcity, flooding, and droughts. This becomes increasingly significant in the context of climate change, which may be altering precipitation patterns and hydrological cycle (Dawadi and Ahmad, 2013; Thakali et al. 2016). Rising population augments this problem (Bailey et al. 2021; Bukhary, 2018; Bukhary, 2024). Thus, historical data for discerning long-term variability becomes essential as a foundation for informed decision-making.

Very short streamflow records present significant challenges in comprehending hydrologic variability. This limitation may hinder accurate predictions of water availability, drought frequency and intensity, and flood risks, particularly, in regions like Upper Indus River Basin (UIRB), where typical instrumental data length is 20-40 years only (Rao et al. 2018). Moreover, without adequate historical data, there is a risk of misinterpreting short-term fluctuations as indicative of broader trends, which can lead to erroneous conclusions in water resource management and climate change assessments. Short records also undermine the development of robust hydrological models essential for predicting future scenarios and informing policy decisions related to water allocation and infrastructure planning. Because current climatic and hydrologic records do not span a sufficient timeframe to fully capture climatic variability and trends, alternative proxy data sources are essential for documenting these changes (Cook et al. 2013). The most utilized proxies include layered ice cores, pollen profiles derived from bog, swamp, or lake sediments, stream geometry and morphology data, and tree rings. While the first three sources generally provide data that extends further back in time than tree rings, they lack precise dating and the ability to preserve high-frequency variations in climatic conditions.

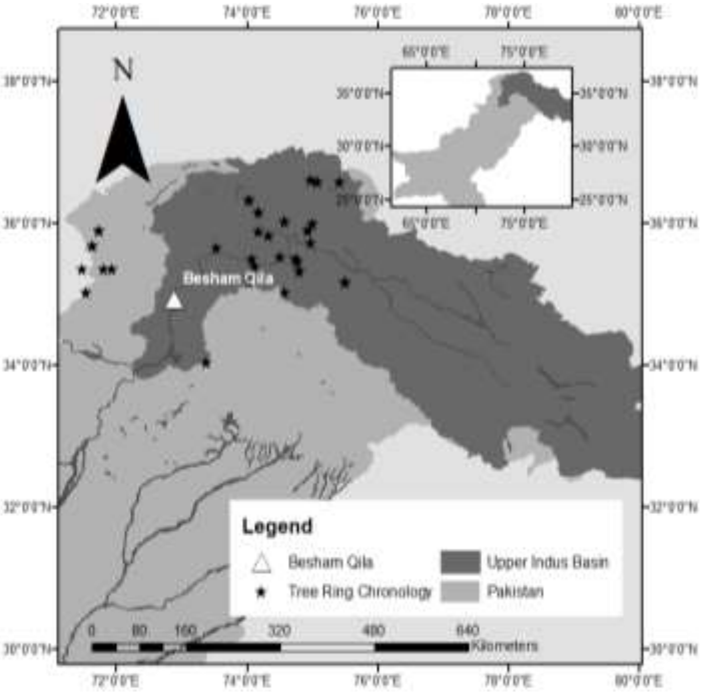

Figure 1: Map of the study area showing the location of the Besham Qila gauging station and the tree ring chronology data used in the current study, located in the Upper Indus River Basin in Northern Pakistan.

Dendrohydrology combines the analysis of tree rings (dendrochronology) with the study of hydro-climatology to investigate past hydrological events. By analyzing the growth rings of trees, researchers in this field can reconstruct historical patterns of streamflow, floods, and droughts, offering insights into long-term hydrological and climatic changes (Galelli et al. 2021). This information is valuable for understanding the impacts of climate change on water resources, identifying trends and anomalies, and informing water management and conservation strategies (Bukhary et al. 2015; Bukhary et al. 2016). Tree ring chronologies (TRC) serve as indirect indicators of past hydrological conditions, providing additional insights into streamflow variability beyond what is captured by direct measurements (Anderson et al. 2012 a&b). In this study, TRC is used as a predictor in a stepwise linear regression model to reconstruct streamflow in Northern Pakistan.

Tree-rings possess several advantageous features as repositories of hydrological information. They are numerous in quantity, spanning many years, and crucially, the information they contain accumulates annually. This annual cumulative nature makes tree-ring data a valuable supplementary source of information for hydrologists. They can be precisely dated to the year of formation and can preserve both high-frequency (short-term) and low-frequency (long-term) variations in climatic patterns. Additionally, samples from tree rings can be replicated extensively, enhancing the reliability and robustness of the data compared to other proxy sources. However, the reliability of hydrological conclusions drawn from such data hinges on the application of rigorous statistical controls to ensure the validity and accuracy of the inferences made. Tree-ring widths are sensitive to climate influences, serving as a natural indicator of past environmental conditions. Long-term reconstructions of temperature, precipitation, and streamflow patterns from tree rings and other proxies reveal that recent climate conditions may not be representative of the broader climatic variability that has occurred over centuries to millennia. These proxy records are essential for informing predictions of future climate scenarios, which may deviate significantly from recent trends (Bukhary et al. 2021).

Streamflow reconstruction is used to understand historical patterns of water flow in rivers and streams over long periods, typically spanning decades to centuries for gaining insights into long-term hydrological variability. Several studies have demonstrated that tree-ring data can be utilized to extend existing records of runoff further into the past (Jones et al. 1984, Meko and Graybill, 1995; Guo et al. 2010; Bukhary et al. 2014; Ferrero et al. 2015; Maxwell et al. 2017). Jones et al. (1984) employed TRC to reconstruct river discharge (1755-1979) in three river catchments in southern Britain. TRCs were used by Meko and Graybill (1995) to reconstruct annual flows from the year 1663 in the upper Gila River basin using a multiple linear regression model and explained 66% of the variance. Tree rings were utilized to reconstruct Tangnaihai Station discharge for the upper Yellow River basin from the year 1234 onwards with a correlation coefficient of 0.66 (Guo et al. 2010). The May-October discharge of the Río Bermejo River, located in Argentina and Bolivia was reconstructed (from the year 1680 to 2001) by Ferrero et al. (2015) by employing a principal component regression model. The analysis successfully explained 52% of the variance in the instrumental discharge (adjusted $R^2 = 0.5$) over the period from 1941 to 1992. Maxwell et al. (2017) performed TRC-based reconstructions in the eastern United States from the year 1675 to 2000 for the Beaver Kill River in New York, New York, the Potomac River in Washington, DC, and the Flint River in Atlanta, Georgia and explained 40% to 61% of variance in the instrumental data.

In this study, a tree-ring based streamflow reconstruction was performed for UIRB in Northern Pakistan, using a stepwise linear regression model.

II. STUDY AREA

The Indus River is one of the world's longest rivers, spanning approximately 3,180 km from its source in the Tibetan Plateau to its delta in the Arabian Sea. As Pakistan's principal river, it is the main source of water for irrigation, drinking, and hydroelectric power, thereby supporting the nation's economy and food secuity. It has a basin size of 1.1 million km², and is one of the most significant river systems in the world, playing a crucial role in sustaining the lives and livelihoods of millions in Pakistan.

The UIRB is a hydrologically significant region that plays a pivotal role in water resources management in South Asia, particularly for Pakistan. It is situated in the elevated areas of the Karakoram, Himalaya, and Hindu Kush Mountain ranges. The UIRB comprises mainly of two climatic fronts. One is the monsoon pattern of rainfall that originates from the Bay of Bengal and Arabian Sea. The second is the westerlies climatic front originating from the Caspian Sea and Mediterranean region during winters and springs. Most of the annual precipitation in the UIRB falls in the form of snow during the winter and spring season due to westerlies. Mean annual precipitation in Gilgit ranges from 150 mm at lower elevations to 1800 mm in the snow accumulation zone in Bagrot valley (Ul Hussan et al. 2020). The UIRB receives its water supply from three main sources: seasonal snowmelt, meltwater from permanent glaciers, and direct runoff from rainfall during both the winter and summer monsoon seasons, ensuring a consistent flow of water into the basin (Archer 2003). Immerzeel et al. (2010) suggested that up to 80% of the UIRB runoff is due to seasonal snowmelt (40%) and meltwater from glaciers (40%).

Besham Qila gauging station (Figure 1) is a vital monitoring point of the River Indus as it represents 100% of UIRB discharge (Hasson et al. 2017). From 1969 to 2003, the average annual discharge at Besham Qila was 2385 m³/sec, with a standard deviation of 317 m³/sec. The station, located at an elevation of 580 m, is situated approximately 1,408.8 km along the Indus River. It tracks the water flow from an upstream basin area of 164,475 km². The Indus basin receives over 1000 mm of annual precipitation, with peaks in March from the western disturbances and in July from the summer monsoons (Hussain et al. 2020). The average annual discharge at Besham Qila encompasses contributions from precipitation, snowmelt, and glacial melt in the upper Indus catchment. Further, Besham Qila gauging station is situated about 60 km upstream of the Tarbela Dam on the Indus River. The Tarbela Dam receives the vast majority (93%) of its water inflow from areas situated upstream of Besham Qila (Roca, 2012). This highlights the station's importance in providing vital hydrological data for effective dam management. The station continuously tracks the river's water level, flow rate, and sediment load, offering real-time insights that inform inflow forecasting, water storage management, and water release regulation. This data is crucial for optimizing power generation, flood prevention, and safe dam operation. By providing essential information, the Besham Qila gauge station supports efficient water resource management, irrigation, drinking water supply, and power generation (3500 MW) in Pakistan. This study aimed to reconstruct the historical streamflow data at Besham Qila to better understand the region's long-term hydrological variability.

In this study, a tree-ring based streamflow reconstruction was performed for UIRB in Northern Pakistan, using a stepwise linear regression model. Despite its importance, no previous research has undertaken the reconstruction of streamflow for Besham Qila station, leaving a significant gap in the understanding of the region's hydrological history. The current study addresses this research gap by utilizing dendrohydrological analysis to reconstruct the streamflow of the station using a stepwise linear regression model.

III. METHODOLOGY

This study followed the methodology of Woodhouse et al. (2006) and Anderson et al. (2019) for streamflow reconstruction, and employed a stepwise linear regression model to investigate the ability of moisture-sensitive TRC to predict streamflow This approach selects the most relevant predictors, adding or removing them based on their statistical significance (p-values ≤ 0.05 for entry and ≤ 0.10 for retention). Various statistical metrics were employed to evaluate the performance of the streamflow reconstruction model. Calibrated R^2 or coefficient of determination evaluates the goodness of fit of a model, representing the proportion of the variance in the dependent variable that can be predicted from the independent variables. The predicted R^2 value measures a model's ability to predict new, unseen data, helping to identify overfitting or underfitting of the model. Other metrics also assess model performance. The standard error of the estimate (SEE) indicates the accuracy of predictions made by the regression model. A low value indicates that the model has a good fit. The Durbin-Watson (D-W) statistic was computed to check for autocorrelation as a value of 2 indicates no autocorrelation. The Nash-Sutcliffe Efficiency (NSE) and the ratio of the root mean square error to the standard deviation of the observed data (RSR) were also estimated. These metrics collectively evaluate model's reliability.

IV. RESULTS AND DISCUSSION

The tree ring data, downloaded from the international tree-ring data bank, was detrended and standardized to remove non-climatic growth trends and highlight annual environmental signals, using the conservative negative exponential method among others. Autoregressive modeling was applied to the standardized series to remove autocorrelation, isolating the environmental signal. This process involved using ARSTAN software (Cook et al. 2017), which facilitated the detrending, standardization, and autoregressive modeling steps, ultimately generating the residual chronologies used in the current analysis.

The average annual streamflow data was correlated with each of the 41 TRC using Pearson's correlation method. Chronologies that showed a positive and significant correlation ($p < 0.05$) with the streamflow were kept. To assess the temporal stability of the relationship between tree-ring data and streamflow, correlation coefficients were calculated for a 20-year moving window. Chronologies that were positively correlated with regional streamflow at a confidence level of 90% or higher for all windows, indicating a stable relationship over time, were retained. Two TRCs were retained as predictors. The tree species were Himalayan spruce (TRC length: 1387-2005) and Juniper (TRC length: 1593-1993), located at Naltar Gilgit and Bagrot Valley, respectively.

Stepwise linear regression model successfully reconstructed the average annual streamflow for the Besham Qila gauging station as shown in Figure 2. Results showed that 63% of the variance in Besham Qila streamflow can be explained by the model, demonstrating a reasonably good fit. The predicted R^2 value was estimated as 0.31. The D-W statistic was 2.2. This value is close to 2, suggesting no significant autocorrelation, which is a positive indicator of model quality. The SEE was estimated as 139.3 m3/sec which is a low value. Value of NSE=0.63 aligned with the calibration R^2, indicating that the model has a good fit to the observed data during the calibration period. The RSR of 0.59, which, being below 0.7, indicates a relatively good performance according to the thresholds explained by Moriasi et al. (2007).

The ten-year moving average of the discharge, as plotted in Figure 2a, helps smooth out short-term fluctuations and provides insights into historical periods of high or low discharge. The scatter plot and the comparison of the reconstructed and the observed flow is shown in Figure 2b and 2c. The reconstructed streamflow was averaged at 2371 m^3/sec with a standard deviation of 237.4 m^3/sec, showing a slight increasing trend over time. The reconstruction reveals a rich history of hydrologic extremes. The four lowest reconstructed streamflow values were 1783 m^3/sec in the year 1694, 1823 m^3/sec in 1865, 1857 m^3/sec in 1630, and 1870.5 m^3/sec in the year 1788. Conversely, the four highest reconstructed streamflow values were 2982.9 m^3/sec in the year 1689, 2941.5 m^3/sec in 1919, 2884.1 m^3/sec in 1779, and 2877.2 m^3/sec in the year 1747. Notably, the late 17th century contained some of the most extreme values, both high and low, in the reconstructed streamflow record. Specifically, it included three of the ten lowest values in the years of 1694 (1783 m^3/sec), 1666 (1931.7 m^3/sec), and 1667 (1932.3 m^3/sec). It also includes two of the seven highest values in the year of 1689 (2982.9 m^3/sec) and 1671 (2855.8 m^3/sec). This period highlights significant variability in streamflow, reflecting potentially dramatic climatic conditions during that time.

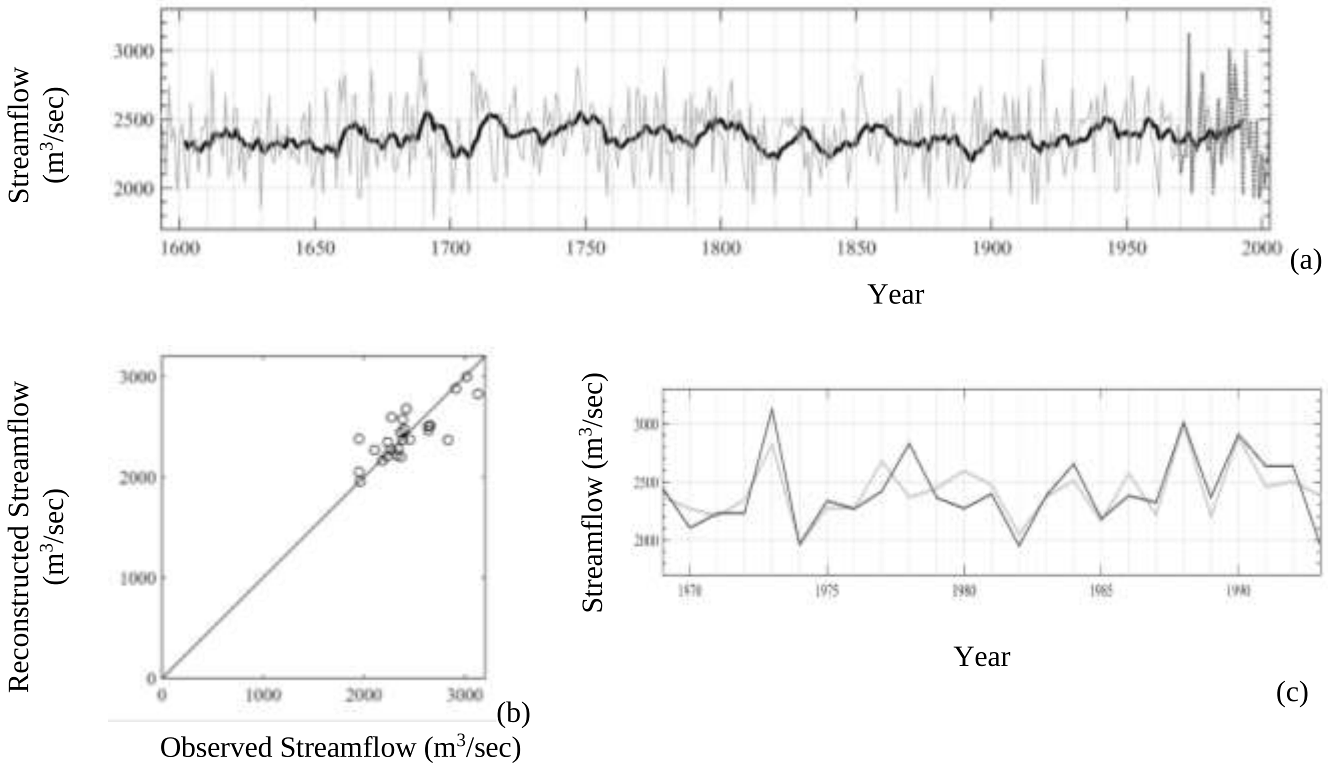

Figure 2. Results for the streamflow reconstructions performed for Besham Qila gauging station. (a) Grey line displays reconstructed streamflow, blackline displays 10-year moving average of the reconstructed flow, and dotted black line represents the observed flow. (b) Scatter plot between the observed and the reconstructed flow. (c) Display of the reconstructed flow (grey line) against the observed flow (black line) for Besham Qila Gauge station for the calibration period of 1969-1993.

Examination of the observed flow values illustrates that the late 20th century also marked a period of extreme values. Highest flow value remained the observed flow value of 3127.4 m^3/sec in the year 1973. The late 1980s till the mid-1990s marked a period of high flows at Besham Qila. The flow values were 3017.6 m^3/sec in the year 1988, 2909.4 m^3/sec in 1990, and 3007 m^3/sec in the year 1994. The 1990s also experienced low flow conditions, with several years having significantly lower than average flow values. The discharge values were 1950.7 m^3/sec in the year 1993 and 1928.2 m^3/sec in the year 1997 and 1999. Overall, this suggests that the river's streamflow has varied significantly over the centuries, with both high and low extremes occurring in different periods. This information can be useful for understanding the river's behavior, managing water resources, and predicting future changes in the river's flow.

Rao et al. (2018), Cook et al. (2013) and Chen et al. (2021) have reconstructed river discharge for UIRB using TRC. The current study fills a significant research gap by reconstructing the streamflow of Besham Qila, a crucial gauging station that represents 100% of the UIRB discharge. The reconstruction provides valuable insights into the long-term hydrologic variability of the region, exposing patterns of droughts and floods that have shaped the streamflow over centuries. The findings are particularly important for Pakistan, a water-scarce country with a rapidly growing population (241.5 million, with a 2.55% growth rate) (PBS, 2024). The changing climate exacerbates the issue, putting significant strain on the country's water resources (Ul Hussan et al. 2010; Bukhary et al. 2017). While some studies suggest that water scarcity in Pakistan may be more related to management issues rather than availability (Mirza and Mahmood, 2023), understanding historical streamflow patterns is crucial for informing water resource management and climate change adaptation strategies in the UIRB. By situating recent hydrologic conditions within a broader historical context, this research highlights the importance of considering long-term hydrologic variability in decision-making processes. The reconstructed streamflow record provides a valuable tool for water resource managers, policymakers, and researchers to better understand and prepare for future hydrologic extremes in the region.

V. CONCLUSION

This study successfully reconstructed streamflow for the Besham Qila gauging station using tree-ring chronologies from Himalayan spruce and Juniper trees. The stepwise linear regression model explained 63% of the variance in streamflow, indicating a reasonably good fit. The predicted R^2 value was 0.31. The D-W statistic of 2.2 suggest that the model performed well illustrating no significant autocorrelation. The low standard error of the estimate (139.3 m3/sec) and good performance metrics (NSE = 0.63, RSR = 0.59) further validate the model's performance as relatively good. The reconstructed streamflow record revealed a rich history of hydrologic extremes, with both high and low flow values occurring in different periods. The late 17th century and late 20th century marked periods of significant variability in streamflow, reflecting potentially dramatic climatic conditions. Overall, this study demonstrates the potential of tree-ring data in reconstructing past streamflow records in data-scare regions. It provides valuable insights into the long-term hydrologic variability through application of dendrohydrology, thus supporting informed decision-making in water resource management.

Future research on tree-ring based streamflow reconstructions should focus on expanding the network of tree-ring chronologies. This will enhance the robustness and spatial coverage of the models, helping to capture more localized climatic influences and improving the accuracy of reconstructions across different regions. Additionally, integrating other paleoclimatic proxy data, such as ice cores, sediment records, and sea surface temperatures may validate and complement the tree-ring data, providing a more comprehensive understanding of past hydrological conditions. Long-term data management programs should be established to update tree-ring chronologies and streamflow records. This can significantly enhance the understanding and applicability of tree-ring based streamflow reconstructions, contributing to more informed and resilient water resource management practices.

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REFERENCES

[1] Anderson, S., Aziz, O., Tootle, G., Grissino-Mayer, H. and Barnett, A., 2012a. Using Pacific Ocean climatic variability to improve hydrologic reconstructions. Journal of hydrology, 434: 69-77.

[2] Anderson, S., Tootle, G. and Grissino-Mayer, H., 2012b. Reconstructions of Soil Moisture for the Upper Colorado River Basin Using Tree-Ring Chronologies 1. JAWRA Journal of the American Water Resources Association, 48(4), pp.849-858.

[3] Anderson, S., Ogle, R., Tootle, G. and Oubeidillah, A., 2019. Tree-Ring Reconstructions of Streamflow for the Tennessee Valley. Hydrology, 6(2): 34.

[4] Bukhary, S., Kalra, A. and Ahmad, S., 2021. Incorporating Pacific Ocean climate information to enhance the tree-ring-based streamflow reconstruction skill. Journal of Water and Climate Change, 12(5), pp.1891-1909.

[5] Bukhary, S., Weidhaas, J., Ansari, K., Mahar, R.B., Pomeroy, C., VanDerslice, J.A., Burian, S. and Ahmad, S., 2017. Using Distributed Solar for Treatment of Drinking Water in Developing Countries. In World Environmental and Water Resources Congress 2017 (pp. 264-276).

[6] Bailey, J.R., Bukhary, S., Batista, J.R. and Ahmad, S., 2021. Renewable energy generation and GHG emission reduction potential of a satellite water reuse plant by using solar photovoltaics and anaerobic digestion. Water, 13(5), p.635.

[7] Bukhary, S., Chen, C. and Ahmad, S., 2016. Analysis of Water Availability and Use for Solar Power Production in Nevada. In World Environmental and Water Resources Congress 2016 (pp. 164-173).

[8] Bukhary, S., Chen, C., Kalra, A. and Ahmad, S., 2014. Improving streamflow reconstructions using oceanic-atmospheric climate variability. In World Environmental and Water Resources Congress 2014 (pp. 846-855).

[9] Bukhary, S., Kalra, A. and Ahmad, S., 2015, May. Insights into reconstructing sacramento river flow using tree rings and Pacific Ocean climate variability. In World Environmental and Water Resources Congress 2015 (pp. 1040-1049).

[10] Bukhary, S.S., 2024. The renewable energy–water nexus. In The Renewable Energy-Water-Environment Nexus (pp. 143-176). Elsevier.

[11] Bukhary, S., Kalra, A. and Ahmad, S., 2015, May. Insights into reconstructing sacramento river flow using tree rings and Pacific Ocean climate variability. In World Environmental and Water Resources Congress 2015 (pp. 1040-1049).

[12] Bukhary, S.S., 2018. Water-Energy Nexus Approaches for Solar Development and Water Treatment in the Southwestern United States (Doctoral dissertation, University of Nevada, Las Vegas).

[13] Chen, F., Opała-Owczarek, M., Khan, A., Zhang, H., Owczarek, P., Chen, Y., Ahmed, M. and Chen, F., 2021. Late twentieth century rapid increase in high Asian seasonal snow and glacier-derived streamflow tracked by tree rings of the upper Indus River basin. Environmental Research Letters, 16(9), p.094055.

[14] Cook, E.R., Palmer, J.G., Ahmed, M., Woodhouse, C.A., Fenwick, P., Zafar, M.U., Wahab, M. and Khan, N., 2013. Five centuries of Upper Indus River flow from tree rings. Journal of hydrology, 486, pp.365-375.

[15] Cook, E.R., Krusic, P.J., Peters, K., Holmes, R.L., 2017. Program ARSTAN, Autoregressive tree–ring standardization program. Tree–Ring Laboratory of Lamont–Doherty Earth Observatory.

[16] Dawadi, S. and Ahmad, S., 2013. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. Journal of environmental management, 114, pp.261-275.

[17] Ferrero, M.E., Villalba, R., De Membiela, M., Hidalgo, L.F. and Luckman, B.H., 2015. Tree-ring based reconstruction of Río Bermejo streamflow in subtropical South America. Journal of Hydrology, 525, pp.572-584.

[18] Galelli, S., Nguyen, H.T., Turner, S.W. and Buckley, B.M., 2021. Time to use dendrohydrological data in water resources management?. Journal of Water Resources Planning and Management, 147(8), p.01821001.

[19] Gou, X., Deng, Y., Chen, F., Yang, M., Fang, K., Gao, L., Yang, T. and Zhang, F., 2010. Tree ring based streamflow reconstruction for the Upper Yellow River over the past 1234 years. Chinese Science Bulletin, 55, pp.4179-4186.

[20] Hasson, S., Böhner, J. and Lucarini, V., 2017. Prevailing climatic trends and runoff response from Hindukush–Karakoram–Himalaya, upper Indus Basin. Earth System Dynamics, 8(2), pp.337-355.

[21] Hussain, K., Shahab, M. and Štibinger, J., 2020. Detection of trend change in long-term flow series of Upper Indus River Watershed, Pakistan. International Journal of Energy and Water Resources, 4, pp.109-118.

[22] Jones, P.D., Briffa, K.R. and Pilcher, J.R., 1984. Riverflow reconstruction from tree rings in southern Britain. Journal of Climatology, 4(5), pp.461-472.

[23] Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. Science 328, 1382–1385.

[24] Mirza, M.N. and Mahmood, N., 2023. Securitising and de-securitising water scarcity in Pakistan: a case study of the Diamer Basha Dam. Water Policy, 25(1), pp.1-14.

[25] Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50 (3), 885–900.

[26] Meko, D. and Graybill, D.A., 1995. Tree-Ring Reconstruction of Upper Gila Rwer Discharge 1. JAWRA Journal of the American Water Resources Association, 31(4), pp.605-616.

[27] Maxwell, R.S., Harley, G.L., Maxwell, J.T., Rayback, S.A., Pederson, N., Cook, E.R., Barclay, D.J., Li, W. and Rayburn, J.A., 2017. An interbasin comparison of tree-ring reconstructed streamflow in the eastern United States. Hydrological Processes, 31(13), pp.2381-2394.

[28] PBS, 2024. Pakistan Bureau of Statistics (PBS). https://www.pbs.gov.pk/sites/default/files/population/2023/Press%20Release.pdf. (Accessed: 21-6-2024)

[29] Rao, M.P., Cook, E.R., Cook, B.I., Palmer, J.G., Uriarte, M., Devineni, N., Lall, U., D'Arrigo, R.D., Woodhouse, C.A., Ahmed, M. and Zafar, M.U., 2018. Six centuries of Upper Indus Basin streamflow variability and its climatic drivers. Water Resources Research, 54(8), pp.5687-5701.

[30] Roca., M. Tarbela Dam in Pakistan. Case study of reservoir sedimentation. Published in the proceedings of River Flow, 2012. 5-7.

[31] Thakali, R., Kalra, A. and Ahmad, S., 2016. Understanding the effects of climate change on urban stormwater infrastructures in the Las Vegas Valley. Hydrology, 3(4), p.34.

[32] Woodhouse, C.A., Gray, S.T. and Meko, D.M., 2006. Updated streamflow reconstructions for the Upper Colorado River basin. Water Resources Research, 42(5).

[33] Ul Hussan, W., Khurram Shahzad, M., Seidel, F., Costa, A. and Nestmann, F., 2020. Comparative assessment of spatial variability and trends of flows and sediments under the impact of climate change in the Upper Indus Basin. Water, 12(3), p703

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