International Journal of Science and Technology (IJST)
ISSN: 3049-1118, Volume- 2, Issue- 3 (Jul – Sep 2025)

A Comprehensive Water Balance Assessment of Northern Pakistan's Catchment Based Using the Budyko Framework Approach

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Abstract:

This study presents a comprehensive hydrological evaluation of the Astore catchment (Northern Pakistan), integrating long-term observational data with advanced modeling techniques to assess water balance dynamics and runoff simulation accuracy. Spanning two decades (2000–2020), the dataset includes key parameters such as annual rainfall (1144 mm), actual evapotranspiration (278 mm), and groundwater recharge (494 mm), offering insights into the catchment's hydrometeorological behavior. These variables are influenced by diverse environmental factors including topography, land use, soil composition, and microclimatic conditions. To simulate runoff and validate hydrological responses, a Budyko-based model was calibrated at both monthly and yearly scales. The optimization of parameters Smax, α1, α2, and d yielded high-performance metrics, with a Pearson correlation of 0.99, NNSE of 0.97, and RMSE of 0.02. These findings validate the model's capability to replicate observed runoff patterns with remarkable precision. Visual comparisons between observed and simulated rainfall and runoff data underscore the model's effectiveness in capturing seasonal variability and hydrological trends. Furthermore, sensitivity analysis revealed the model's responsiveness to parameter changes, highlighting the importance of careful calibration for reliable predictions. The integration of empirical data and robust simulation techniques provides a valuable framework for understanding catchment-scale water dynamics. This approach supports improved forecasting, resource management, and environmental planning, particularly in regions vulnerable to hydrological extremes such as landslides and droughts. The findings contribute to the broader field of hydrological modeling by demonstrating the utility of Budyko-based frameworks in complex mountainous terrains.

Keywords: Budyko model, Water balance assessment, Hydrological model, Northern Pakistan

1-Introduction:

Water balance assessment is a critical aspect of hydrological studies, especially in regions facing water scarcity or climate variability. Northern Pakistan, home to diverse climatic zones

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Published: 05/09/2025
DOI: https://doi.org/10.70558/IJST.2025.v2.i3.241085

and significant hydrological resources, requires a comprehensive evaluation of its water balance to support sustainable water management. The Budyko framework provides a robust approach to understanding the partitioning of precipitation into evapotranspiration and runoff, considering both climatic and catchment characteristics. The Budyko framework, introduced (Mianabadi et al., 2019) developed the relationship between potential evapotranspiration and precipitation to determine actual evapotranspiration, using an aridity index as a key parameter. This model has been widely applied in various hydrological settings to assess the influence of climatic and landscape factors on water availability. Previous studies have demonstrated the effectiveness of the Budyko model in different geographical contexts, including arid and semi-arid regions (D. Wang & Tang, 2014a), (Zhang et al., 2008a), tropical climates (X. Li et al., 2016), (D. Li et al., 2013a) and Temperature zones (Maurer et al., 2022). However, limited research has focused on its application in the mountainous catchments of Northern Pakistan, where complex topography and seasonal variations significantly impact hydrological processes.

Numerous studies have explored the applicability of the Budyko framework in hydrological assessments. (D. Wang & Tang, 2014b) introduced a one-parameter version of the Budyko model, demonstrating its efficiency in capturing water balance variations across different climatic conditions. This study highlighted that the model provides a useful tool for evaluating long-term water partitioning, even with limited hydrological data.(D. Li et al., 2013b) examined the role of vegetation in controlling water and energy balance within the Budyko framework. Their findings indicated that changes in land cover and vegetation significantly affect evapotranspiration rates, which in turn influence water availability in catchments. This aspect is particularly relevant for Northern Pakistan, where deforestation and land-use changes could alter the region’s hydrological patterns.

(Maurer et al., 2022) assessed the impact of drought on water balance using the Budyko approach. Their research emphasized that prolonged dry periods can shift the equilibrium between evapotranspiration and runoff, leading to changes in water availability. Given the increasing climate variability in Northern Pakistan, such studies underscore the need to incorporate climatic fluctuations into water balance assessments. (Xu et al., 2022a) expanded the Budyko framework by incorporating anthropogenic influences, such as water extraction and land-use changes, into the model. Their research demonstrated that human activities significantly modify the natural hydrological cycle, making it crucial to include such factors in water balance assessments. (F. Wang et al., 2022) conducted a comparative analysis of different Budyko formulations to determine the most effective parameterization for diverse climatic regions. Their findings suggested that the choice of Budyko parameterization plays a crucial role in accurately modeling water balance, particularly in regions with complex hydrological processes such as Northern Pakistan. (Buri et al., 2023) applied the Budyko model to high-altitude catchments and found that snowmelt and glacial contributions must be explicitly accounted for in water balance calculations. Given that Northern Pakistan's hydrology is heavily influenced by snow and glacier melt, this research highlights the necessity of adapting the Budyko model for such conditions. (Xu et al., 2022b) developed a modified Budyko framework incorporating seasonal variability to improve predictions in regions experiencing significant intra-annual changes in precipitation and temperature. Their work is particularly relevant for Northern Pakistan, where seasonal variations dramatically impact water availability.

This Research provide valuable insights, there remains a research gap in applying the Budyko model to high-altitude catchments with significant seasonal variations, such as those in Northern Pakistan. This study aims to fill this gap by integrating hydrometeorological data with the Budyko framework to a) Budyko framework to evaluate the partitioning of water resources in the study area and validate its applicability in complex mountainous terrains. b) Investigate the influence of topography, vegetation, soil properties, and land-use changes on water balance components. c) Examine the effects of climate variability and projected climate change on water availability using the Budyko model.

2 Material and Methodology:

2.1 Study area:

The study area for this research is the Astore district, located in the Gilgit-Baltistan region of northern Pakistan as shown in Fig 1. This region is known for its diverse topography, which includes towering mountains, deep valleys, and glacial rivers. It forms part of the greater Himalaya Mountain range and is home to some of the world's highest peaks, such as Nanga Parbat. Astore is a prime location for studying hydrological processes and water balance due to its unique geographic and climatic characteristics having elevation ranging from 2,500 meters to over 4,000 meters above sea level. Its climate is primarily alpine, with distinct seasonal variations. Winters bring heavy snowfall, especially in the higher altitudes, while summers are relatively short and warmer, with rainfall being a critical source of water. The region's diverse climate and topography result in various microclimates, which influence both the distribution of water and the hydrological cycle. This area is characterized by a combination of steep mountain slopes, lush green meadows, and deep forests. It is also a convergence point for several glaciers that feed into the region's rivers and streams. These rivers considered as most crucial components in the water cycle, contributing significantly to the local water balance. The region relies heavily on both snowmelt and rainfall for water, which is then used by local communities for agricultural, domestic, and industrial purposes. In terms of hydrology, Astore is an ideal study area for understanding the interaction between precipitation, evapotranspiration, and runoff in high-altitude regions. The primary water sources in Astore come from snowmelt and glacial runoff during the warmer months, while the monsoon season brings additional precipitation. However, due to the region's high altitude and rugged terrain, access to accurate meteorological data can be a challenge, making this area even more important for detailed studies on water availability. The population in Astore is primarily dependent on subsistence farming, with small-scale agriculture being the main livelihood. Water resources are crucial for irrigation, especially in the lower altitudes of the valley. In the higher regions, where the snowmelt is more abundant, the water is often used for domestic purposes and hydroelectric power generation. As per its geographical and climatic features, area bids a unique setting to examine water balance models, especially in the context of climate change. The region's water resources are vulnerable to shifts in temperature and precipitation patterns, which makes understanding these hydrological dynamics vital for future water management and conservation efforts in the region.

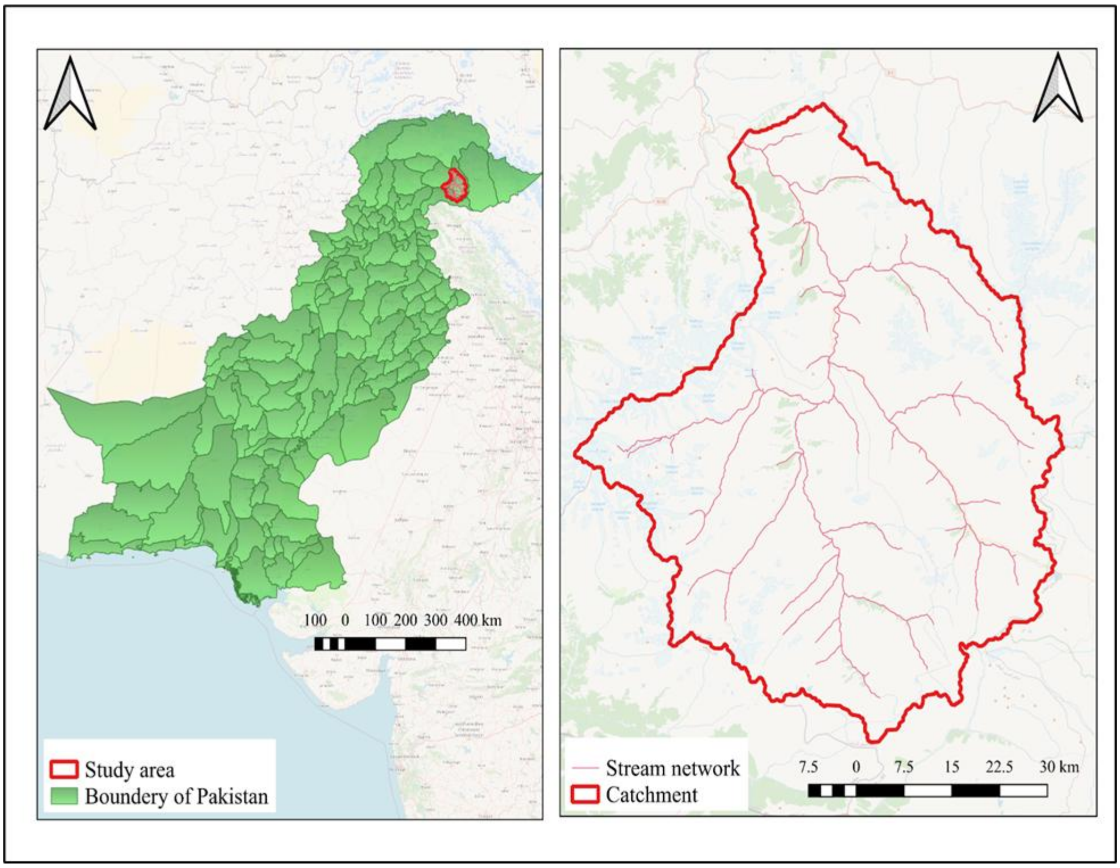

Figure 1:*Shows the Characteristics of study area*

2.2 Data collection and Processing.

Table 1*: Data collection details for the selected catchment.*

Sr. No	Variable	Spatial Resolution	Dataset	Source
1	Runoff-(RO)	-	Ground	PDMA
2	Evapotranspiration (ET)	4 × 4 km	TerraClimate	Google earth engine
3	Precipitation(P)	9 × 9	ERA5-Land	Google earth engine
4	Recharge (GR)	-	Literature	(Petrone et al., 2024)

The data variables used in this study are crucial for assessing the water balance of the Astore region. Runoff (RO) is a key component, providing insight into the water that flows out of the system. For this, ground-based data from the PDMA is used. Although the spatial resolution for runoff is not explicitly specified, ground observations offer accurate local measurements. Evapotranspiration (ET), is estimated using the TerraClimate dataset, having spatial resolution of 4 × 4 km. TerraClimate provides monthly climate data that is highly valuable for understanding the distribution and variability of evapotranspiration in the study area, especially under different climatic conditions. Precipitation (P), due to unavailability of rain gauges; derived from the ERA5-Land dataset with a spatial resolution of 9 × 9 km, dataset offers high-quality climate reanalysis data, which is useful for evaluating the precipitation patterns over time and space in the region. Finally, Recharge (GR), the amount of water that infiltrates into the ground and replenishes groundwater, is sourced from the literature, specifically (Petrone et al., 2024). This secondary data helps estimate groundwater recharge, an important but often challenging variable to measure directly in high-altitude regions like Astore. Together, these datasets from ground measurements, satellite observations, and literature sources provide a comprehensive basis for evaluating the water balance. Observed runoff by the department validated by comparing with runoff estimated by the simple water balance equation (1).

$$\mathrm{P} - \mathrm{AET} - \mathrm{GR} = \mathrm{RO} \ldots\ldots\ldots\ldots \text{(i)}$$

For the estimation of water storage at the catchment scale, water balance approach (Budyko, 1961)based model used as expressed in Equation(2).

$$\Delta S = P - ET - \mathrm{GR} - \mathrm{RO} \ldots\ldots\ldots\ldots \text{(ii)}$$

Where P (mm) is the Precipitation, AET (mm) Actual evapotranspiration, GR (mm) ground water recharge and RO (mm) is the total runoff. Over a long period, the change in water storage has been negligible. Evaluating the water balance equation requires comprehensive data on catchment physical characteristics, climatic variables, and their interrelationships. One of the primary challenges in understanding hydrological behavior at the catchment scale lies in the uncertainties associated with accurately determining the spatial and temporal distribution of climatic variables, particularly precipitation (Zhang et al., 2008b).

The mean annual water balance can be modeled using the method of (Budyko, 1961) by only considering dominant controls on evapotranspiration. By many procedures and hypothesis from the equation (3), we obtain the following expression for mean annual streamflow.

$$Q = ((P)^{\frac{1}{1-\alpha}} + (E_0)^{\frac{1}{1-\alpha}})^{1-\alpha} - E_0 \ \ldots\ldots\ldots\ldots (iii)$$

The extended Budyko water balance was developed by (Zhang et al., 2008a) to access the water balance at finer scale such as monthly and weekly scale called as Dynamic water balance model (DWBM). The DWBM model operates with two stores of water for a catchment: the vadose zone (S) and groundwater (G). Model is trained on monthly and weekly scale to simulate the runoff (Q) and soil storage at the catchment scale. In DWBM, Precipitation is distributed among various components of the water balance, such as direct runoff (Surface flow and base flow flow) evapotranspiration (ET), storage in the vadose zone (S), and recharge to groundwater another factor “deep groundwater recharge” introduced based on Case study of Campania region, due to pyroclastic and rock layers , loss occurred in system (Marino et al., 2020).

The model described above was selected because it requires only four parameters (α1, α2, d, and Smax), making it reliable in situations with limited calibration data as Fig 2/. However, these parameters have physical significance, and relevant information for some of them is available in existing literature (Bai et al., 2020). The model has been run for the years 2002–2023, on monthly and weekly time resolution for each catchment to obtain the optimized parameters.

Table 2:Adopted water balance model flow Chart

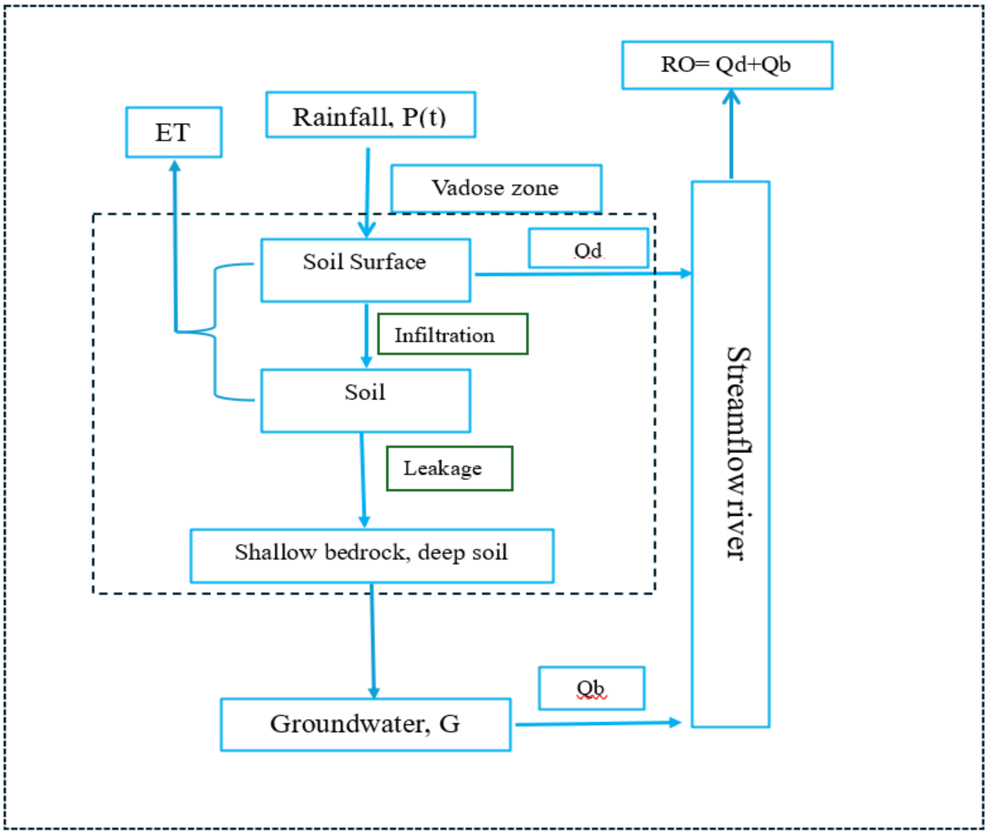

***Table 3**:DWBM Parameters and Characteristics*

Parameters	Description	Affected by LUC	Affected by LUU
Smax	Maximum catchment storage capacity	0.71	-309
α1 [0-1]	Catchment retention	1.8e-4	-.15
α2 [0-1]	Evapotranspiration efficiency	4.1e-4	-.30
d [0-1]	Groundwater store time constant	N.A.	N.A.

The Distributed Water Balance Model (DWBM) simulates water distribution in a catchment by incorporating essential hydrological processes, including precipitation, evapotranspiration, runoff, infiltration, and groundwater recharge. It utilizes Fu's curve to describe the interactions between these processes, with key parameters such as the maximum catchment storage capacity (Smax), catchment retention (α_1), evapotranspiration efficiency (α_2), groundwater storage time constant (d), outlined in Table 2. These parameters are sensitive to changes in land use (LUC) and climate (CC), both of which can significantly impact the model's performance and outcome.

3. Results and Discussion.

Hydrological and meteorological parameters for selected catchment on an annual basis as shown in Table 3 presents the data for catchment, highlighting their area, observation period, and critical hydrological variables. The catchment areas 4040 km², with data spanning from 2000 to 2020. The average annual rainfall varies between 1144 mm. Similarly, average actual evapotranspiration ranges from 278 mm, and average groundwater recharge occur 494 mm. The differences in rainfall, evapotranspiration, and groundwater recharge across these catchments are influenced by variations in topography, land use, soil types, microclimates, and human activities. These factors play a significant role in shaping local water availability and environmental conditions, as further illustrated in Fig. 4.

Table 4*:Annually Estimated P, AET and Ground water recharge at Catchment scale*

Catchment	Area (Km^2)	Observation Period	Average Rainfall (mm/y)	Average AET (mm/y)	Average Ground water recharge. (mm/y)
Astore	4040	2000-2020	1144	278	494

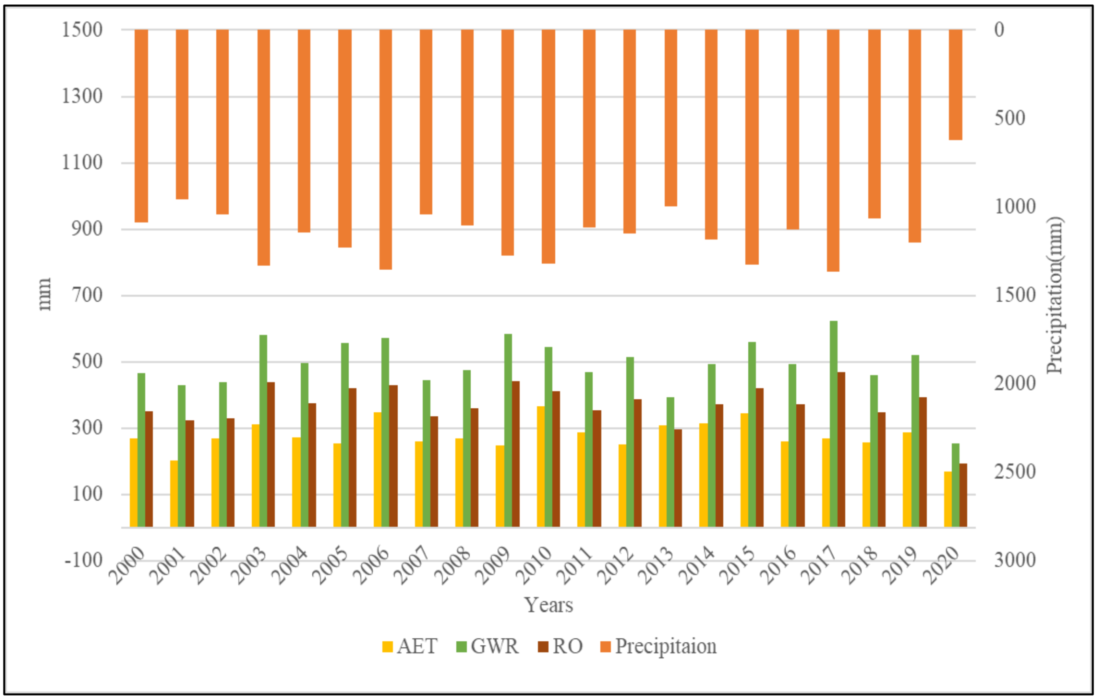

Figure 2: *Graphical representation of Annually Estimated P, AET, RO and Ground water recharge at Catchment scale*

The model was trained on both monthly and yearly scales for selected catchment. To achieve the best correlation between observed and simulated runoff, the Budyko parameters were

ISSN: 3049-1118, Volume- 2, Issue- 3 (Jul – Sep 2025)

optimized See Table 5. The results showed a strong correlation at both scales, with coefficients of 0.99, a normalized Nash-Sutcliffe efficiency (NNSE) of 0.97, and root mean square errors (RMSE) of 0.02, as shown in Figure. 3

Table 5:Optimized Parameters for four catchments at weekly scale

Catchment	Smax (mm)	α1	α2	d (month^{-1})
Astore	471	0.88	0.80	0.60

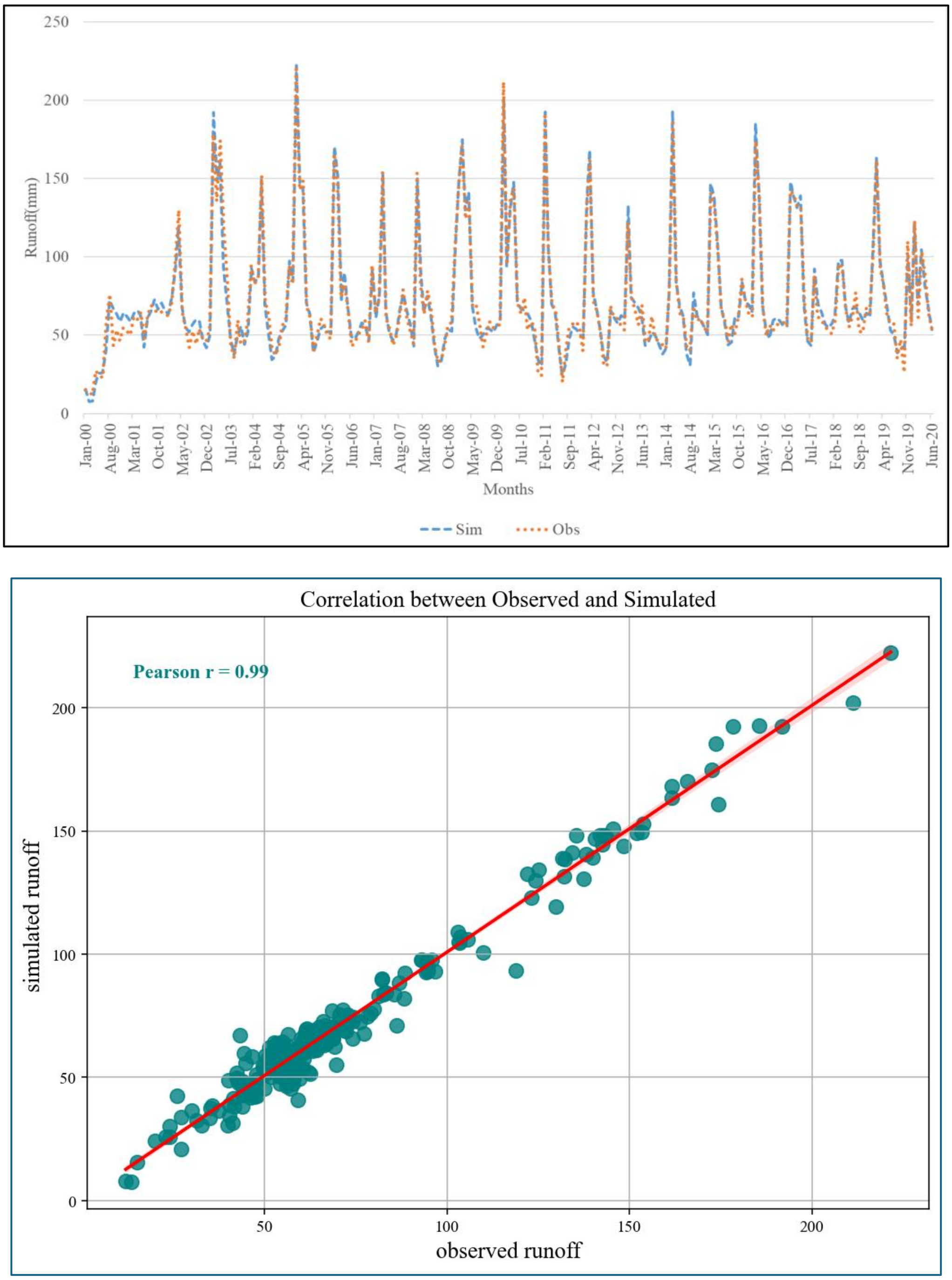

__Figure 3__: a) shows the strong correlation b) Correlation between Observed runoff and Simulated runoff at monthly scale corresponding their NNSE, RMSE

Fig .3(a) illustrates a two-decade comparison between simulated and observed monthly rainfall data, spanning from January 2000 to January 2020. Rainfall values—highlight the temporal variability and alignment between the datasets. Both curves exhibit pronounced fluctuations, with recurring peaks that suggest seasonal rainfall patterns and troughs indicating drier periods. The close tracking of the two lines in several segments underscores the effectiveness of the simulation model in capturing real-world precipitation dynamics. This visual comparison is instrumental for validating hydrological models, improving predictive accuracy, and informing environmental planning, especially in contexts like landslide risk assessment and water resource management. Fig 3(b) represents strong relationship between observed and simulated runoff, with a Pearson correlation of 0.99, almost a perfect match. The red trend line cuts cleanly through the data, showing that the model mirrors reality with impressive precision. Such alignment expresses statistically satisfying validation of the modelled reliability hydrological forecasting.

3.1 Sensitivity analysis:

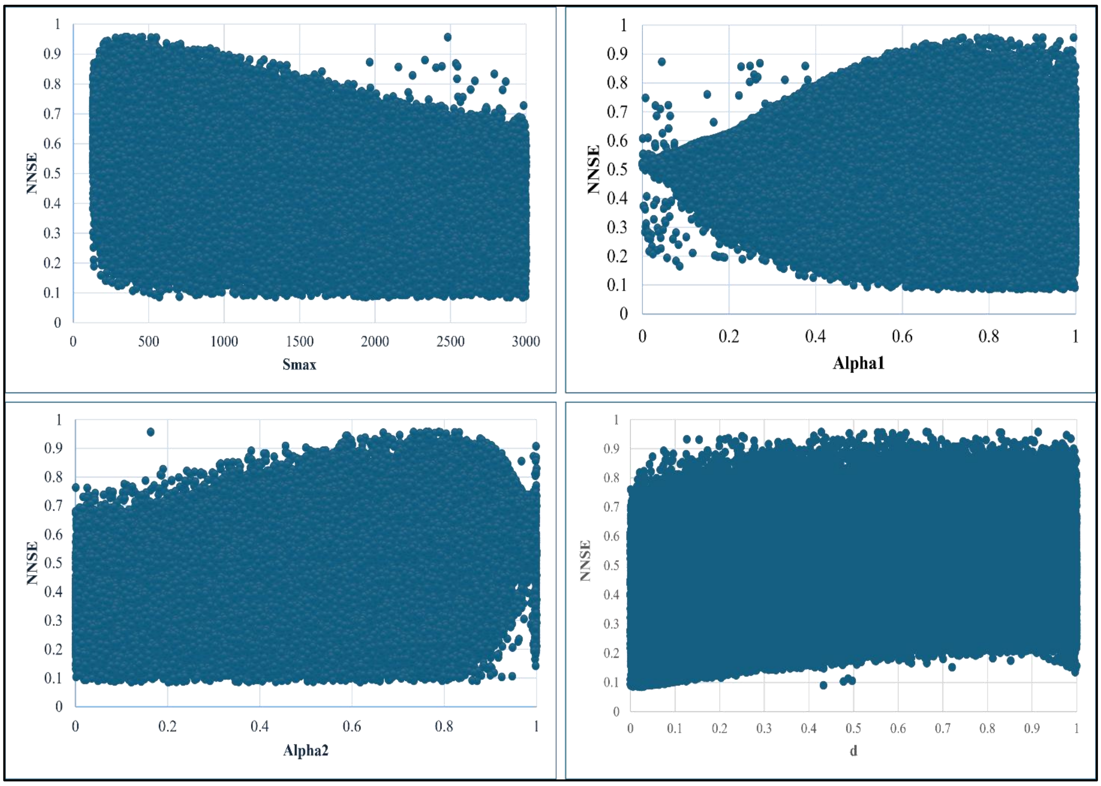

Figure 4:*Represent the sensitivity of the Budyko parameters based on Selected catchment*

Fig 5; sensitivity analysis explores how variations in Budyko parameters Smax, Alpha1, Alpha2, and d, affect the model's predictive performance, as measured by the normalized Nash-Sutcliffe Efficiency (NNSE). Each scatter plot reveals a dense spread of NNSE values across the parameter ranges, highlighting the model's responsiveness to these inputs. Notably, the wide distribution suggests that even small changes in parameters can significantly influence simulation accuracy. This analysis is indispensable for calibrating the Budyko framework, guiding researchers toward optimal parameters selection for robust hydrological modeling and improved water balance predictions.

4. Conclusion:

The hydrological assessment of the Astore catchment over a 20-year period (2000–2020) reveals a dynamic interplay between climatic inputs and water balance components. With an average annual rainfall of 1144 mm, actual evapotranspiration of 278 mm, and groundwater recharge of 494 mm, the catchment demonstrates substantial water retention and recharge capacity. These values are shaped by underlying topographic, pedologic, and anthropogenic factors, underscoring the importance of localized environmental conditions in hydrological behavior. The Budyko-based model, calibrated at both monthly and yearly scales, achieved exceptional performance metrics highlighted by a Pearson correlation, NNSE, and RMSE. This near-perfect alignment between observed and simulated runoff validates the robustness of the modeling framework and its applicability for predictive hydrology, particularly in contexts such as landslide risk forecasting and water resource planning. Sensitivity analysis further emphasized the model's responsiveness to variations in key parameters (Smax, α1, α2, and d), with NNSE values exhibiting wide dispersion across tested ranges. This reinforces the critical need for precise parameter calibration to ensure reliable simulation outcomes.

In summary, the integration of high-resolution hydrometeorological data with optimized Budyko parameters has yielded a highly accurate and adaptable hydrological model. Its predictive strength and sensitivity make it a valuable tool for environmental engineers and decision-makers aiming to enhance water management strategies and mitigate hydro-climatic risks in mountainous catchments.

References:

1. Bai, P., Liu, X., Zhang, D., & Liu, C. (2020). Estimation of the Budyko model parameter for small basins in China. *Hydrological Processes*, *34*(1), 125–138. https://doi.org/10.1002/hyp.13577

2. Budyko, M. I. (1961). The Heat Balance of the Earth's Surface. *Soviet Geography*, *2*(4), 3–13. https://doi.org/10.1080/00385417.1961.10770761

3. Buri, P., Fatichi, S., Shaw, T. E., Miles, E. S., McCarthy, M. J., Fyffe, C. L., Fugger, S., Ren, S., Kneib, M., Jouberton, A., Steiner, J., Fujita, K., & Pellicciotti, F. (2023). Land Surface Modeling in the Himalayas: On the Importance of Evaporative Fluxes for the Water Balance of a High-Elevation Catchment. *Water Resources Research*, *59*(10), e2022WR033841. https://doi.org/10.1029/2022WR033841

4. Li, D., Pan, M., Cong, Z., Zhang, L., & Wood, E. (2013a). Vegetation control on water and energy balance within the Budyko framework. *Water Resources Research*, *49*(2), 969–976. https://doi.org/10.1002/wrcr.20107

5. Li, D., Pan, M., Cong, Z., Zhang, L., & Wood, E. (2013b). Vegetation control on water and energy balance within the Budyko framework. *Water Resources Research*, *49*(2), 969–976. https://doi.org/10.1002/wrcr.20107

6. Li, X., Xie, S.-P., Gille, S. T., & Yoo, C. (2016). Atlantic-induced pan-tropical climate change over the past three decades. *Nature Climate Change*, *6*(3), 275–279. https://doi.org/10.1038/nclimate2840

7. Marino, P., Comegna, L., Damiano, E., Olivares, L., & Greco, R. (2020). Monitoring the Hydrological Balance of a Landslide-Prone Slope Covered by Pyroclastic Deposits over Limestone Fractured Bedrock. *Water*, *12*(12), 3309. https://doi.org/10.3390/w12123309

8. Maurer, T., Avanzi, F., Glaser, S. D., & Bales, R. C. (2022). Drivers of drought-induced shifts in the water balance through a Budyko approach. *Hydrology and Earth System Sciences*, *26*(3), 589–607. https://doi.org/10.5194/hess-26-589-2022

9. Mianabadi, A., Coenders-Gerrits, M., Shirazi, P., Ghahraman, B., & Alizadeh, A. (2019). A global Budyko model to partition evaporation into interception and transpiration. *Hydrology and Earth System Sciences*, *23*(12), 4983–5000. https://doi.org/10.5194/hess-23-4983-2019

10. Petrone, P., De Vita, P., Marsiglia, P., Allocca, P., Coda, S., Cusano, D., Lepore, D., & Allocca, V. (2024). Hydrogeological conceptual model and groundwater recharge of Avella Mts. karst aquifer (southern Italy): A literature review and update. *Journal of Hydrology: Regional Studies*, *54*, 101871. https://doi.org/10.1016/j.ejrh.2024.101871

11. Wang, D., & Tang, Y. (2014a). A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models. *Geophysical Research Letters*, *41*(13), 4569–4577. https://doi.org/10.1002/2014GL060509

12. Wang, D., & Tang, Y. (2014b). A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models. *Geophysical Research Letters*, *41*(13), 4569–4577. https://doi.org/10.1002/2014GL060509

13. Wang, F., Xia, J., Zou, L., Zhan, C., & Liang, W. (2022). Estimation of time-varying parameter in Budyko framework using long short-term memory network over the Loess Plateau, China. *Journal of Hydrology*, *607*, 127571. https://doi.org/10.1016/j.jhydrol.2022.127571

14. Xu, X., Li, X., He, C., Tia, W., & Tian, J. (2022a). Development of a simple Budyko-based framework for the simulation and attribution of ET variability in dry regions. *Journal of Hydrology*, *610*, 127955. https://doi.org/10.1016/j.jhydrol.2022.127955

15. Xu, X., Li, X., He, C., Tia, W., & Tian, J. (2022b). Development of a simple Budyko-based framework for the simulation and attribution of ET variability in dry regions. *Journal of Hydrology*, *610*, 127955. https://doi.org/10.1016/j.jhydrol.2022.127955

16. Zhang, L., Potter, N., Hickel, K., Zhang, Y., & Shao, Q. (2008a). Water balance modeling over variable time scales based on the Budyko framework – Model development and testing. *Journal of Hydrology*, *360*(1), 117–131. https://doi.org/10.1016/j.jhydrol.2008.07.021

17. Zhang, L., Potter, N., Hickel, K., Zhang, Y., & Shao, Q. (2008b). Water balance modeling over variable time scales based on the Budyko framework – Model development and testing. *Journal of Hydrology*, *360*(1), 117–131. https://doi.org/10.1016/j.jhydrol.2008.07.021