INTERCOMPARISON OF CLIMATE CHANGE IMPACT ON RAINFALL CHARACTERISTICS AND FLOOD MITIGATION STRATEGIES IN FOUR MAJOR RIVER BASINS OF PAKISTAN

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ABSTRACT

The Indus River basin and its tributaries, the Kabul, Jhelum, and Chenab (the western rivers of Pakistan), are crucial water resources for Pakistan, supporting its food and energy security. In addition to precious water resources, these rivers often produce huge floods causing havoc, as observed during the last decade from 2010 to 2015 and, most recently, in 2022, whereby flood events brought almost one-third of the country underwater. This multi-basin study employed the Data Integration and Analysis System (DIAS) for the selection of GCMs to assess the impact of climate change on the rainfall characteristics of each basin. The findings suggest decreased average annual rainfall and increased floods and droughts in the future under RCP 8.5. Flood simulations of the Jhelum River Basin using the Water and Energy Budget-based Rainfall Runoff Inundation (WEB-RRI) model predict future intensified flood events under changing climate. A comprehensive sensitivity analysis of the operation of Mangla Dam, the functioning of its purposely built flood storage zone, and the implementation of the Rohtas Dam Project indicate a significant reduction in flood inundation downstream of the dam, thereby mitigating potential flood damage in the basin. This study also proposes policy recommendations to provide decision-makers with evidence-based information to formulate policies for disaster risk reduction and aid sustainable water availability in the future.

Keywords: Climate Change, GCMs, WEB-RRI, Floods/Droughts, Reservoir Operation Optimization

INTRODUCTION

Pakistan is the eighth most vulnerable country to climate change (German Watch, 2021) despite its insignificant contribution to global greenhouse gas (GHG) emissions. The high vulnerability of Pakistan to climate change poses a significant threat to its development and prosperity. The study area (Figure 1) is comprised of four western rivers of the Upper Indus Basin (UIB), including Indus, Kabul, Jhelum, and Chenab. These four major river basins are critical regions in Pakistan supporting the livelihoods of millions of people and the economy of the country by providing water for agriculture, hydropower, and various industries. However, the UIB faces various challenges, including water scarcity, large variability in river runoff, climate change resulting in extreme floods and droughts, and unsustainable development practices, which have significant implications for the social, economic, and environmental sustainability of the country. Spatial and temporal variations in precipitation are the major causes of floods and droughts in the study area, resulting in severe damage to the socioeconomic status of Pakistan. Previous studies have been conducted

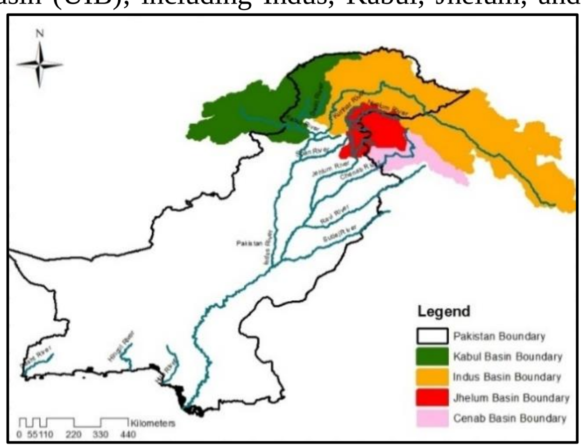

Figure 1. Study Area – Western Rivers of Pakistan

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on a broader scale, considering the UIB as a whole, whereas this study aims to provide an in-depth analysis of the intercomparison of the four basins by examining their rainfall characteristics under changing climatic conditions. Scientific and technologically advanced tools such as the Data Integration and Analysis System (DIAS) have been employed for GCMs selection and bias correction, whereas flood simulations for the Jhelum River Basin have been carried out using the Water and Energy Budget-based Rainfall Runoff Inundation (WEB-RRI) model. The multi-basin study also focused on a sensitivity analysis of the Mangla Dam operation, the functioning of its flood storage zone, and the construction of a dam for flood mitigation. This study also proposes policy recommendations for the country's water resources, supporting the development of policies for disaster risk reduction and aiding sustainable water availability in a changing climate.

THEORY AND METHODOLOGY

This study has four major components: 1) climate change impact assessment, 2) hydrological impact assessment, 3) sensitivity analysis of dam operation and inundation, and 4) policy recommendations for disaster risk reduction and sustainable water availability. Figure 2 illustrates the research methodology.

1) Climate Change Impact Assessment: Five GCMs were selected for the study area using the CMIP5/DIAS tool. Special Correlation (Scorr) and Root Mean Square Error (RMSE) indices were used to rank the GCMs. The selected GCMs were CCSM4, CESM1(BGC), CESM1(CAM5), GFDL-ESM2G, and GFDL-ESM2M. In-situ rainfall data from 1980 to 2005 for the Kabul, Indus, and Jhelum Basins and APHRODITE datasets for the Chenab Basin were employed for statistical bias correction of the rainfall data of the GCMs using DIAS. Extreme rainfall, normal rainfall, and no-rain-day corrections were employed using the Generalized Pareto Distribution, Gamma Distribution, and Statistical Ranking Order, respectively (Nyunt, Koike, and Yamamoto, 2016). Bias-corrected rainfall was used to assess the meteorological impact of climate change on rainfall characteristics in all four river basins and their intercomparison for past (1980-2005) and far future (2075-2100) scenarios.

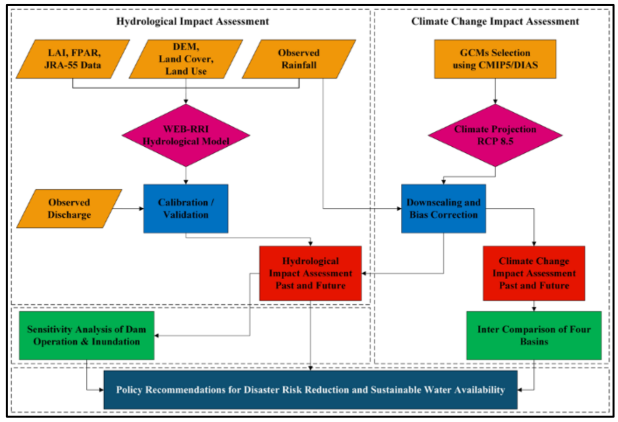

Figure 2. Research Methodology Flow Chart

2) Hydrological Impact Assessment: The WEB-RRI was developed by Rasmy et al. (2019) to improve the accuracy of flow estimation, the timing of flood onset, peak flood discharges, inundation depth/flood extent, and the reliability of flood and drought risk assessments for past and future events by incorporating evapotranspiration fluxes, soil and vegetation interceptions, and soil moisture dynamics. Climate change impact assessments of the study area have revealed that there will be more frequent and intense flood events in the future. Therefore, considering the time, data, and model constraints, the Jhelum River Basin (Figure 3) was selected for flood simulations as it has less snowmelt contribution to river runoff compared to the other three (3) basins and flood peaks could be simulated with rainfall data alone.

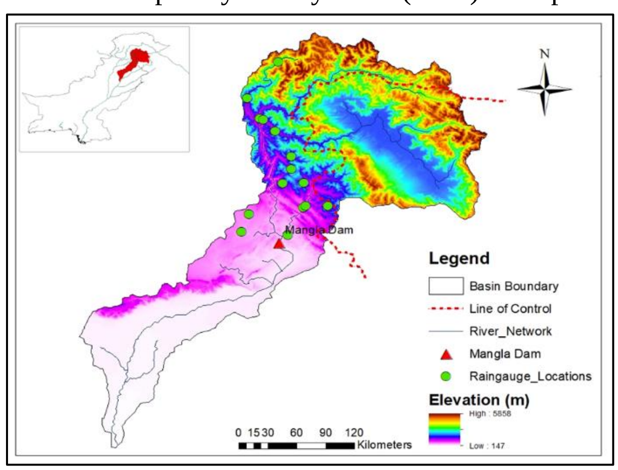

Figure 3. Elevation Profile of Jhelum River Basin

3) Sensitivity Analysis of Dam Operation and Inundation: Mangla Dam is an important hydraulic structure in the Jhelum River Basin, with a reservoir capacity of approximately 9 BCM. It plays a vital role in flood management in downstream areas, along with the storage of precious water. The sensitivity of dam operation to past and future flood events was analyzed in this study to determine its role in flood mitigation.

4) Policy Recommendations for Disaster Risk Reduction and Sustainable Water Availability: Based on the findings of this multi-basin study, policy recommendations are suggested for disaster risk reduction and sustainable water availability to promote the prosperity and socioeconomic well-being of the people of Pakistan.

DATA AND MODEL SETUP

In-situ precipitation and discharge data collected from the PMD and WAPDA were used for the Kabul, Indus, and Jhelum River Basins, whereas the APHRODITE dataset was used for the Chenab River Basin. To set up the WEB-RRI model, elevation and hydrographic data from HydroSHEDS, soil and land use data from the FAO and USGS, dynamic vegetation data (FPAR and LAI) from MODIS, and hydrological model forcing data (JRA-55) from JMA were used. Field-verified flood inundation data for the Jhelum River Basin downstream of Mangla Dam were obtained from the Punjab Irrigation Department for the 2014 flood event, along with the processing of the MODIS surface reflectance product (MOD09A1) using the Normalized Difference Water Index (NDWI).

RESULTS AND DISCUSSION

1. Climate Change Impact Assessment

1.1. Climate Change Impact on Seasonal and Annual Rainfall: Pakistan has three seasons of rainfall: i) pre-monsoon (April–June), ii) monsoon (July–September), and iii) winter (December–March). All seasons along with annual rainfall were analyzed to determine the seasonal behavior of rainfall in the future. The percentage change in the average annual, pre-monsoon, monsoon, and winter rainfall in all four basins is presented in Figure 4 for the far future under RCP 8.5. The results are quite interesting– in the Kabul, Jhelum, and Chenab River Basins, most of the GCMs projected a decrease in average rainfall in all seasons, whereas, for the Indus River Basin, there was an increasing trend. The maximum decrease occurred in winter rainfall, which means that already water-deficient winters will be drier in the future. Not all GCMs predicted the same rainfall trend; rather, some GCMs predicted the opposite, which could be a misrepresentation of the topography of the basin owing to the very coarse resolution of GCMs, the physics behind the model calculations, etc. An uncertainty analysis was performed which revealed that specific humidity was the cause of the different behaviors of the GCMs.

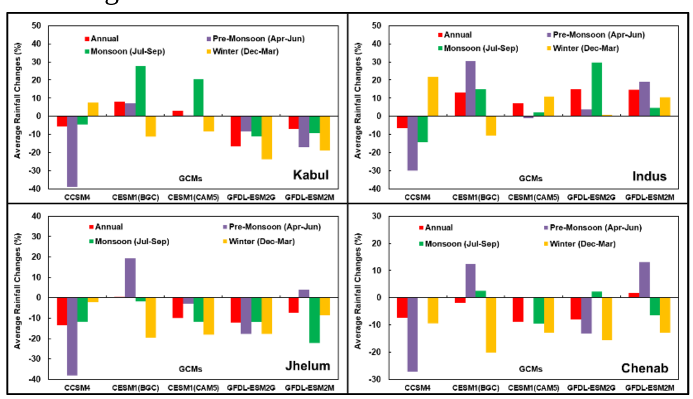

Figure 4. Percentage Change in Rainfall between Past and Far

1.2. Climate Change Impact on Rainfall Extremes and Droughts: To analyze rainfall extremes and droughts, the average annual occurrence of rainfall events greater than 50 mm was estimated along with non-rainy days in all four basins in the study area. Almost all models predicted an increase in rainfall events greater than 50 mm in all four basins, except for one model (CCSM4), which predicted a decrease in the Kabul River Basin. A maximum increase in rainfall events greater than 50 mm was observed for the Jhelum River Basin. Similar to the >50 mm rainfall events, the average annual occurrence of non-rainy days also increased in all river basins in the study area. All GCMs depict an increase in non-rainy days in all basins except one model, CESM1(CAM5), which shows a decrease in the Chenab River Basin only. The results are shown in Figure 5.

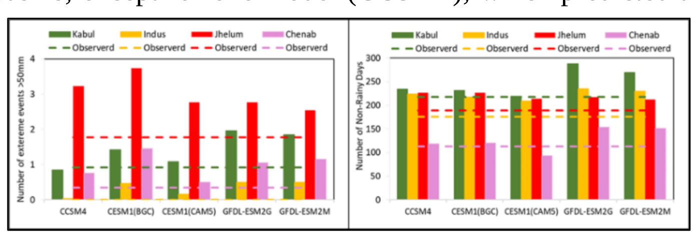

Figure 5. Average Annual Occurrence of >50mm Rainfall Events (Left) and Non-Rainy Days (right)

1.3. Climate Change Impact on Return Period Rainfall: In this study, the GCMs output was used to compare return period rainfall for past and future scenarios for the four river basins in the study area. All selected GCMs predicted an increase in rainfall intensity for the Kabul and Chenab River basins, with an increase in the return period for the far future scenario. For the Indus and Jhelum River basins, two models (CCSM4 and GFDL-ESM2M) predicted a decrease and three models (CESM1(BGC), CESM1(CAM5), and GFDL-ESM2G) predicted a likely increase in rainfall intensity with an increase in the return period. Overall, the analysis shows that rainfall intensity in all river basins is likely to increase in the future, as the majority of GCMs show an increase. This means that more intense flood events will be expected in the future, requiring more careful planning, especially for flood risk reduction. Figure 6 shows a comparison of past and future rainfall intensities for different return periods for the four river basins for the selected GCMs.

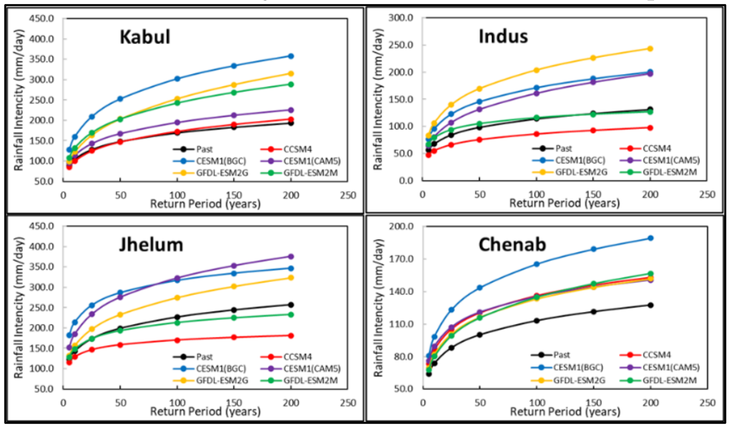

Figure 6. Rainfall Intensity and Return Period Comparison

2. Hydrological Impact Assessment

2.1. WEB-RRI Model Calibration and Validation (Discharge and Inundation): The model calibration for discharge was performed for the 2014 flood event, resulting in 0.72 NSE, 39.16 MBE, and 145.38 RMSE values. The same calibration parameters were subsequently used for model validation, specifically for the 1992 and 2010 flood events. The model performance indices and simulated hydrograph (Figure 7) demonstrate its capability to accurately simulate the peak discharge and timing of the discharge. The 2014 flood event was used to validate flood inundation. The model results were compared with MODIS and field-verified data and a good fit was found.

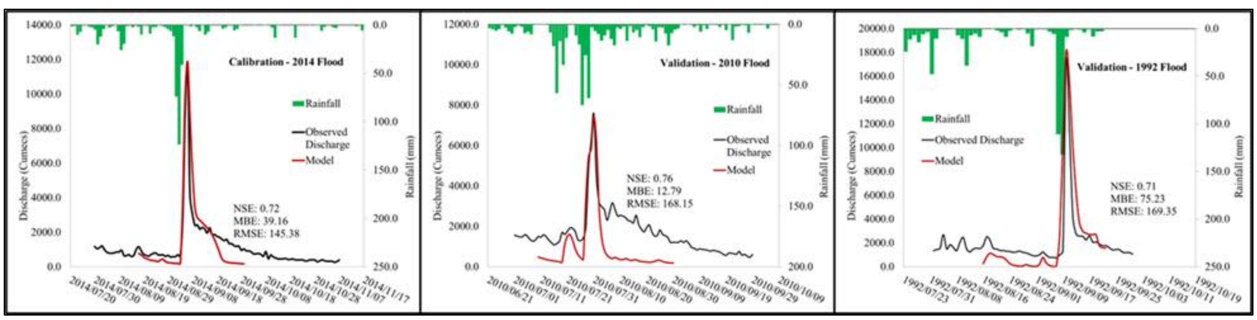

Figure 7. Calibration (2014) and Validation (1992 & 2010) of the WEB-RRI Model

2.2. Climate Change Impact on Peak Discharge: Maximum rainfall events from all selected GCMs were extracted for the far future scenario being the worst case and fed into the model by generating rainfall data using the Thiessen polygon method. The temperature differences for the past and far future scenarios were calculated using the GCMs temperature data from CMIP5/DIAS. All GCMs peak rainfall events were simulated using an already calibrated and validated hydrological model (WEB-RRI), and the peak discharges were obtained for each GCM. The CESM1(BGC) GCM generated the maximum flood hydrograph, with a peak discharge of approximately 28000 cumecs as shown in Figure 8.

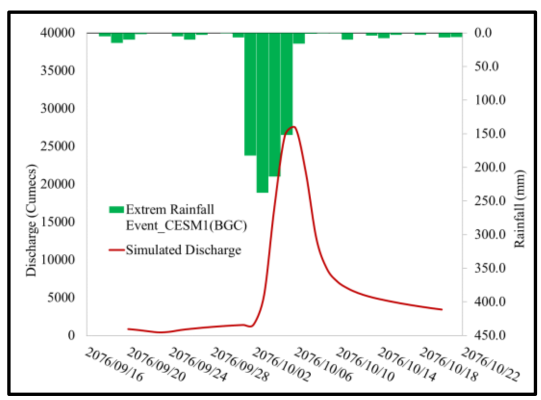

Figure 8. Flood Hydrograph for Extreme Rainfall Event of CESM1(BGC)

3. Sensitivity Analysis of Dam Operation and Inundation

3.1. Dam Operation for Past Floods: To analyze dam operation sensitivity, the operation of the Mangla Dam during the 2014 flood event was examined in detail. This was a major flood event in the Jhelum River Basin that caused huge losses of human life and the economy. The dam operated inefficiently during this flood event, causing significant inundation and damage downstream of the dam. There was minimum water release as per the irrigation requirements until the onset of peak inflow, and suddenly, a huge amount of water was released, which caused havoc downstream. The full storage potential of the dam was not utilized, and the reservoir was filled later with comparatively lesser inflows. This may have been due to unreliable flood forecasts and directions from the regulator to fill the dam as soon as possible. This study proposes that if the release of water could have started with an increase in the inflow, the maximum release could have been kept as low as 2,800 cumecs instead of 14,000 cumecs, and the flood peak could have been trimmed efficiently without jeopardizing the filling of the reservoir up to its maximum conservation level (MCL). The proposed reservoir operation could have resulted in less inundation, as observed from the comparison (Figure 9) and prevented or minimized flood damage in the downstream areas of the dam. Dam operators may need flexibility in reservoir operations during floods to minimize inundation and damage downstream.

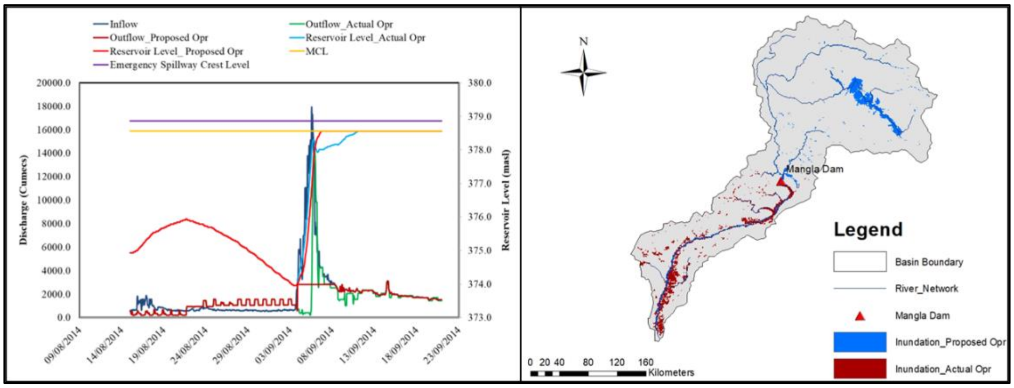

Figure 9. Comparison of Dam Operation (left) and Flood Inundation (right)

3.2. Dam Operation Scenarios for Future Extreme Floods under Changing Climate: Extreme future flood discharge data obtained using CESM1(BGC) projections were used for dam operation scenarios for flood mitigation and a comparison of flood inundation downstream of the dam. The Mangla Dam storage capacity is primarily used for irrigation supplies, and as per existing SOPs, the dam can be depleted to 1.5 m, maximum only in case of Category III flood forecast (>20,000 Cumecs) which is not sufficient to absorb big floods. The dam has a flood storage zone with a 1.9 BCM storage capacity but currently, it cannot be utilized because of the non-operation of the emergency spillway. Considering the operational constraints and current SOPs, four scenarios were developed to study the impact of the dam operation on flood inundation downstream of the dam. Scenario 1: Without dam operation (inflow=outflow); Scenario 2: Dam operation without utilizing the Flood Storage Zone, Scenario 3: Dam operation with the utilization of the Flood Storage Zone, and Scenario 4: Dam operation with the utilization of the Flood Storage Zone and Rohtas Dam (construction of new dam). Figure 10 shows the percentage of inundation area resulting from dam operation for the four scenarios described above. This study suggests that because of the existing operational constraints, the Mangla Dam will not be able to mitigate future extreme floods efficiently, as we can see from the inundation results for Scenario 2. For efficient flood routing, the emergency spillway must be operationalized by utilizing the flood storage zone of the Mangla Dam. However, flood inundation resulting from extreme flood events will occur in the future, as observed in Scenario 3. The construction of the Rohtas Dam, along with the utilization of the flood storage zone, will be a great initiative for mitigating the impact of extreme floods in the future. The implementation of the Rohtas Dam Project will not only help mitigate floods but also support the achievement of sustainable water availability in the case of droughts in the future.

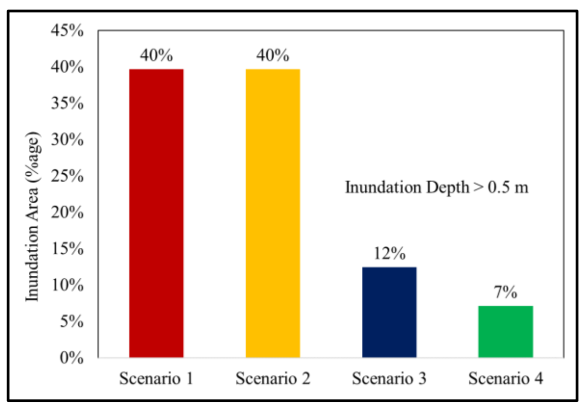

Figure 10. Comparison of Percentage Inundation Area for Dam Operation Scenarios

4. Policy Recommendations for Disaster Risk Reduction and Sustainable Water Availability: Climate change analysis of the study area indicates that more frequent and intense flood and drought events will occur in the future, posing serious challenges to disaster risk reduction and sustainable water availability. Despite the existence of numerous policies, their effectiveness is hindered by inadequate implementation and the need for timely revisions, particularly in the context of evolving climate and weather patterns. These adjustments should be based on global research outcomes to ensure optimal benefits. Disaster management requires a comprehensive approach because no single measure is sufficient. The suggested policy recommendations include a review of existing reservoir operation SOPs; providing more flexibility to the dam operator, dam construction, and resilient infrastructure; strengthening early warning systems; improving the accuracy and reliability of flood forecasts and climate-resilient practices; implementing land-use planning and zoning; strengthening water resources management and promoting community engagement and awareness.

CONCLUSION AND RECOMMENDATION

Pakistan faces formidable climate change challenges, necessitating immediate measures to alleviate their impact on the economy, environment, and society. This study assessed the impact of climate change on rainfall characteristics in four major river basins in the country and their intercomparison, along with a hydrological impact assessment and dam operation sensitivity analysis for the Jhelum River Basin. The findings of the climate change analysis indicate an astonishingly reduced annual and seasonal average rainfall in most basins, impacting water availability and agriculture. However, increased extreme rainfall events will further intensify flood risks in the future, demanding adaptive flood-mitigation strategies. This study also found an increase in drought occurrences that could exacerbate water scarcity in the future, especially in already water-deficient winters, which require sustainable drought mitigation measures. Hydrological simulations of future extreme rainfall events indicated an increase in flood inundation under a changing climate. The dam operation sensitivity analysis suggests that the utilization of the Mangla Dam flood storage zone and the implementation of the Rohtas Dam Project would be an effective combination for the mitigation of intensified future flood risks. Finally, this study proposes policy recommendations for disaster risk reduction and sustainable water availability. This intercomparison study serves as a foundation for future research and policy formulation, emphasizing the need for ongoing monitoring and assessment of climate change impacts on the water resources of the country. By recognizing the changing rainfall patterns and reduction in average annual and seasonal rainfall, acknowledging the increasing frequency of extreme rainfall events and droughts, and taking prompt and informed action, Pakistan can build resilience to climate change, protect its communities, and ensure sustainable development in the face of a changing climate.

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