Assessing Sediment Yield and Reservoir Sustainability in the Indus Basin: A 30-Year Hydrological Modeling Approach for Tarbela Dam Management

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Over the past thirty years, sedimentation in Pakistan's Tarbela Reservoir—a critical hub for irrigation and hydropower—has significantly reduced its active storage capacity, driven primarily by sediment influx from the Upper Indus Basin (UIB). This research evaluates sedimentation dynamics (1994–2023) through an integrated approach combining satellite-derived data (USGS STRM, ERA5-Land Climate Reanalysis, FAO Soil Maps, and Global Land Cover datasets) with field measurements from the Surface Water Hydrology Project and Tarbela Dam archives. A spatially distributed model of the 102,028 km² UIB watershed was developed using ArcSWAT, incorporating 26 subbasins and 64 hydrological response units (HRUs) to address heterogeneity. Sensitivity analysis, calibration, and validation were conducted via SWAT-CUP with the SUFI-2 algorithm, employing 22 parameters. The model demonstrated strong performance, yielding calibration metrics ($R^2 = 0.89$, NSE = 0.84) and validation results ($R^2 = 0.81$, NSE = 0.68). Simulations revealed that 78% of precipitation at Besham Qila contributes to streamflow, dominated by surface runoff (61%). Peak rainfall, sediment flux, and discharge coincided in July. Annual surface runoff averaged 505.35 mm, with upland sediment yields ranging between 2,086.09 and 5,772.90 Mg/ha. Substantial in-channel sediment deposition (-2,082.52 Mg/ha) exacerbates flood vulnerability. Decadal analysis indicated a decline in sediment yields from 5.9–385.3 to 2.7–370.6 tons/ha. To mitigate sedimentation impacts on reservoir capacity and energy production, the study proposes targeted interventions such as afforestation, terraced agriculture, check dam installation, and sustainable land management. Long-term monitoring collaboration is emphasized to preserve hydraulic infrastructure efficiency and resilience.

Keywords: SWAT; SWAT-Cup; Sedimentation; Tarbela Dam; Upper Indus Basin; storage capacity