ABSTRACT

This research responds to key challenges in hydrological modelling, particularly the inadequate representation of spatial heterogeneity, poor performance of internal hydrological processes when using streamflow (SF) only calibration, and high uncertainties in future climate projections derived from General Circulation Models (GCMs). To address these gaps, a comprehensive methodological framework was adopted. First, the Soil and Water Assessment Tool (SWAT) was calibrated using both Single-Site Calibration (SSC) and Multi-Site Calibration (MSC) at three gauging locations Muri (upstream), Jamshedpur (midstream), and Ghatshila (downstream) in the Subarnarekha River Basin (SRB). MSC effectively captured spatial heterogeneity, achieving higher Nash–Sutcliffe Efficiency (NSE) (up to 0.89), lower percent bias, and reduced model uncertainty. Second, to improve internal hydrological process representation, the study advanced beyond traditional Single-Variable Calibration (SVC), which relied solely on SF, by employing Multi-Variable Calibration (MVC) scheme that integrate the different combination of satellite-based evapotranspiration (ET) and soil moisture (SM) with SF. The calibration schemes (SF, SF+SM, SF+ET, SM+ET, and SF+ET+SM) were systematically assessed using a Repeated Measures Design to evaluate the stability of major hydrological components, including surface runoff (SURQ), SM, ET, and key sensitive parameters (CN_2 and ALPHA_BNK). The SM+ET calibration scheme, however, showed limited capability in streamflow simulation, highlighting the necessity of including observed SF data in calibration. The SF+ET+SM scheme demonstrated the highest stability across all indicators, outperforming SVC by reducing uncertainties in water balance components and enhancing the robustness of hydrological simulations; therefore, it was selected for further analysis. Third, to generate best climate projections for future water scarcity assessment, 13 GCMs were evaluated using the Taylor skill score and rating metric. The five best-performing GCMs were chosen to construct a machine-learning-based ensemble employing random forest, linear regression, and Gradient Boosting (GB) techniques and compared with Mean Ensemble (ME). The GB approach provided the most accurate representation of climate extremes and seasonal rainfall variability, outperforming the simple ME. Accordingly, the GB-based MME climate projections for the Near Future (NF: 2021–2060) and Far Future (FF: 2061–2100) were used as inputs to the SWAT model to assess Green Water Scarcity (GWS) and Blue Water Scarcity (BWS) under the SSP2-4.5 and SSP5-8.5 scenarios, with 1991–2020 serving as the Base Period (BP) for comparison. Although annual rainfall is projected to increase under both climate scenarios compared to BP, the results reveal worsening water scarcity caused by pronounced monsoonal concentration, extended dry-season deficits, and increased ET under warming conditions. GWS intensifies during the rabi cropping periods, despite monsoon surpluses, indicating reduced effectiveness of rainfall for crop needs. BWS becomes more severe under SSP5-8.5 due to elevated irrigation requirements associated with higher ET, particularly during post-monsoon months. This mismatch between water availability and irrigation demand underscores the increased hydrological stress expected in SRB. Finally, to address these projected water scarcity challenges, three nature-based adaptation strategies, Increased Forest Cover (IFC), pond development, and their combined implementation (IFC + Pond), were simulated using the multi-site, multi variable validated SWAT model. The results indicate that while pond development alone enhances local water storage with limited basin-scale influence and IFC improves soil moisture, their combined implementation strategy substantially greater hydrological benefits. The integrated IFC + Pond strategy reduces SURQ by 3–17% during monsoon months, increases groundwater contribution to streamflow (GW_Q) by 3–7%, and enhances blue water availability by up to 6.4% during dry periods. Collectively, these improvements highlight the superior effectiveness of the combined strategy in mitigating both BWS and GWS strengthening basin-scale hydrological resilience under future climate stress.

Keywords: SWAT, Multi-Site Calibration, Multi-Variable Calibration, Climate Model Selection, Multi Model Ensemble, Blue Water Scarcity, Green Water Scarcity, Improved Forest Cover, and Pond development.