ABSTRACT

In the 21st Century, river basins are facing an alarming decline in high-quality freshwater reserves due to unremitting groundwater depletion and inadequate natural replenishment, leading to significant alterations in the basin-scale recharge–discharge dynamics. Addressing these challenges necessitates an integrated basin-scale hydrological and groundwater flow modelling framework to support sustainable aquifer management and river restoration initiatives. However, deltaic river systems pose unique modelling challenges owing to their complex river networks, flat topography, and multiple outlets, which limit the applicability of conventional basin models that rely on a single common outlet. Under these circumstances, the present study was undertaken with the overarching objective of developing an integrated hydrodynamic routing and groundwater flow modeling framework for a multi-layered deltaic aquifer system in the Lower Mahanadi Basin, Odisha, India. This study includes field investigations and data collection, in-depth analyses of hydrologic and hydrogeologic data, estimation of spatiotemporal variation in the groundwater recharge, development of bivariate copula-based and hybrid machine learning-based multi-Digital Elevation Model ensemble models for generating high-accuracy river cross-sections at ungauged river sections, and the development of loosely coupled streamflow routing and quasi-three-dimensional groundwater-flow model.

The results of the long-term analysis of rainfall and groundwater level indicated non-linear and non-monotonic trends (increasing and/or decreasing trends) with periodicities for most of the rainfall clusters and groundwater monitoring sites. The linear trend analysis of rainfall revealed an increasing trend (1.3 to 17.6 mm/year) in the northern part of the study area, whereas a decreasing trend (12.13 to 33.25 mm/year) was observed in the southern part. On the other hand, a consistent decline was observed in the low flow (-2.71 to -27.6 m^3/s/year) and medium flow (-1.83 to -12.43 m^3/s/year) for the deltaic river systems. About 60% of the total wells exhibited a significantly decreasing trend during the pre-monsoon season (0 to 0.18 m/year), whereas about 50% of the wells had a declining trend in the post-monsoon season (0 to 0.13 m/year). Regarding the interaction between rainfall and groundwater level, the results of the Cross-Wavelet Transform analysis indicated significant coherence (>0.7) with a mean lag time ranging from 2.25 ± 1.31 to 64 ± 27 days, which highlights considerable spatial heterogeneity in recharge dynamics. The average groundwater recharge in the study area varied from 11.6 to 161.92 Mm^3, with higher and lower standard deviations for the WTF and Entropy methods (3.7 to 5.5 Mm^3) and the Empirical methods (0.4 to 0.8 Mm^3). For simulating the observed streamflow and water level hydrographs in the deltaic river systems, the MIKE11-HD model performed the best with the surveyed river cross-sections (streamflow: NSE = 0.81–0.92; water level: NSE = 0.7–0.78) followed by the copula-based CSRTM model derived cross-sections (streamflow: NSE = 0.74–0.88; water level: NSE =

0.54–0.71) and the CASTER model generated cross-sections (streamflow: NSE = 0.61–0.82; water level: NSE = 0.51–0.72). Compared to these copula-based models, the MDE models-derived cross-sections were found to be robust, with improved efficiency, while simulating spatially varying streamflow and water for deltaic river systems. The MIKE11-HD-RFMDE and MIKE11-HD-DNNMDE models have NSE values ranging from 0.78 to 0.91 and 0.76 to 0.91, respectively, for streamflow. The NSE values for the simulated water level hydrographs range from 0.68 to 0.77 and 0.67 to 0.76, respectively. The stratigraphy analysis of the basin indicated the existence of an uppermost unconfined aquifer of thickness 3.57 to 132 m and a lower confined aquifer of thickness 4.6 to 199 m, separated by a confining layer (aquitard) of thickness 3.44 to 60 m. Moreover, the coupled streamflow and multi-aquifer groundwater-flow model was successfully calibrated and validated using the MIKE11-HD and Visual MODFLOW Flex 11.0 software. During calibration, the NSE, RMSE, and NRMSE values range from 0.8–0.95, 0.15–0.5 m, and 5.3–14.9%, respectively for the unconfined aquifer, whereas they vary from 0.81–0.94, 0.29–0.58 m, and 7.14–13.4%, respectively for the confined aquifer system. Likewise, during validation, the NSE, RMSE, and NRMSE values for the unconfined aquifer range from 0.70–0.83, 0.27–0.81 m, and 10.3–17.4 m, respectively, with corresponding values of 0.7–0.89, 0.24–0.74, and 10–20.4%, respectively for the confined aquifer system. The sensitivity analysis of the groundwater-flow model revealed that the groundwater level is most sensitive to the hydraulic conductivity of both the aquifers, followed by the changes in river stage, specific yield of the unconfined aquifer, specific storage of the confined aquifer, and rainfall recharge of the unconfined aquifer.

Keywords: *Linear and Non-linear trend analysis; Rainfall-groundwater interaction dynamics; Public domain DEMs; Bivariate copula models; Hybrid Machine Learning techniques, Particle Swarm Optimization, Dynamic streamflow routing; Coupled streamflow and Groundwater-flow modeling; Deltaic River distributary system.*