

LONG-TERM HYDROLOGICAL ASSESSMENT AND WATER SUSTAINABILITY USING SWAT+ FOR THE AL-JOUF WATERSHED

INTERNAL RESEARCH CONTRIBUTION

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- Building on the earlier internal research on water footprints and SWAT-based water-resource assessment in Al-Jouf, the modeling team has extended the work toward a long-term, Earth observation-driven hydrological assessment of the Al-Jouf watershed. The updated study applies SWAT+ to characterize water-balance behavior under severe data limitations by integrating climate reanalysis, satellite-derived evapotranspiration, remote-sensing imagery, soil, terrain, and land-use information.

- The analysis establishes a 25-year hydrological baseline for 2000-2024. ERA5-Land was used for meteorological forcing, while GLEAM evapotranspiration supported model calibration and validation. The model showed good performance against GLEAM, with R^2 = 0.80 and NSE = 0.74 during calibration and R^2 = 0.78 and NSE = 0.72 during validation. This provides confidence for using the framework to examine hydrological variability in a poorly gauged hyper-arid environment.

- The results highlight the exceptional water limitation of Al-Jouf. Approximately 91.7% of precipitation was returned to the atmosphere through evapotranspiration, whereas only about 0.053% was simulated as surface runoff. This confirms that the watershed is strongly evapotranspiration-dominated and that opportunities for surface-water generation are limited and highly dependent on episodic winter rainfall.

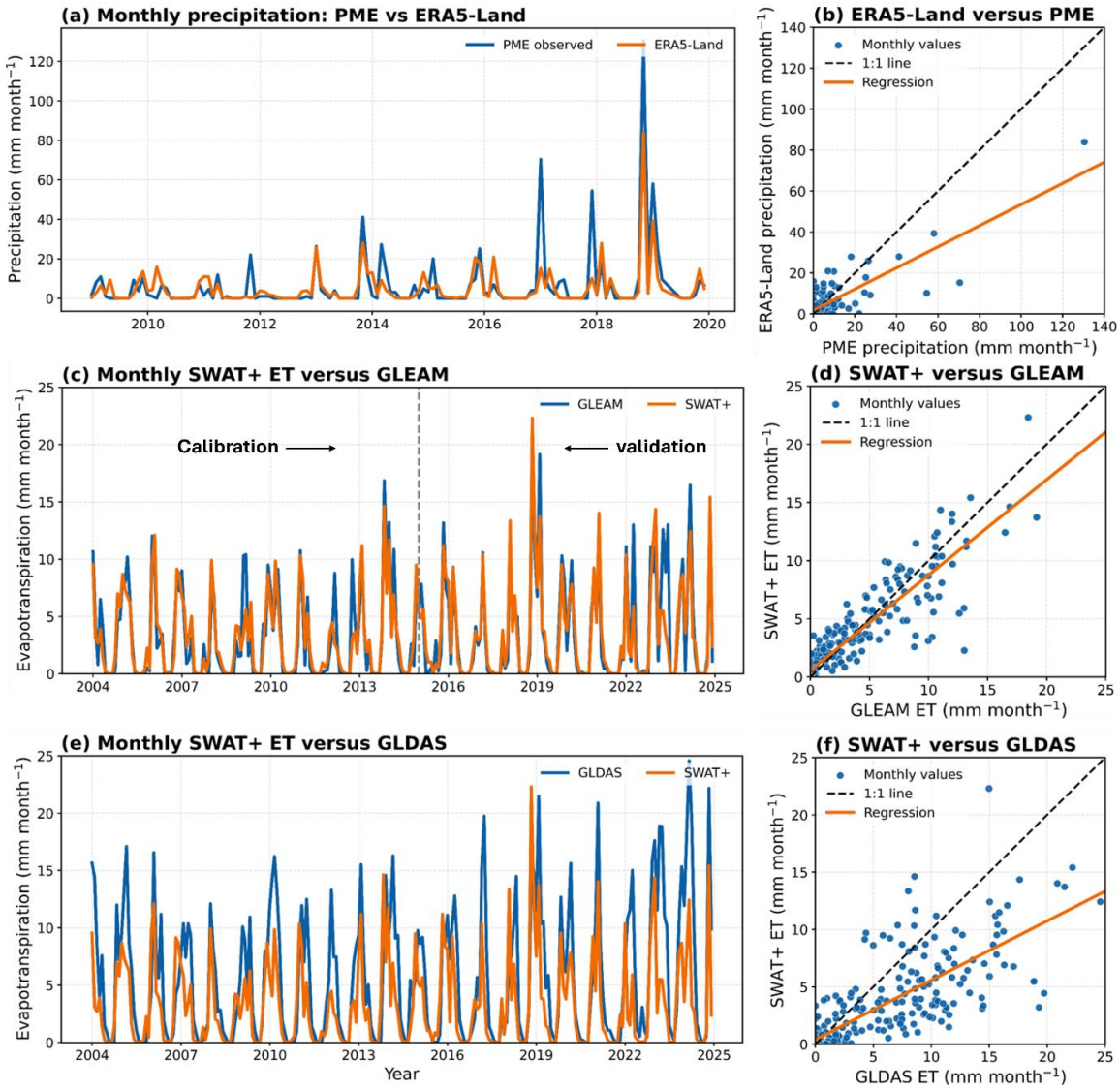


Fig. 1. Evaluation of ERA5-Land precipitation and SWAT+ evapotranspiration performance against PME, GLEAM and GLDAS datasets.

A major advancement in the current phase is the assessment of wet, normal, and dry hydrological conditions. During the representative wet year, watershed-average precipitation reached about 148 mm, with evapotranspiration of approximately 105 mm, surface runoff of about 0.15 mm, and water yield of about 1.1 mm. In contrast, the dry year received only around 16 mm of precipitation and generated negligible runoff and water yield. These results demonstrate the strong sensitivity of the basin to interannual rainfall variability and emphasize the importance of winter rainfall for both immediate runoff and delayed subsurface contributions.

Spatial analysis shows that runoff and water-yield generation are highly localized. The most responsive areas occur around Dumat Al-Jandal and Al Safah Al Shimali, while large

parts of the northern and western watershed remain hydrologically weak. These hotspots are particularly important for future groundwater-recharge assessment, floodwater harvesting, managed aquifer recharge, and targeted hydrological monitoring.

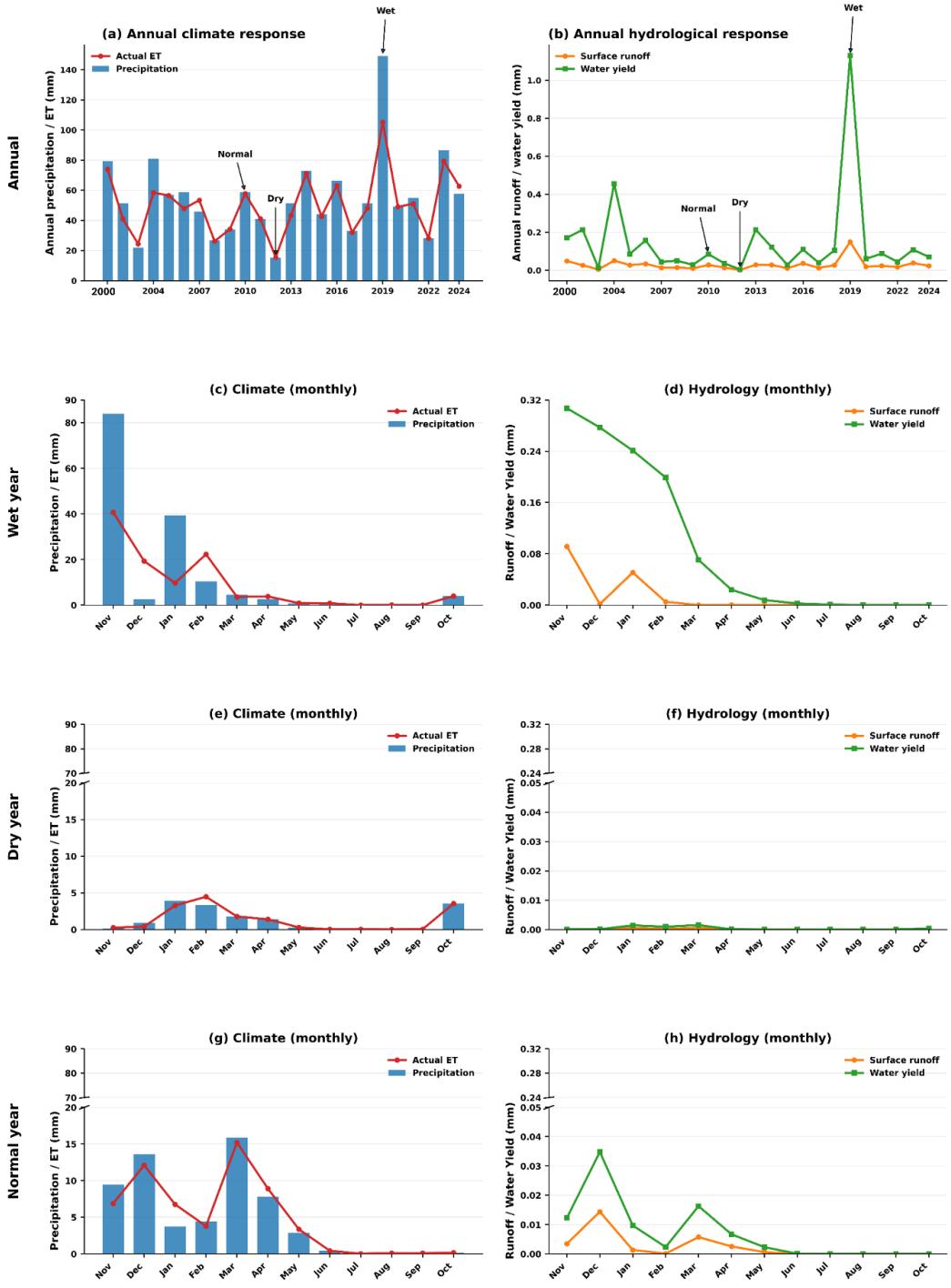


Fig. 2. Temporal variability of precipitation, evapotranspiration, surface runoff and water yield during 2000-2024, including representative wet, dry and normal years.

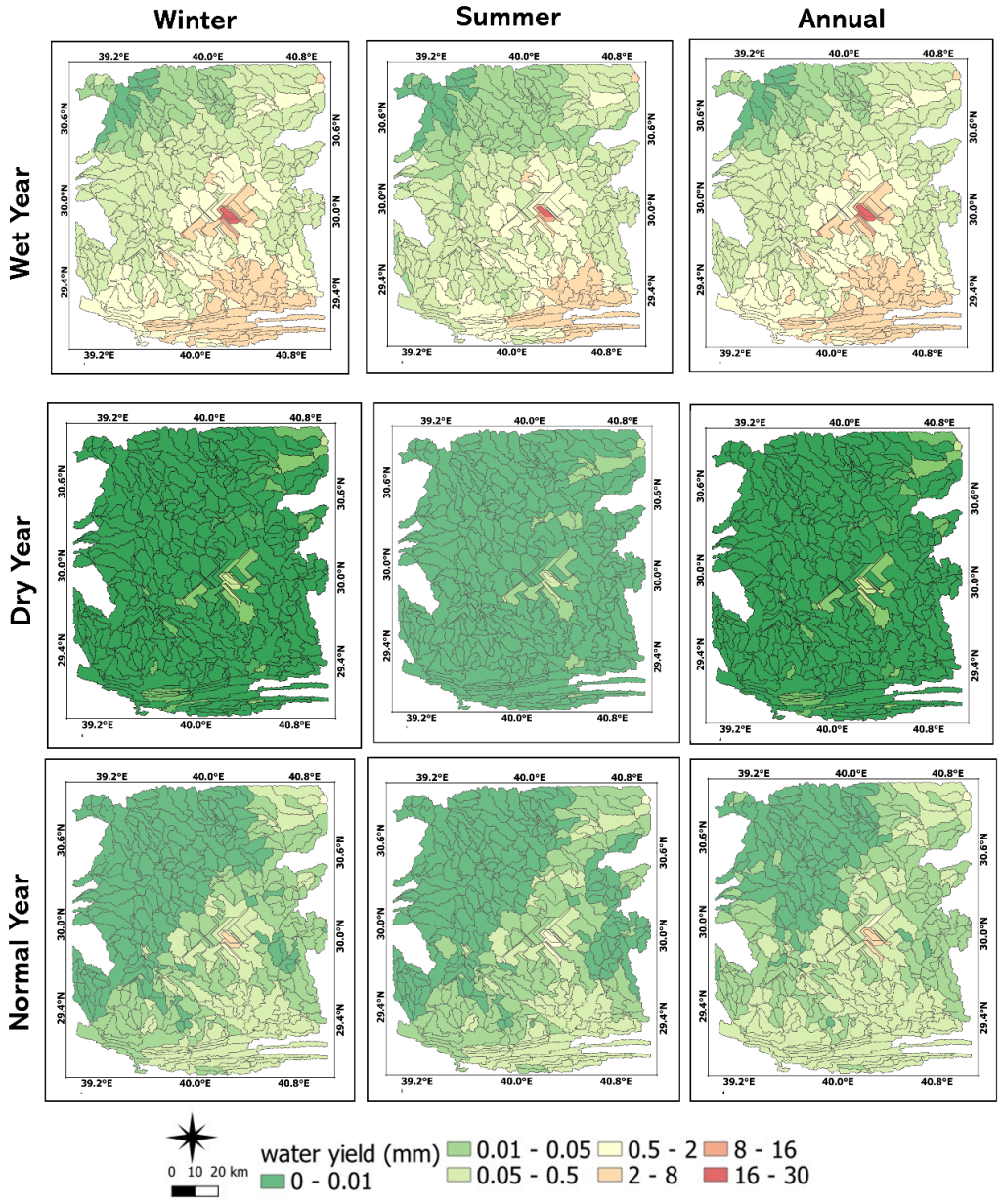


Fig. 3. Spatial distribution of simulated water yield showing localized hydrological response in the central Al-Jouf subbasins.

The hydrological simulations were complemented with Landsat- and Sentinel-2-derived Modified Normalized Difference Water Index (MNDWI) maps processed in Google Earth Engine. Seasonal surface-water patterns at representative locations showed qualitative agreement with the central zones where SWAT+ simulated stronger runoff and water yield. The combined use of physically based modeling and multi-sensor Earth observation

strengthens the ability to assess water resources in areas where continuous streamflow monitoring is unavailable.

The present study establishes a baseline hydrological framework for the Al-Jouf watershed, which will support future climate-change assessments using CMIP6 projections under different Shared Socioeconomic Pathway (SSP) scenarios. The next phase will evaluate potential future changes in precipitation, evapotranspiration, runoff, water yield, and overall water availability, providing a basis for climate-resilient water-resource management and adaptation planning

This work contributes directly to the broader sustainability agenda. It supports SDG 6 (Clean Water and Sanitation) by improving knowledge of water availability, hydrological response, and priority areas for sustainable water-resource planning; SDG 2 (Zero Hunger) by providing a scientific basis for more water-efficient and climate-resilient agricultural planning in a groundwater-dependent region; and SDG 13 (Climate Action) by quantifying the response of a hyper-arid watershed to wet and dry climatic variability. The spatial monitoring and Earth observation component also supports ecosystem and land-resource management relevant to SDG 15 (Life on Land).

The updated research therefore moves beyond the earlier water-footprint focus by providing a long-term hydrological baseline, calibrated SWAT+ framework, spatial identification of runoff and water-yield hotspots, and satellite-based evaluation of surface-water response. These outputs can guide future field monitoring, groundwater-recharge studies, floodwater-harvesting strategies, and sustainable water-management interventions in Al-Jouf and comparable hyper-arid regions.

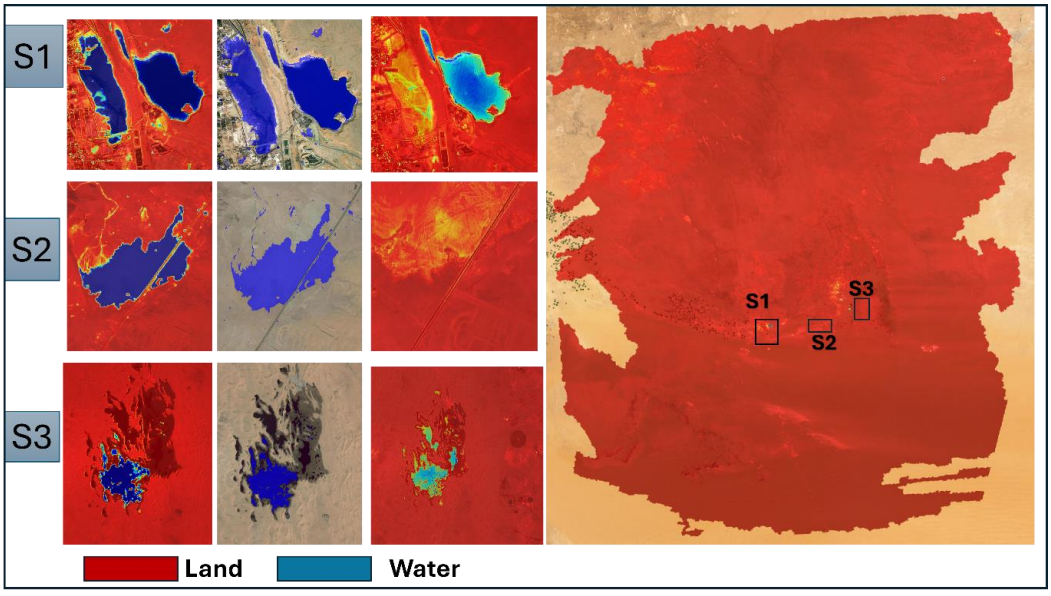


Fig. 4. MNDWI-derived open surface-water features from Landsat and Sentinel-2 imagery at representative locations in the Al-Jouf watershed.