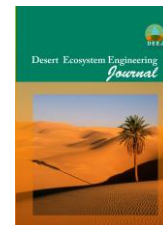




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Spatiotemporal Prediction of Precipitation Distribution in the Urmia Basin Using an EEMD-SVM-LSTM Hybrid Model

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Extended Abstract

Introduction: Accurate prediction of monthly rainfall is crucial for water resource management and risk mitigation in semi-arid regions, particularly under climate change. The Lake Urmia Basin in northwestern Iran has faced significant environmental degradation in recent decades, driven by climatic variability, unsustainable agriculture, and inadequate water management. Forecasting future rainfall patterns is therefore essential for developing adaptive strategies to restore ecological balance and ensure sustainable development. However, traditional statistical models often fail to capture the nonlinear and non-stationary characteristics of hydrological data. This limitation has prompted the exploration of advanced machine learning and deep learning techniques. Hybrid models that integrate signal decomposition with intelligent algorithms have shown superior performance in time series forecasting by improving feature extraction and reducing noise. This study introduces a novel hybrid framework that combines Ensemble Empirical Mode Decomposition (EEMD), Support Vector Machine (SVM), and Long Short-Term Memory (LSTM) networks to simulate and predict monthly rainfall in the Lake Urmia Basin. The proposed EEMD-SVM-LSTM model leverages the complementary strengths of each component to capture both short-term fluctuations and long-term trends, thereby significantly enhancing predictive accuracy.

Materials and Methods: Monthly rainfall data from four synoptic stations—Urmia, Khoy, Tabriz, and Sazez—were collected for the period 1980–2020 for model development and validation. Future projections were then generated for the 2030–2050 period under a business-as-usual scenario. The proposed methodology involved decomposing the original rainfall time series into several Intrinsic Mode Functions (IMFs) and a residual component using the Ensemble Empirical Mode Decomposition (EEMD) method. This decomposition facilitated a multi-resolution analysis by isolating distinct frequency components, thereby simplifying the modeling of complex, non-stationary rainfall dynamics.

The high-frequency IMFs, which represent short-term noise and rapid fluctuations, were modeled using a Support Vector Machine (SVM) algorithm, selected for its effectiveness with nonlinear relationships and limited data. Conversely, the low-frequency residual component, encapsulating the long-term trend, was predicted using a Long Short-Term Memory (LSTM) network, chosen for its ability to learn and retain long-term dependencies in sequential data. The final integrated prediction was obtained by summing the forecasted results from all SVM and LSTM components.

Model performance was quantitatively evaluated using Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). To demonstrate the superiority of the hybrid approach, its predictive accuracy was benchmarked against standalone SVM and LSTM models.

Results: The EEMD process successfully decomposed the rainfall signals into distinct intrinsic mode functions, enabling a more targeted modeling approach. The hybrid EEMD-SVM-LSTM model demonstrated superior predictive performance compared to the standalone SVM and LSTM models. This was evidenced by consistently

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lower error metrics across all stations during both training and validation phases. The RMSE values for the hybrid model ranged from 0.07 to 0.11 mm, outperforming the standalone SVM (0.10–0.29 mm) and LSTM models. Projections for the 2030–2050 period revealed spatially variable changes in rainfall across the basin. Khoy station exhibited the highest annual rainfall increase (+18.8%), whereas Saqez experienced the most significant decrease (–14.9%). At the basin level, the mean annual rainfall is projected to decline by approximately 4%, from 334.5 mm to 320.7 mm. Spatially, the analysis indicated a northward shift in precipitation concentration, with increases projected over Tabriz and Urmia, and decreases in the southern and western parts of the basin. Temporally, a shift toward a more uniform seasonal distribution was observed, characterized by a relative increase in winter and spring precipitation and a more pronounced decline in late-summer rainfall.

Discussion and Conclusion: This study demonstrates that the hybrid EEMD-SVM-LSTM framework effectively captures the multi-scale dynamics of rainfall by integrating signal decomposition with machine learning. The model's superior predictive accuracy over standalone ML and DL models underscores the value of a hybrid approach for processing complex, non-stationary hydrological data, a finding consistent with previous research (e.g., Diop et al., 2020; Yeditha et al., 2023; Jyostna et al., 2025).

The projections indicate a concerning 4% decline in the basin's mean annual rainfall, coupled with a significant spatial redistribution toward northern and central sub-basins. This pattern implies a substantial shift in the regional water balance, potentially increasing flood risks in receiving areas while exacerbating drought and water stress in the southern and western zones. These spatially heterogeneous changes highlight the urgent need for adaptive water resource management. Key strategies should include optimizing irrigation efficiency, updating reservoir operation rules, and revising agricultural cropping calendars to align with the new hydrological regime.

Despite its robust performance, this study is subject to the inherent uncertainties of climate projections and data-driven modeling. Future research should enhance model robustness by incorporating additional climatic predictors—such as temperature, and large-scale circulation indices like ENSO and NAO—as well as high-resolution satellite-based rainfall products to improve spatial representativeness.

In conclusion, the EEMD-SVM-LSTM model provides a powerful and generalizable framework for high-fidelity rainfall forecasting in semi-arid regions. It serves as a critical tool for informing climate-resilient planning and promoting sustainable water resource management in the Lake Urmia Basin and other similarly vulnerable ecosystems worldwide.

Keywords: Rainfall, Climate Change, Lake Urmia Basin, Hybrid Model, Deep Learning, Machine Learning, Time Series Forecasting, Water Resource Management.