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Enhancing Rainfall Estimation for Water Resource Management through Multiple Linear Regression Approach in Khordha District, Odisha, India

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A B S T R A C T

Rainfall estimation holds paramount significance for optimizing water resource utilization and effective management, particularly in countries like India, characterized by an agro-based economy and limited irrigation infrastructure. This paper introduces a multiple linear regression (MLR) model tailored for estimating annual rainfall in Khordha district, Odisha, India. The model is designed to predict rainfall for a given year by leveraging data from the preceding three years. Through rigorous testing on a century-long dataset of annual rainfall, the model demonstrated exceptional performance. By setting the intercept of the MLR model to zero, the derived equation yielded highly accurate results. The predicted values exhibited a robust correspondence with observed data, resulting in a R^2 value of 0.963. This remarkable R^2 value underscores the model's suitability for application across the study area. The robustness and accuracy of this model offers valuable insights for enhancing hydro-meteorological assessments and informing strategic water resource management decisions in the region.

Keywords: Annual rainfall, Multiple linear regression, Khordha district, forecast

1. Introduction

Precipitation holds significant importance in the development, planning, and management of water resources projects (Aadhar et al. 2019; Dayal et al. 2019; Guptha et al. 2021, 2022; Swain et al., 2015, 2017a, 2017b, 2018a, 2018b, 2022c; Verma et al. 2016). In India, where over two-thirds of population relies on agriculture directly, rainfall plays a crucial role, particularly due to the Southwest monsoon (Bahita et al. 2021a, 2021b; Dhal and Swain 2022; Kannan et al. 2010; Swain 2014, 2017; Swain et al. 2019a, 2019b, 2020a, 2021a, 2021b, 2021c, 2022a; Sharma et al. 2020). The majority of annual rainfall is attributed to monsoon rains, making any alterations or fluctuations in precipitation a substantial factor impacting the country's agriculture and food security (Nandi et al. 2024; Swain, 2014; Swain et al. 2020b, 2022b, 2022d, 2022e, 2022f, 2022i, 2022j, 2022k, 2022l). Therefore, proactive measures are essential to mitigate potential disasters or inconveniences arising from precipitation anomalies, necessitating the accurate estimation of annual precipitation (Gagiu et al., 2015). Moreover, with climate change trends exacerbating the variability and intensity of rainfall patterns globally, the need for precise rainfall estimation becomes even more pronounced (Nayak et al. 2013; Olatayo and Taiwo 2014; Patel et al. 2022; Praveen et al. 2020; Swain et al. 2023). Climate models project shifts in precipitation distribution, potentially altering agricultural landscapes and water availability in regions heavily reliant on seasonal rainfall (Nandi and Swain 2023). Therefore, developing robust methodologies for accurately predicting rainfall trends and patterns is paramount for ensuring sustainable water resource management and food security in vulnerable regions. Additionally, the socio-economic implications of erratic rainfall patterns cannot be overstated (Swain et al. 2022g, 2022h, 2023). In regions where agriculture serves as the primary livelihood for a significant portion of the population, fluctuations in precipitation can have far-reaching consequences, impacting incomes, employment opportunities, and overall economic stability (Sahoo et al. 2021, 2022). As such, integrating advanced forecasting techniques and leveraging historical data to refine rainfall prediction models becomes imperative for fostering resilience and adaptive capacity in vulnerable communities. By enhancing our understanding of rainfall dynamics and improving prediction accuracy, stakeholders can better anticipate and prepare for potential challenges associated with climate variability, ultimately safeguarding livelihoods and promoting sustainable development initiatives.

To forecast precipitation in advance, various methods are employed, broadly grouped into two classes: Empirical and Dynamical (Liyew and Melese 2021; Nayak et al. 2006; Nolan et al. 2015; Novotná et al. 2015; Sethi and Garg 2014). The empirical method involves analyzing historical data and their correlation with other variables, typically employing regression techniques. The multiple linear regression (MLR) stands out among empirical methods due to its widespread use, as it effectively illustrates the linkage between several contributing factors, providing an accurate prediction of rainfall (Amiri et al. 2015; Andrews 1974; Krzywinski and Altman 2015; Raval et al. 2021). Additionally, multiple linear regression aids in identifying the more influential variables compared to others (Tuleya et al. 2007; Yu et al. 2015; Zhang et al. 2023).

The conventional belief is that studying climatic patterns should span an extended period, ideally around 30 years. This extended timeframe allows for the observation that the rainfall behavior in a particular year is closely related to the precipitation in its preceding years. This study hypothesizes that the prediction of rainfall in a given year is linked to rainfall in three preceding years. Hence, an accurate prediction of annual rainfall can be achieved by MLR with preceding years' rainfall as predictors.

2. Study area (Khordha District)

The study focuses on Khordha (also known as Khurda) District, located in the state of Odisha, India. Covering an area of 2888 square kilometers (1115 square miles), this district includes the state capital, Bhubaneswar. The central location coordinates of the district is 20.13^0N latitude and 85.48^0E longitude. Khordha (Khurda) district's geographical location in Odisha, India, is depicted in Figure 1 below.

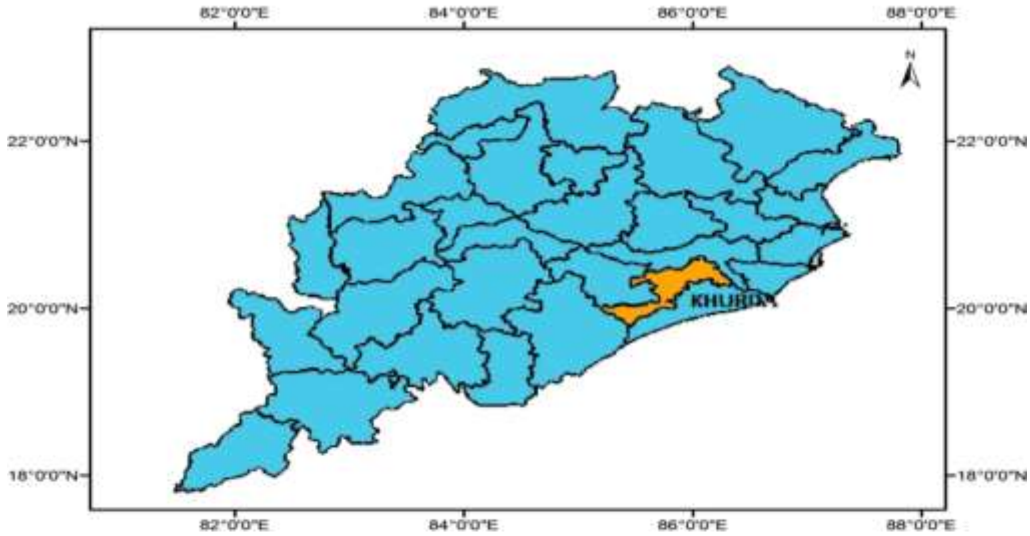

Fig. 1 - Location of Khordha District in Odisha Map.

Regarding climatology, the mean yearly rainfall over the district is around 1400 millimeters. The temperature seems moderate for all over the year except for the summer months (March, April, May, and June). The average minimum and maximum temperature in a year over the Khordha district are 9.6 ^{0}C and 41.4 ^{0}C, respectively.

3. Materials and methods

Data spanning from 1901 to 2002 regarding the annual rainfall in Khordha district was sourced from the India Water Portal. Employing MLR, a model was constructed to forecast annual rainfall values based on this dataset. Regression, a statistical method, leverages the relationship between multiple variables within an observational database to anticipate outcomes based on other variables. Among various regression analyses, MLR is frequently utilized due to its simplicity (Mamani 2015; Nolan et al., 2015; Preacher et al., 2006). This technique assumes a linear relationship between quantitative variables (Piña-Monarrez & Ortiz-Yañez, 2015). In this study, the MLR utilized is shown by Equation 1.

$$P = aX_{-1} + bX_{-2} + cX_{-3} + K \qquad (1)$$

Equation 1 illustrates the relationship used to predict annual rainfall, where P represents the desired annual rainfall; X_{-1}, X_{-2}, and X_{-3} denote the 3 preceding years' annual rainfall; a, b, and c are the coefficients that determine the strength of the linkage between the predictors and the predictand. The constant K serves as the intercept, adjusting the shift between the mean predicted and observed values (Krzywinski and Altman, 2015; Novotna et al., 2015; Yu et al., 2015). In this study, we assumed the intercept to be zero. Validation/testing were conducted on rainfall data spanning from 1904 to 2002 to evaluate the accuracy of the model, comparing the predicted values over this 99-year period with the collected data.

4. Results and discussion

The MLR analysis yielded highly favorable outcomes. The coefficients derived for 1st, 2nd and 3rd preceding years are 0.459, 0.272, and 0.262, respectively. These findings are compelling, indicating a diminishing influence of the predictors as we move to the past, i.e., the immediate previous year's rainfall is the most dominant predictor. The resulting MLR equation is depicted in Equation 2.

$$P = 0.459X_{-1} + 0.272X_{-2} + 0.262X_{-3} \qquad (2)$$

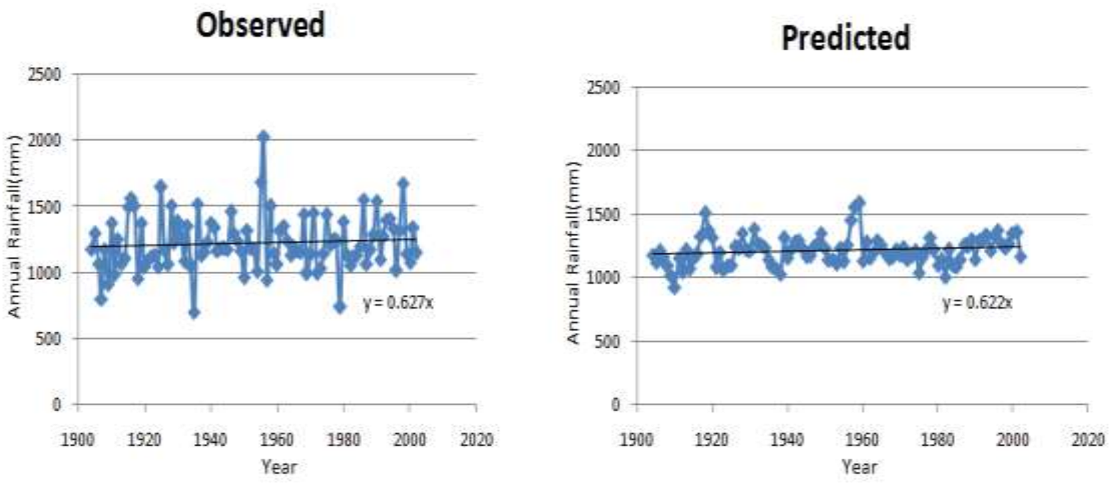

Fig. 2 - Comparison of actual and regressed Annual rainfall over 1904-2002

Upon validating this equation with annual rainfall data spanning from 1904 to 2002, the regressed values closely align with the observed values, indicating a strong match. The efficiency measures for validating this equation/model includes coefficient of correlation (R) and its squared value (R^2). The generated values from the model exhibit a remarkably high level of agreement with the actual data, yielding a R of 0.981 and a R^2 of 0.963. Figure 2 provides a clear picture comparing the difference between the observed data and the regressed values over the 100-year period. Notably, the regressed values demonstrate less variability compared to the observed data, while accurately capturing the mean values. Additionally, examining the equations displayed in Figure 1, it's evident that the observed values are following a relationship of y= 0.627x, whereas the regressed values adhere to a relationship of y= 0.622x concerning time (where x denotes the year and y represents annual rainfall), with the intercept being set as zero. Thus, the MLR model produces highly precise results.

In this study, we reflect on the implications of our findings for water resource management and agricultural sustainability. Our study underscores the critical role of accurate rainfall estimation in mitigating risks associated with climate variability, particularly in regions heavily reliant on seasonal precipitation like Khordha district, Odisha. The robust performance of our multiple linear regression model, validated over a century-long dataset, highlights its potential utility for informing proactive measures and enhancing resilience against precipitation anomalies. By providing a reliable framework for forecasting annual rainfall, our model can empower decision-makers to develop targeted interventions aimed at optimizing water allocation, crop planning, and disaster preparedness strategies. Furthermore, our findings emphasize the importance of integrating advanced forecasting techniques and leveraging historical data to improve prediction accuracy and enhance adaptive capacity in vulnerable regions. Moving forward, collaboration between scientists, policymakers, and local stakeholders is crucial for translating research insights into actionable measures that promote sustainable water resource management and ensure food security in the face of climate change challenges.

While it's true that there are numerous data-driven models available for various applications, MLR models offer several advantages in certain contexts. Firstly, MLR is a straightforward and interpretable statistical technique that allows for the examination of the relationships between multiple predictor variables and a single outcome variable. This simplicity makes MLR particularly useful when the underlying relationships between variables are relatively linear and can be adequately captured by a linear model. Additionally, MLR provides insights into the relative importance of different predictor variables in explaining variability in the outcome variable. By examining the coefficients associated with each predictor variable, researchers can assess the significance and direction of their influence on the outcome, aiding in the identification of key drivers or factors contributing to the observed patterns. Furthermore, MLR models are often more robust to multicollinearity compared to other complex data-driven models. This means that MLR can handle situations where predictor variables are highly correlated with each other, which is a common issue in datasets with multiple variables. Overall, while there are certainly more complex data-driven models available, the simplicity, interpretability, and robustness of multiple linear regression make it a valuable tool in many analytical contexts, including rainfall estimation and other hydro-meteorological studies.

5. Conclusions

Proper estimation of rainfall holds significant importance in enhancing water resource engineering. In this study, a MLR model was devised to predict the Khordha District's annual rainfall, utilizing data from the preceding three years. The model demonstrated remarkable accuracy, exhibiting a strong alignment with actual data and yielding an impressive coefficient of determination (R^2) of 0.963. This high value of R^2 attests to the model's efficacy in forecasting annual rainfall in the region, thus laying a robust foundation for future hydro-meteorological inquiries and analyses.

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