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Seasonal rainfall variability, drought characterisation and efficacy of interpolation techniques: Case of Kenya's central highlands

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Abstract

Drier parts Eastern Kenya, endure persistent crop failure and declining agricultural productivity which have been attributed, in part, to high temperatures, prolonged dry-spells and particularly erratic rainfall. Understanding spatial-temporal rainfall variability is a key facet to agricultural productivity and Natural Resource Management (NRM) in the region. However, meteorological stations in the region are sole sources of climatic data but only limited to single locations, far away from each other, with inadequate or inconsistent and missing meteorological data. This study examined the extent of rainfall variability and the efficacy of interpolation techniques in the arid regions, east of Kenya's central highlands. Rainfall raw data gaps were filled using multiple imputations. Cumulative Departure Index (CDI), Rainfall Anomaly Index (RAI) and Coefficients-of-Variance (CV) and probabilistic statistics were utilised in the analyses of rainfall variability. Evaluation of interpolation techniques utilized the ArcGIS environmental tool combined with the digital elevation model (DEM) to generate spatial rainfall maps under Spline, Kriging and Inverse Distance Weighting (IDW) techniques whose efficacy was evaluated using root mean square errors (RMSE), mean absolute errors (MAE) statistics and gauged-data validation. Analyses showed 90% chance of below cropping-threshold rainfall (500 mm) exceeding 258.1mm (Embu) during short rains (SRs) for one year return-period. Rainfall variability was found to be high in seasonal amounts (CV=0.56) and in number of rainy-days (CV=0.88). Monthly rainfall variability was found to be high during peak (April and November) (CV=0.48 and 0.76) with high probabilities (0.67) of droughts exceeding 15 days. Dry-spell probabilities within growing months were high (81%) and (60%) in Machang'a and Embu respectively. Kriging technique emerged as the most appropriate Geo-statistical interpolation techniques to be used in the region. To optimize yield in the area, use of soil-water conservation and supplementary irrigation, crop selection and timely accurate rainfall forecasting should be prioritized.

Key words: Cumulative-Departure-Index, drought-probability; Rainfall-Anomaly-Index, Seasonal Rainfall-variability

Résumé

Le parties les plus sèches de l'Est Kenya, endure la persistance des mauvaises récoltes et la baisse de la productivité agricole qui ont été attribuées, en partie, à des températures élevées, à des saisons sèches prolongées et des précipitations particulièrement erratiques. La compréhension de la variabilité spatio-temporelle des précipitations est un aspect clé de la productivité agricole et de la gestion des ressources naturelles (GRN) dans la région. Toutefois, les stations météorologiques de la région sont les seules sources de données climatiques, mais seulement limitées à des endroits simples, loin de l'autre, avec les données météorologiques insuffisants ou incohérents et disparus. Cette étude a examiné l'étendue de la variabilité des précipitations et de l'efficacité des techniques d'interpolation dans les régions arides, à l'est de hautes terres centrales du Kenya. Les lacunes des données brutes de précipitations ont été remplies à l'aide des imputations multiples. Le Cumulatif d'Index de Départ (CDI), l'Index d'Anomalie de pluie (RAI), le Coefficients de Variance (CV) et des statistiques de probabilités ont été utilisés dans les analyses de la variabilité des précipitations. L'évaluation des techniques d'interpolation avait utilisé l'outil de l'environnement ArcGIS combiné avec le modèle numérique d'élévation (DEM) pour générer des cartes des précipitations spatiales sous Spline, Kriging et les techniques de la Pondération Inversée de la Distance (IDW) dont l'efficacité a été évaluée à l'aide des erreurs quadratiques moyennes (RMSE), moyenne absolue d'erreurs (MAE) des statistiques et des données-calibrées de validation. Les analyses ont montré 90% de chance d'avoir moins de culture sur le seuil de précipitations (500 mm) dépassant 258.1mm (Embu) pendant les pluies courtes (SR) pour la période d'une année. La variabilité des précipitations a été jugée élevée en quantités saisonnières (CV = 0,56) et du nombre de jours de pluie-(CV = 0,88). La variabilité des précipitations mensuelles a été jugée élevée en période de pointe (avril et novembre) (CV = 0,48 et 0,76) avec des probabilités élevées (0,67) des sécheresses de plus de 15 jours. La période des probabilités de sécheresse de la de croissance mensuelle était élevé (81%) et (60%) dans Machang'a et Embu, respectivement. Les Technique de krigeage est apparu comme les techniques les plus appropriés d'interpolation géostatistique à être utilisées dans la région. Pour optimiser le rendement dans le domaine, l'utilisation de la conservation des sols, de l'eau et l'irrigation d'appoint, la sélection des cultures et en temps opportun précise la prévision précipitations devraient être une priorité.

Mots clés: Index-Cumulatif-Départ-, la probabilité de la sécheresse; Index-d'Anomaly-Pluie, variabilité saisonnière des pluies

Background

Drier parts of Embu County, Eastern Kenya continue to experience elevated unpredictable rainfall patterns, persistent dry-spells/droughts coupled with high annual potential evapo-transpiration (2000-2300 mm year^{-1}) (Micheni *et al.,* 2004). There is generally enough water on the total; however, it is poorly re-distributed over time (Kimani *et al.,* 2003) with 25% of the annual rain often falling within a couple of rainstorms, that crops suffer from water stress, often leading to complete crop failure (Meehl *et al.,* 2007). Recha *et al.* (2012) noted that, most studies do not provide information on the much-needed character of within-season variability despite its implication on soil-water distribution and productivity. Understanding the average amount of rain per rainy day and the mean duration between successive rain events aids in understanding long-term variability and patterns (Akponikpè *et al.,* 2008). Nonetheless, meteorological stations are sole sources of climatic data but are only limited to single locations. Geographic information systems (GIS) and modelling have become critical tools in agricultural research and, natural resource management (NRM) yet there utilization in the study area in quite minimal and inadequate. Utilization of the spatial tools, Inverse Distance Weighted (IDW), Spline and Kriging interpolation techniques are some of the applications exhausted in the ArcGIS tool essential for data reconstruction. Since rainfall, in particular, is the most critical factor determining rain-fed agriculture yet not homogeneous, knowledge of its statistical properties derived from long-term observation could be utilized in developing climate mitigation strategies in the area. To redress problems of inadequate, missing and inconsistent point data especially for un-gauged areas within the study area, this study further sought to evaluate the efficacy of geo-statistical and/or deterministic interpolation techniques (embedded in ArcGIS tools) to reconstruct rainfall.

Literature summary

Understanding spatio-temporal rainfall patterns rainfall has been directly implicated to combating extreme poverty and hunger through agricultural enhancement and natural resource management (IPPC, 2007). The amount of soil-water available to crops depends on rainfall onset, length and cessation which influence the successfulness or failure of a growing season (Ati *et al.,* 2002). It's thus palpable that, climatic parameters and rainfall in particular are prime inputs of improving the socio-economic wellbeing of smallholder farmers. This is particularly important in Sub-Saharan Africa (SSA) where agricultural productivity is principally rain-fed yet highly variable (Jury 2002). Atmospheric circulation is a major determinant of climate variation in SSA (Dore, 2005; Akponikpè, 2008; Zhang *et al.,* 2008). Rainfall seasons are typical between March and July (Long Rains; LR) and October to December (Short Rains; SR) with the remainder of the year being very dry (Dai *et al.,* 2004). Long term rainfall trend towards aridification has been reported in SSA with different rainfall datasets indicating that the isohyets have shifted 100-150 km southwards since the 1960s (Sivakumar *et al.,* 1993). Dai *et al.* (2004) and Hulme (2001) confirmed aridification trends to be real and continuing. Temporal variability of rainfall is also very high on the annual, monthly and daily time scales (Akponikpè *et al.,* 2008). Sivakumar *et al.* (1993) asserts that understanding the average amount of rain per rainy day is essential in assessing inter/intra seasonal variability. Evaluating mean duration between successive rain events also aids in understanding seasonal variations (Akponikpè *et al.,* 2008). Graef and Haigis (2001) reported that annual rainfall differences may occur in any direction spatially and temporally but a difference of 200 mm to 300 mm can be recorded within 100 km, or within 6-day radius, respectively.

Study description

The study was conducted in the humid tropics (Embu sub-county) and semi-humid agro-climatic arid (Mbeere sub-county) regions, in Embu County, in Kenyan central highlands (Fig. 1).

The county lies in the lower midland 3, 4 and 5 (LM 3, LM 4 and LM 5), Upper midland 1, 2, 3 and 4(UM 1, UM 2, UM 3 and UM 4), Upper highlands (UH0, UH1) and Inner lowland 5(IL 5) (Jaetzold *et al.,* 2007) at an altitude of approximately 500 m to 1800 m above sea level (a.s.l) (Fig. 1). Embu-sub County represents a densely populated high potential humid

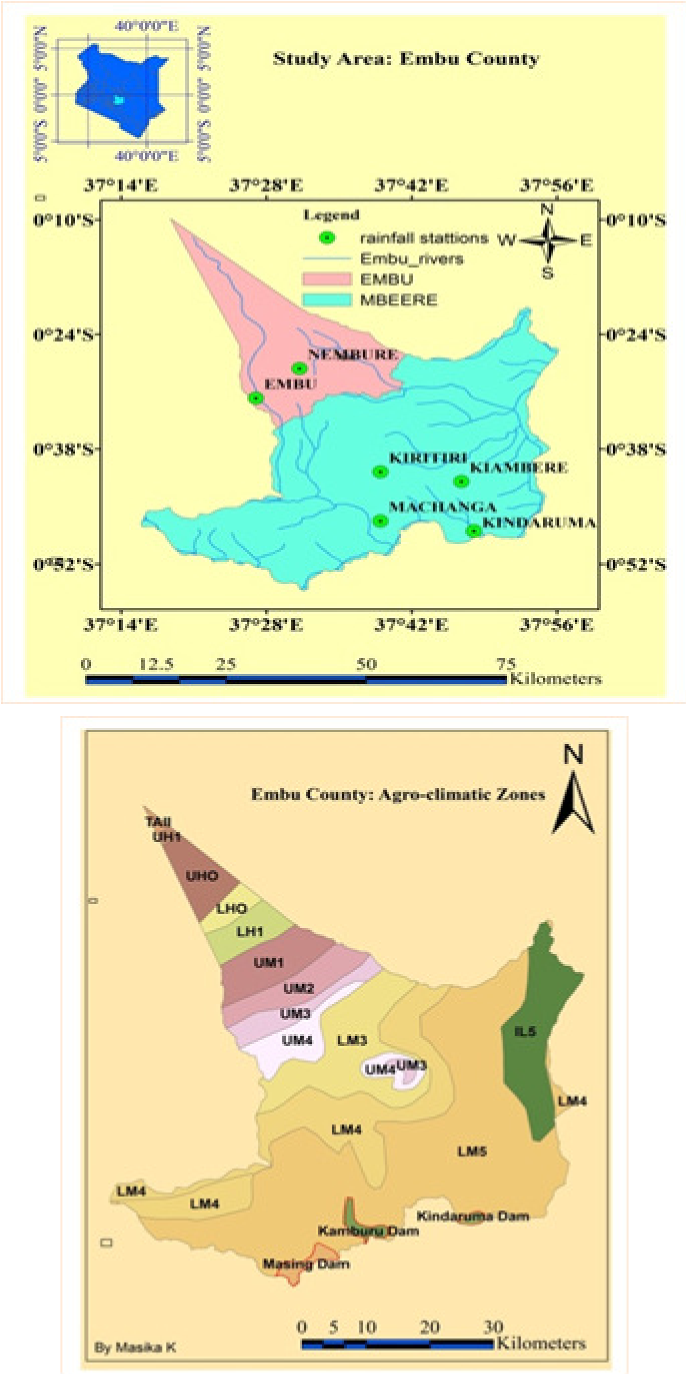

Figure 1. Map showing the study area and its AEZs with selected point gauged rainfall data; Mbeere and Embu, Nembure, Kindaruma and Kiambere.

area with Humic Nitosols soils and generally annual rainfall above 800 mm. Conversely, Mbeere sub-county is emblematic of a low agricultural potential region with less fertile and low soil water-holding Ferralsols, frequent droughts and annual rains less than 600mm (Jaetzold, et al., 2007). However, Mbeere sub-county continues to experience population pressure occasioned by the influx of immigrants from the over-populated high potential areas. The two districts represent Kenya's central highlands and those of East Africa, predominant of smallholder rain-fed, non-mechanized agriculture and diminutive use of external inputs. Rainfall raw data gaps were filled using multiple imputations. Cumulative Departure Index (CDI), Rainfall Anomaly Index (RAI) and Coefficients-of-Variance (CV) and probabilistic statistics were utilized in the analyses of rainfall variability. Evaluation of interpolation techniques utilized the ArcGIS environmental tool combined with the digital elevation model (DEM) to generate spatial rainfall maps under Spline, Kriging and Inverse Distance Weighting (IDW) techniques whose efficacy was evaluated using root mean square errors (RMSE), mean absolute errors (MAE) statistics and gauged-data validation.

Research application

The study area experienced very high variability in the past decade. Results showed neither station nor season with near average (RAI=0) rainfall. Mbeere recorded more negative anomalies in rainfall amount received compared to Embu (Fig. 2). Additionally, SRs in Embu were less variable but more drier compared to LRs. Conversely, SRs in Mbeere were wetter than SRs in Embu but more variable in the former.

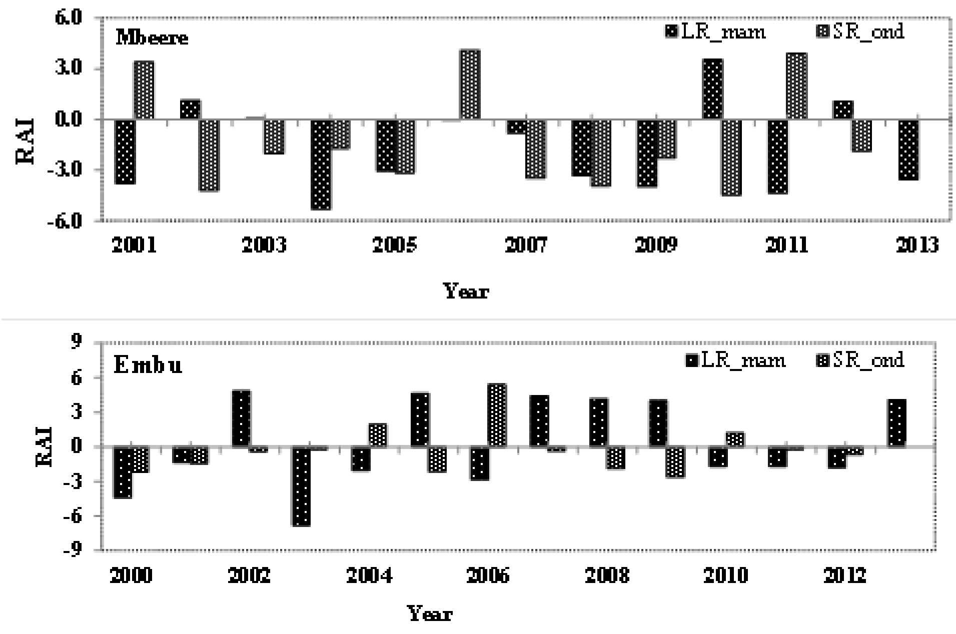

Figure 2. Decadal rainfall anomaly index for both LRs and SRs in Embu site for the period between 2000 and 2013.

In Mbeere, rainfall amounts and number of rainy days during LRs were highly variable (CV = 0.41, CV=0.26) than those in Embu (CV = 0.36, CV=0.09) respectively. In Embu, LRs were found to be significantly different (p = 0.0035 at probabilities of 0.05) from SRs (Table 1).

Probabilities of a 15-day dry-spell were relatively high (0.4 to 0.6) in Embu and Mbeere respectively (Fig. 3).

Evaluation of the mean absolute error (MAE) and root mean square error (RMSE) between predicted and observed rainfall data further showed the Kriging method (MAE=147 mm and RMSE=176.5 mm) would be the best-bet technique to adopt for rainfall interpolation for the region (Table 2).

Figure 4 show the scatter plots of recorded versus predicted decadal average rainfall across the study stations based on Kriging interpolation technique. A comparison of the predicted and recorded rainfall amounts showed further best-fit performance of the Kriging interpolation technique in ArcGIS. Predictions in Machang'a recorded high values of best-fit (R^2 =0.92)

Table 1. Variability analyses: coefficient of variations in seasonal rainfall amounts and number of rainy days for Mbeere and Embu for the period between 2000 and 2013.

Station	LR				SR				M.variations
	RA	CV	RD	CV	RA	CV	RD	CV	T-test values
Mbeere	314.9	0.41	24	0.26	438.7	0.56	53	0.88	0.111
Embu	586.3	0.36	46	0.09	497.1	0.38	40	0.27	0.0035*

MAM=March-May-June and OND=October-November-December and; RA=Rainfall Amount in (mm), RD=Rainy Days CV=Coefficient of Variation and M.variations=mean variations; *=Significant at 0.05 Level.

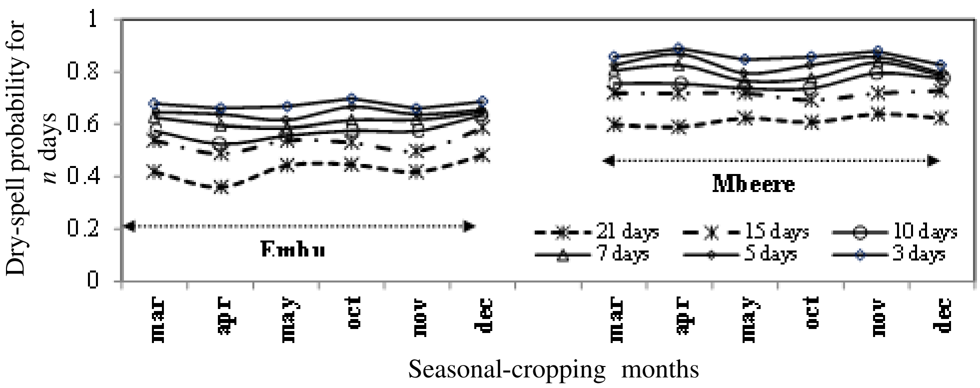

Figure 3. Probability of a dry-spell of length >n days, for n=3, 5, 7, 15, 21, in each seasonal-cropping month, calculated using the raw rainfall data from 2000 to 2013 for stations in Mbeere and Embu.

Table 2. Mean absolute error, RMSE, and R2 values for the interpolation produced from validation of IDW, Kriging and Spline methods.

	IDW	Kriging	Spline
Average P (O)	371.3 (760)	507.6(760)	399.4(760)
SD	115.5	137.5	106.7
MAE	276.7	147.6	248.6
RMSE (mm)	294.7	176.5	264.7
R^2	0.04	0.67	0.23

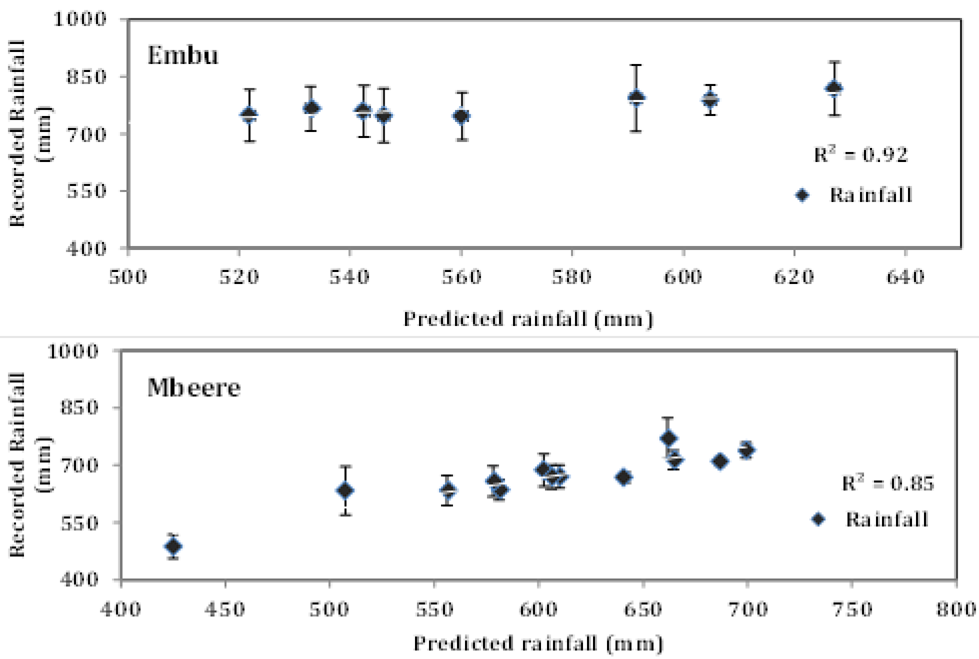

Figure 4. Comparison between recorded and ArCGIS Kriging predicted average decadal rainfall amount across study stations: Error bars denote standard deviation of observed means, n=13.

compared to Kiambere (R^2=0.64) which could be attributed to high missing (high gap filling by imputation) dailies in raw data in the latter (Fig. 4).

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