Chapter 3

Development and Application of Conceptual Rainfall-Altitude Regression Model: The Case of Matahara Area (Ethiopia)

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Additional information is available at the end of the chapter

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Abstract

Rainfall data available, in tropical regions with undulating topography, may provide a valuable information for water resource development as well as for predicting and preventing natural disasters. But in developing countries like Ethiopia, rain gauge stations are sparsely populated, and rainfall data are the limiting factor. Hence, estimation of rainfall is extremely important. The current paper deals with the development of a rainfall-altitude relationship for Matahara area, Awash Basin of Ethiopia. A conceptual rainfall-altitude regression model was formulated and its performance evaluated. The relationship between monthly rainfall totals and gauge elevation over Matahara region (including Lake Basaka catchment) was examined using the conceptual regression model (ordinary least square). The regression parameters were identified and estimated and then used to map the spatial rainfall for Lake Basaka catchment in ArcGIS. The regression analysis showed a strong positive correlation ($r = 0.85$) between the long-term average monthly rainfall and altitude of the region. It is shown that the rate of increase of rainfall with altitude is in the range of 0.020 mm/h at Matahara to 0.067 at Welenchiti, with average value of 0.0475 mm/m/month. The best fit ($R^2 = 0.9187$, $p = 0.015$) was obtained between observed and estimated rainfall depths for all the stations with total standard error of 12.97 mm. The high R^2 reveals that the developed equation is acceptable for the area at 98.5% ($p > 0.015$) confidence limit. The performance of the developed model is found to be within reasonable accuracy, which is limited by the elevation difference and distance from the base station. Therefore, the spatial and temporal structures of rainfall distribution (daily, monthly or annual) for Matahara region (including Basaka Lake catchment) can be determined from the available records of rainfall data at the Matahara Research Station (Merti) meteorological station with acceptable reliability. In general, the performance of the developed model is found to be within reasonable accuracy, which is limited by the elevation difference and distance from the base station.

Keywords: Matahara, orography, performance, rainfall, regression model

1. Introduction

Accurate estimates of the spatiotemporal distribution of rainfall have been found to play a key role in hydrological applications and water resource management [1]. Tropical regions with heavy rainfall and variable topography are characterized by serious natural disasters. Rainfall estimates, in such region, provide valuable information for water resources development and for predicting and preventing natural disasters [2].

Rainfall shows variations in amount and distribution depending upon the factors: wind (speed and direction), topography (altitude and slope), barrier characteristics, mountain scales, etc. (e.g. [2–4]). Although the seasonal and spatial distribution of the rainfall is the key parameter for further differentiation of climate, orography is the crucial parameter for the development of the regional climatic behavior in Ethiopia [3, 5]. It is evident from the previous investigations that rainfall increases with altitude (e.g. [1, 5]). However, understanding the nature of rainfall-elevation relationships in mountainous regions is much difficult.

Matahara area, including Lake Basaka catchment, has a wide range of topographic elevations, ranging from 949 m at the Lake to over 1900 m at the top of Fentalle Mountain [4]. Hence, a spatial rainfall variation in the region is expected. The reliable estimate of rainfall spatial distribution is extremely important for the determination of the regimes of hydrologic processes (runoff, erosion, sedimentation) within the lake catchment and the resulting regime of lake's water balance. No profound study has been made so far on the stochastic model of rainfall-altitude relationship in the study area.

In this study, the topographic effects on rainfall distribution has been investigated and explained. An attempt was made to determine the spatial distribution of the rainfall from the available rainfall recording stations within the region with similar agroclimatic condition and variable altitude coverage. A conceptual rainfall-elevation regression model was formulated and then simulated for Matahara region in order to see its practicability for the area. The regression model formulation is based on the hypothesis: rainfall at certain location is the function of rainfall data measured at the base station, the elevation difference between the two locations, and the incremental rainfall per altitude.

2. Materials and methods

2.1. Study area

Matahara area is situated within Awash River Basin, central rift valley of Ethiopia. It is located within Oromia region. Matahara plain area, in general, has semiarid climate [4], with a mean annual rainfall of about 543.7 mm (**Figure 1**). As evident from **Figure 1**, the plain area is characterized by bimodal and erratic rainfall distribution. Details of Matahara area including Lake Basaka are well documented [4, 6–9]. The study area is attracting the attention of many scholars due to the fact that the highly expanding Lake Basaka is situated within the region. The lake is expanding at very fast rate in the past about 5 decades. The main problem with

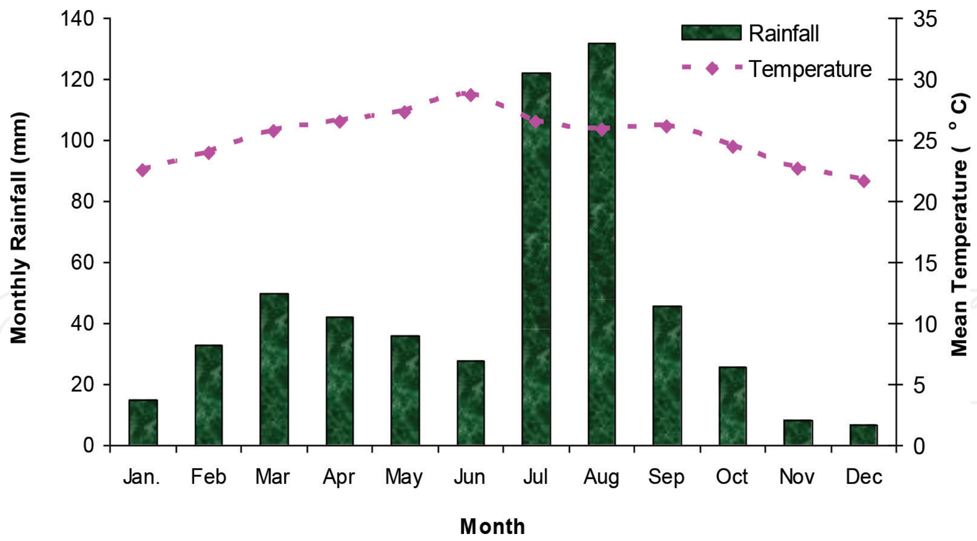

Figure 1. Mean average seasonal variability of rainfall and temperature in Matahara area.

the lake expansion is due to its poor water quality (high salinity, sodicity and alkalinity), and it is not usable for domestic or irrigation purpose. Moreover, the lake is also situated within the main rift valley of Ethiopia (at a close distance to Afar Triangle), where many changes are happening.

2.2. Rainfall estimation

There are two meteorological stations in Matahara region with long years of recorded data: one at Matahara Breeding Station (MSF) and one at Matahara town just near to the lake (**Figure 2**). Unfortunately both stations are outside the Lake catchment and even cannot be representative for the entire catchment since they are located almost at the lower elevation. There are also other two meteorological stations (Awash and Nura-Era) in the vicinity of the Lake. Though the second station is being located at the southern most part within the Lake catchment, it cannot be representative for the entire catchment too. Furthermore, there are a number of rain gauges (about 12) distributed in the sugar plantation section with 12-year (1996–2008) rainfall records, 4 of which are located in the lake catchment from Abadir side. Even these rain gauges are concentrated at one location (with low elevation), and their measurements are less reliable.

Therefore, an attempt was made to determine the spatial rainfall distribution for the area from the available rainfall recording stations within the region with similar agroclimatic condition (semiarid) and variable altitude coverage. About seven rain gauge stations with long year's measurement data were selected, namely, Matahara Research Station (MRS) at Merti, Matahara, Nura-Era, Awash, Welenchiti, Adama and Wonji Research Station (WRS) (**Figure 2**). These stations have good-quality, continuous records of data for the period of 1966–2010. As confirmed by quality check, the recorded data of the seven stations are homogeneous (at the >95% confidence level) and consistent. Data records of Welenchiti station are found to be relatively poor compared to the others.

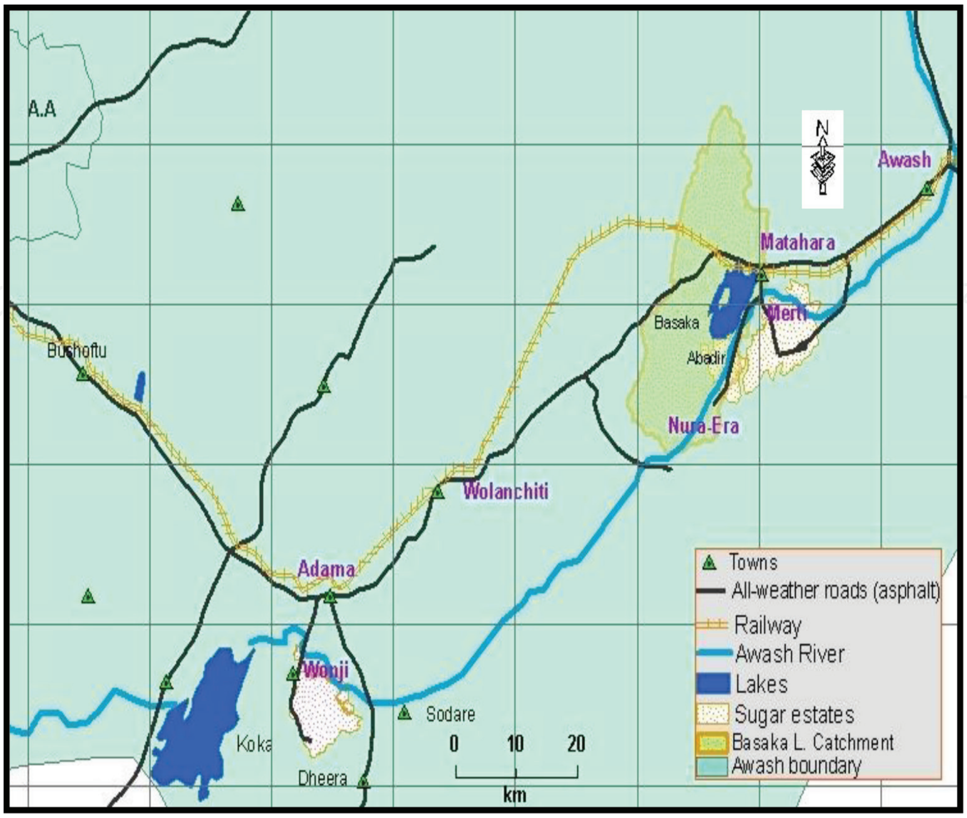

Figure 2. Distribution of meteorological stations considered in the region.

2.3. Formulation of the regression model

Most studies conducted in the mid-latitudes have proved that a simple linear rainfall-altitude regression model well fits the observed data [10]. Accordingly, a conceptual regression model (Eq. (1)) was first formulated based on the hypothesis that rainfall at certain location is the function of rainfall data measured at the base station, the elevation difference between the two locations, and the incremental rainfall per altitude. The simple linear regression model was fitted by ordinary least squares (OLS) method:

$$P_H = P_b + k*(H - H_b) \pm \varepsilon \tag{1}$$

where P (mm) = rainfall at elevation H, P_b = rainfall at base station H_b, H (m) = elevation at which P is to be determined, H_b (m) = elevation of the base station, k (mm/m) = constant as function of rainfall increment per altitude and ε = error term that considers the effect of error in measurement and effect of other factors on rainfall. The rainfall increment per altitude (k) value is different for monthly and annual rainfall values. The expectation from the regression model is that the rainfall increases with altitude, i.e., k should be positive.

The above equation (Eq. (1)) was optimized until the computed and measured rainfalls (P) are approximately equal or until the sum of the deviations between the observed and computed

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rainfalls are approximately zero (standard error). For the lake catchment (Matahara area), the meteorological station at MRS was considered as the base station since it has long years of measurement data and its records are found to be relatively reliable and consistent (as checked by double mass curve) and is also at close vicinity to the lake and its catchment.

3. Results and discussion

3.1. Rainfall-altitude relationship

The temporal variability of long-term (1966–2008) mean monthly rainfall values for the selected meteorological stations (excluding Adama and Awash Melkassa) is plotted in **Figure 3**. The regression analysis showed a strong positive correlation (r = 0.85) between the LYA monthly rainfall and altitude of the region (**Figure 4**). The correlation becomes even stronger (r = 0.97)

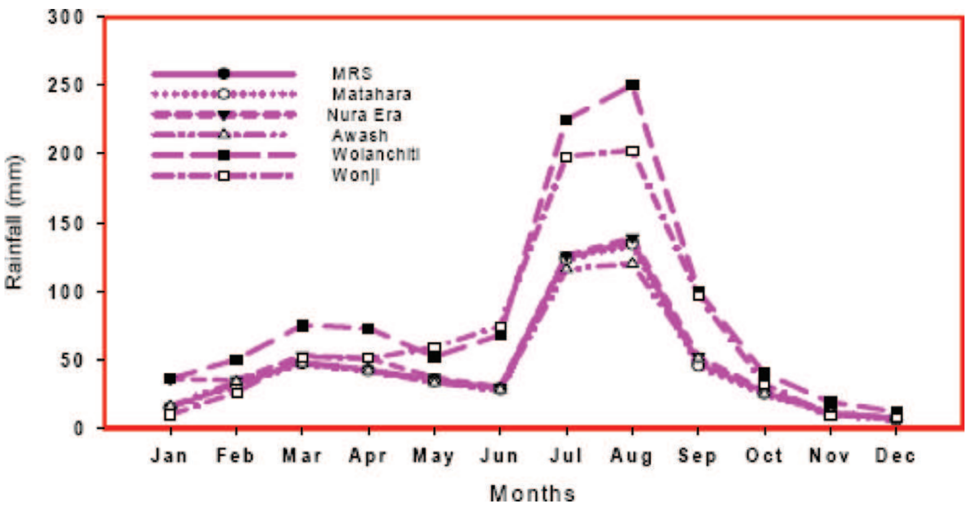
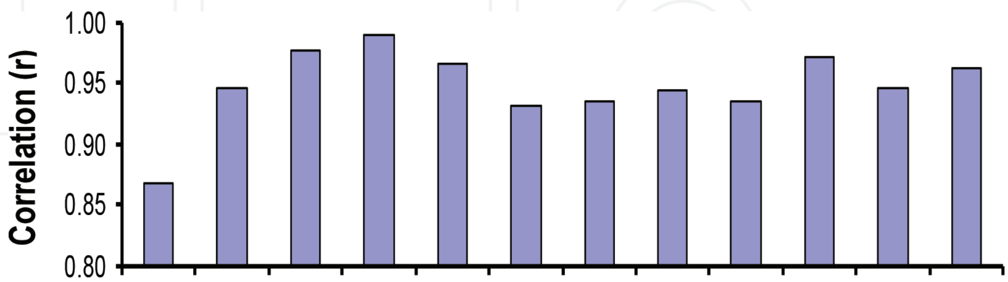


Figure 3. Temporal variability of LYA annual rainfall of Awash valley at six recording stations.



Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
r	0.869	0.948	0.978	0.991	0.967	0.932	0.936	0.945	0.936	0.972	0.948	0.964	0.970

Figure 4. Correlation analysis between rainfall and altitude (for all considered stations).

between the long years' average annual rainfall and the elevation, which reveals how topography (orography) is the most decisive factor for rainfall pattern of the region, which is also true for most part of Ethiopia.

The rainfall of the area is highly erratic and of bimodal type with the main rainy season concentrated to few months (July–September). Analysis of the seasonal rainfall distribution pattern showed that the most intensive hydrologic processes (runoff, erosion and sedimentation) in the area are expected in the month of July and/or August, which was also confirmed by other studies [4, 9]. It possible to suggest that the irregular rainfall patterns of the area may be related to the cyclic events of climate such as QBO and ENSO in the tropics [11]. African rainfall variability is mostly related to the ENSO indices [11, 12]. Like tropics, Southern Africa regions have high climate variation and hence susceptible to droughts and floods [13–15].

3.2. Developed conceptual regression model

A conceptual regression model was formulated (see Eq. (1)) based on the correlation obtained between rainfall and altitude of the region (**Figure 4**). The conceptual regression model was optimized until the computed and measured rainfalls (P) are approximately equal or until the sum of the deviations between the observed and computed rainfall are approximately zero (standard error). After optimization, the regression model (Eqs. (2) and (3)) was developed for the area. After inserting the elevation value (H_b = 956 m) for the base station (MRS), Eq. (2) is reduced to Eq. (3):

$$\begin{aligned} P(H) &= P_b + 0.0475 * (H - H_b) - 0.9 \quad (monthly) \\ P(H) &= P_b + 0.560 * (H - H_b) - 0.9 \quad (Annual) \end{aligned} \tag{2}$$

$$P = P_b + 0.0475 * H - 530.8 \tag{3}$$

The incremental rainfall per altitude obtained for the considered seven stations is in the range of 0.020 (Matahara) to 0.067 (Welenchiti), with average value of 0.0475 mm/m/month. The monthly rainfall of each of the considered stations was computed using Eq. (3) and compared to the observed values (**Figure 5**). The performance of the developed regression model was evaluated based on the RMSE (**Table 1**). Welenchiti and Wonji have shown the highest RMSE of 70 and 120 mm, respectively. Conversely, the other four stations (MRS, Matahara, Awash and Nura-Era stations) in the close vicinity to the lake have the lowest RMSE, indicating the better fit of data. That means those stations very far (distance > 50 km) and with high elevation difference (>200 m) from the base station perform poor.

The scatter plot of the observed and simulated rainfall for the considered stations in the region is shown in **Figure 6**. The best fit (R^2 = 0.9187, p = 0.015) was obtained between observed and estimated rainfall depths for all the stations (**Figure 6b**) with total standard error of 12.97 mm. The correlation (R^2 = 0.9988) is very strong for the selected four stations (MSE, Matahara, Awash and Nura-Era) in the vicinity of the lake (**Figure 6a**). The high R^2 reveals that the developed equation is acceptable for the area at 98.5% (p > 0.015) confidence limit. Therefore, the monthly or annual rainfall for the lake and its catchment can be estimated from

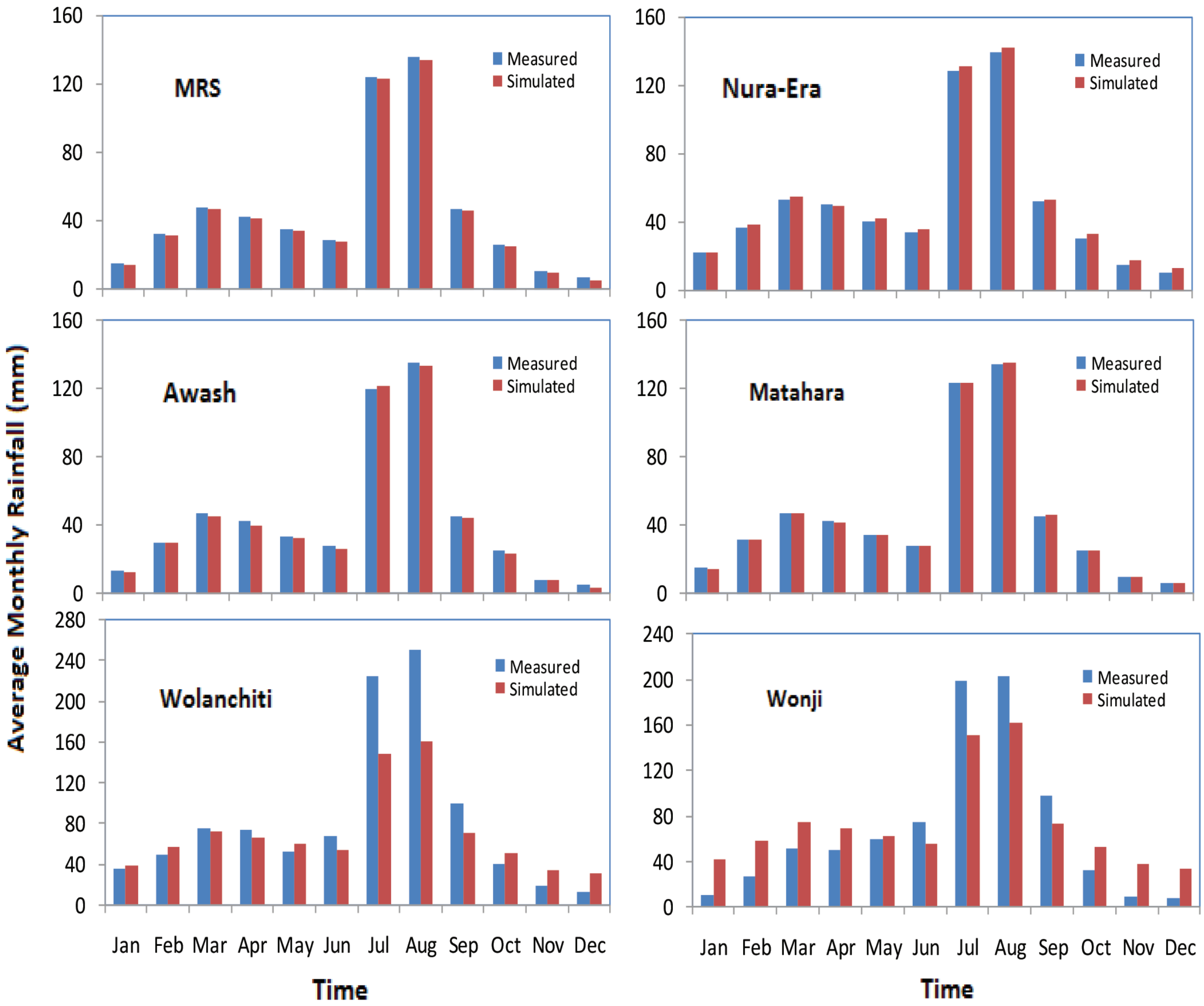


Figure 5. Mean long years' average monthly measured and simulated rainfall (1966–2008).

Station	RMSE (mm)	Elevation difference (m) from base station	Approximate distance from base station (km)
MRS	0.90	0	0
Matahara	0.20	−2	8
Awash	4.01	−30	30
Nura-Era	6.02	165	40
Wonji	70.00	550	100
Welenchiti	120.00	535	70

RMSE, root mean square error.

Table 1. Performance of the developed regression for the different stations.

the measured data at the MRS meteorological station with acceptable reliability. Of course, some discrepancy between the estimated and measured rainfall is expected due to certain factors: measurement error, wind oscillation effects, altitude difference in the watershed, etc.

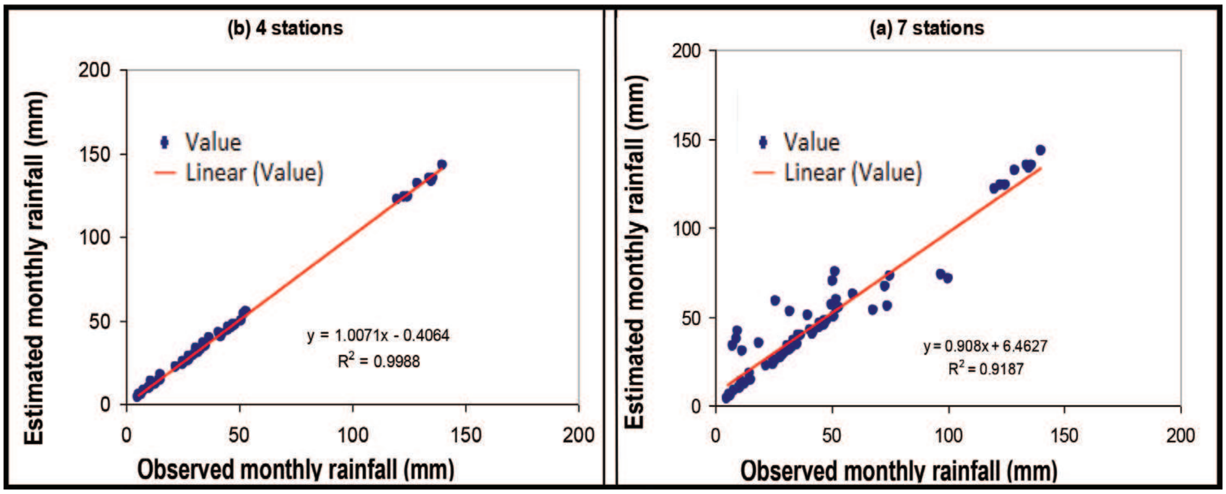


Figure 6. Scatter plot of observed and model estimated monthly rainfall depths: (a) for four stations in the vicinity of the lake and (b) for all stations considered.

4. Conclusion

The rainfall of the area is found to be erratic and of bimodal type, with great seasonal and annual variation. The seasonal variation is indicator of the occurrence of the most intensive hydrologic processes (runoff, erosion and sedimentation) in the months of July and August. Unlike rainfall, temperature showed an increasing trend. The mean average temperature increment observed for the area (+2.4°C) in the past 4–5 decades is slightly higher than that of the country's average and of the globe (+2°C) in the postindustrial period. This could be attributed to the massive deforestation and tectonism (volcanic activity). This change has significant implications on the hydrologic cycle of the area (local scale) and on the global warming (global scale).

Good correlation was observed between altitude and rainfall. The developed conceptual regression model (after optimization) showed that the incremental rainfall per altitude obtained for the eight stations in the region is in the range of 0.25–0.80, with average value of 0.56 mm/m/year. The model performance is in line with the formulated hypothesis and is found to be satisfactory for the region. However, the best performance was observed for four stations in the vicinity of the lake and its catchment. Therefore, the developed conceptual regression model can be applied for the computation of a spatial rainfall distribution of the area, including Lake Basaka catchment.

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