# Objective assessment of the Thiessen polygon method for estimating areal rainfall depths in the River Volta catchment in Ghana

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## Abstract

*Among the problems facing hydro-meteorologists and climatologists is the estimation of rainfall depths at places where there are few or no rainfall stations. A number of models have therefore been developed, evaluated, and recommended by eminent hydrologists and climatology for their applications. These applications are related primarily to specific problems and for the purpose of identifying the most suitable methods for estimating rainfall depths in river basins with very few rainfall records or stations. In this paper, the applicability of the Thiessen polygon method has been reviewed and employed for the purpose of estimating rainfall depths in the River Volta catchment in Ghana. A regression statistic performed to establish the effect of elevation on rainfall distribution in the catchment shows that the former has little or no effect on the latter. The review of the Thiessen method and the results of the analysis of the rainfall field using the polygons show that the method is suitable for estimating rainfall depths in the River Volta catchment in Ghana. The recommendation, however, is that the rain-guage network in the catchment should be improved in other to obtain more but smaller polygons, showing distributions in smaller areas.*

**Keywords**: rainfall depth, rainfall variability, Thiessen polygon assessment

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## Introduction

A large number of meteorological and hydrological applications require knowledge about temporal and spatial variability and deficiency of rainfall, especially in areas that have few rainfall stations or rainfall data. The reason, according to Allen and DeGaetano (2005), is that point rainfall data are only applicable for a relatively small area (< 4 sq km).

Rainfall, that liquid water droplet issued from clouds formed by condensation of water vapour in the earth's atmosphere (Acheampong, 2009), plays important role in the hydrological cycles that control water availability, supplies, and water disasters all over the world (Olawoyin, 2015). As such, rainfall and the prosperity of nations go hand-in-hand; without adequate rainfall, both the farmer and the city dweller may not get water to quench their thirst, water their field crops, and carry on with their social, commercial, and industrial activities (ibid.).

Hence, too much or too little rainfall in an area is a major barrier to the area's wider economic development. And yet, it is not just the direct impact that reduces productivity of farmlands or renders manufacturing industries impossible. There are also indirect costs, such as poor health, hunger, and poverty, which are caused by floods and droughts that reduce productivity in places all over the world. For example, a sudden heavy downpour in a short period of time may cause severe flooding, loss of life, and the destruction of properties (Andoh et al., 2015) in towns and cities and in places where there are no recording gauges. As such, the need to identify ideal methods for estimating the minimum and maximum rainfall depths in all places and countries, including Ghana — and in particular the Volta River catchment (RVC) — for socio-economic planning and development cannot be overemphasized.

Rainfall data in Ghana are collected using rain gauges at weather stations located at agricultural stations and at the Ghana Meteorological stations in the district and regional capitals. Such data are point values. But the use of a single or a few rain-gauge data as rainfall inputs for large areas such as the RVC carries huge uncertainties regarding, for example, overland-flow and runoff estimates (Faur'es et al., 1995; Firdaus & Talib, 2014). This presents major problems for the prediction of discharge, groundwater level, and soil moisture, especially where there are few or no recording rain gauges (Schuurmans & Bierkens, 2007).

Against the above background, applications such as rainfall mapping (Aronica & Ferro, 1997; Goovaerts, 1999; Angulo-Martinez & Begueria, 2009) and hydrological modelling (Kobold & Suselj, 2005; Cole & Moore, 2008) require rainfall data that come from dense and spatially continuous rain-gauge networks. In other words, to estimate rainfall depths properly for large or small areas (that have few rainfall stations or data), there is the need for optimally distributed rain gauges. Where this is not applicable, there is the need to apply the most appropriate models for estimation (Chahouki et al., 2014).

Problems such as rainfall variability and deficiency in Ghana, and especially in the RVC (which contains the Volta Lake and dams), are challenges that can be solved only by estimating the minimum and maximum rainfalls in many places. This is why it is absolutely critical to use the most appropriate method for estimating rainfall depths in the river's catchment.

The three well-known alternative techniques identified in the literature to improve the accuracy of areal rainfall depth estimation are the arithmetic mean, the isohyetal model, and the Thiessen polygon method (Olawoyin, 2015). In this paper, the Thiessen polygon method is considered. The arithmetic mean and the isohyetal methods are considered in subsequent papers. The goal of the present paper is to resolve some of the disagreements on the application of the Thiessen polygon method as far as the conditions in the RVC are concerned, and to justify its use for estimating areal rainfall depths in the catchment.

## The Thiessen polygon

The Thiessen polygons (Figure 1), also known as Voronoi networks and Delaunay triangulations, were discovered in several fields, including climatology, as an essential method for the analysis of proximity and neighbourhood of phenomena, over a century ago. This method is a graphical technique that calculates station rainfall weights based on the relative areas of each measuring station in the Thiessen polygon network. The method proposed by Thiessen (1911) assigns to each rain-gauge station a weighted value based on the percentage of the area it represents in relation to the total area of the region in question. The areal rainfall depth of the region derived by the method then represents a weighted depth. For the above assertion, Wiesener (1970) says that the Thiessen or areal weighting method weights each station's rainfall value according to the area which is closer to the recording station than any other. This area is obtained by drawing perpendicular bisectors on lines joining nearby stations to form a series of polygons, each containing one and only one rainfall station, and leaving the other stations in the centre of polygons which will vary in size according to the spacing of the gauges (Figure 1). The percentage of the total area (of the place) represented by each polygon or part of it is determined by planimetering or by other methods, and is applied to the appropriate station's or rain-gauge total. The model is mathematically given as follows:

## Areal Mean Precipitation

### The Thiessen Polygons Method

Each point location in the watershed is assigned a precipitation equal to that of the closest gauge.

If $A_i$ is area assigned to station $i$, then areal precipitation can be estimated as

$$\overline{P}_{ave} = \sum_{i=1}^{m} \frac{A_i}{A} P_i$$

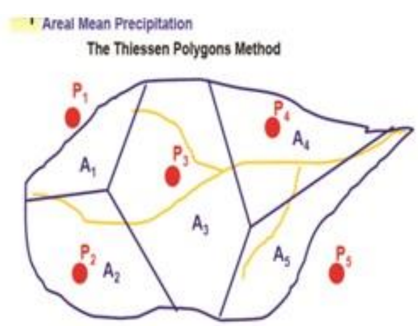
where

$P_{ave}$ : the areal mean precipitation,

$P_i$ : rainfall observed at the $i^{th}$ station inside or outside the basin,

$A_i$ : in-region portion of the area of the polygon surrounding the $i^{th}$ station,

m : the number of area

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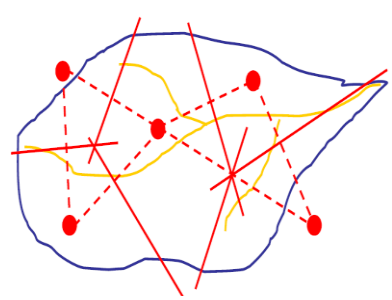

Figure 1: Steps for the determination of the Thiessen polygon method

*Objective assessment of the Thiessen polygon method for estimating areal rainfall depths in the River Volta catchment in Ghana*

Source: Akintug (n.d.)

To determine $A_i$

- All adjacent station locations are joined by straight lines.
- Perpendicular bisectors of the lines are drawn.
- The bisectors are extended to form polygons around each station.
- The area of each polygon is multiplied by the rainfall value of the station that is inside the polygon.
- The values obtained are added and then divided by the total catchment area to get the weighted rainfall.

One of the assumptions of this method is that linear rainfall gradients exist; hence, many researchers recommend that the use of the method should be restricted to relatively flat areas with linear rainfall distribution. Arguments remain, however, concerning the optimal gauge density and spacing conditions for its application. Several authors recommend the method's use for areas characterized by a relatively dense and uniformly spaced rain-gauge network. Weisner (1970), for example, considers that the method is satisfactory with even rainfall distribution, a good gauge network, and flat country. Edwards (1972) also says that the method is most applicable in densely gauged networks.

Contrary to the above observations, others recommend the method's use for sparse and unevenly spaced networks. The World Meteorological Organisation (WMO, 1965), for example, declared that the Thiessen polygon method was suitable for non-uniform station spacing. Bruce and Clark (1966) observed that the method has several advantages for places with relatively few rain gauges unevenly distributed geographically, while Ward (1969) held the view that the method even made some allowances for uneven distribution of gauges, because it enabled data from adjacent areas to be incorporated in the mean. Although studies addressing the relative accuracy of the Thiessen method are not many, some, such as Horton (1923), say that compared with the arithmetic mean method, for example, the Thiessen method is more accurate for a sparser network, and that the method will always give reasonable results if the variability among the rainfall data is not too large.

## Methods

### *The study area*

The study area (Figure 2) is the RVC in Ghana. It covers approximately 160,169.85 sq km in the Ashanti, Brong Ahafo, Eastern, Volta, Upper East, and Upper West regions. The Akosombo Dam is located at the downstream end of the catchment, while the Bui Dam is in the west. The RVC was chosen for four reasons: its vast socio-economic importance (e.g. the Bui and the Akosombo dams, the Volta Lake, the generation of hydro-electricity, irrigation, and tourism); poor rain-gauge network; availability of reliable rainfall data (though from few rainfall stations); and its rich agricultural lands, which vary in altitude from just 122 m to over 300 m above sea level. The area consists mainly of the Voltaian sandstone basin; the rest is a series of escarpments at different heights (for details, see Acheampong, 2009).

The climate of the RVC is tropical (ibid.). The mean temperatures are high and seldom fall below 25 $^{o}$C. The weather patterns are dominated by the north-easterlies or Harmattan airflow, which brings in its wake dry, desiccating, cool winds during the dry season (November–April); the south-west monsoon winds, which bring monsoonal rainfall between May and November; and the equatorial easterlies, which are associated with disturbance lines, vortices, and thunderstorms that occasionally produce heavy and copious rainfall at the beginning and the end of the rainfall season. Rainfall decreases from the south and the east towards the north (Figure 3). South of latitude 7$^{o}$N, there is a double maximal regime; the north has a single maximum (Acheampong, 2014).

The vegetation of the RVC consists of the interior Guinea savannah sub-zone and the Sudan savannah. The dominant vegetation in the interior savannah includes the baobab, the dawadawa, shea, and tall grass. The Sudan savannah has trees with fine-leaved, thorn-less species. The dominant plants are tussock grasses, which form almost continuous cover even beneath trees, especially during the rainfall season.

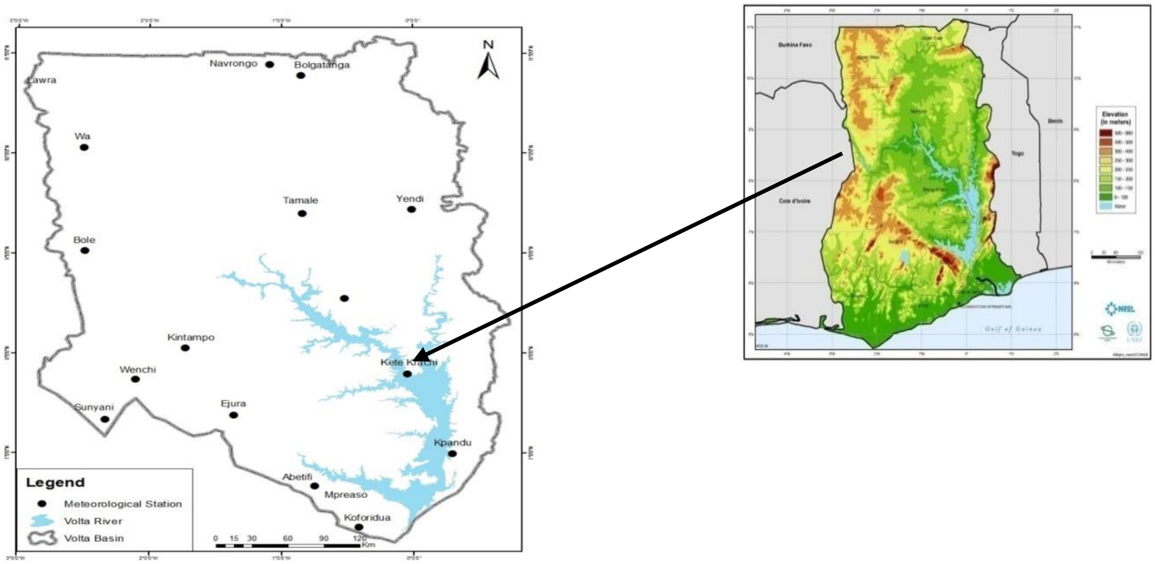


Figure 2: The study area: River Volta catchment

Source: Computer-generated map (2015)

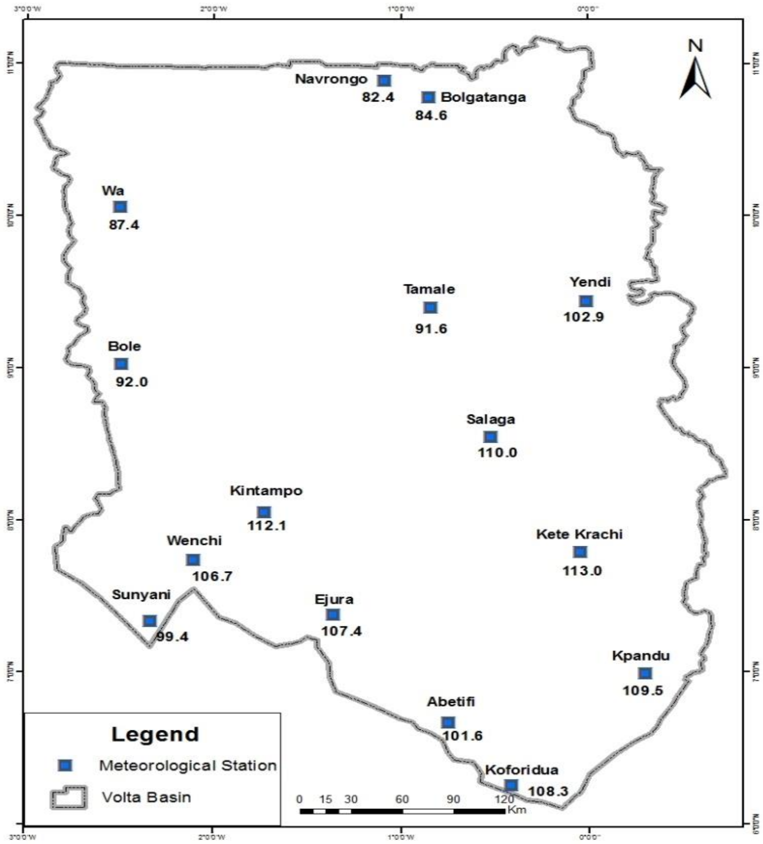


Figure 3: Rainfall distribution over the Volta catchment

## ***Data and source***

The monthly rainfall data (Table1) employed were collected from the records of the Ghana Meteorological Agency in Accra, for the period 1982–2012 for 15 recording stations. The choice of the period was due to the availability and continuity of data. The consistency of the rainfall data was investigated through the study of weather records, which were the following:

- *Hyetographs*: These were the original daily rainfall charts obtained from self-recording rain gauges. Black continuous or broken lines on this chart gave both the amount and the duration of rainfall recorded during a particular period.
- *The daily weather (MET and 101):* This file provided the statistical summary of the weather at each station as well as for given synoptic hours for each day of the month.

- *The summary of daily weather*: This contained the synoptic weather stations for the whole of West Africa, with particular reference to Ghana, for each day of the month.
- *The monthly report of work*: This provided the monthly summary of the weather.
- *The annual summary of observations in Ghana*: This gave the statistical summary of the weather elements at all the stations for each month of the year.
- *The Kalamazoo***:** This was the register which contained the rainfall data for each day of the year.

Table 1: Average annual rainfall amount from rainfall stations 1982–2012 (30 years)

| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sept** | **Oct** | **Nov** | **Dec** | **Total** | **Avg** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abetifi | 16.2 | 35.8 | 113.7 | 136.2 | 153.4 | 197.5 | 97.4 | 83.6 | 158.6 | 154.4 | 47.2 | 25.0 | 1218.9 | 101.6 |
| Bole | 2.4 | 11.5 | 45.0 | 105.4 | 131.0 | 152.7 | 143.8 | 167.2 | 213.8 | 107.8 | 18.0 | 5.8 | 1104.5 | 92.0 |
| Bolgatanga | 0.2 | 2.5 | 12.3 | 43.1 | 113.6 | 141.3 | 176.1 | 268.4 | 189.9 | 59.1 | 5.6 | 3.5 | 1015.5 | 84.6 |
| Ejura | 7.1 | 25.0 | 90.5 | 150.4 | 168.7 | 188.9 | 129.9 | 88.9 | 209.2 | 172.4 | 38.1 | 20.3 | 1289.3 | 107.4 |
| Kete-Krachi | 6.4 | 11.1 | 34.7 | 94.8 | 129.1 | 216.2 | 211.1 | 222.4 | 252.4 | 149.1 | 21.8 | 7.1 | 1356.2 | 113.0 |
| Kintampo | 5.9 | 24.4 | 73.0 | 143.0 | 162.6 | 194.7 | 152.5 | 136.7 | 223.6 | 180.7 | 35.9 | 12.3 | 1345.3 | 112.1 |
| Koforidua | 22.9 | 62.9 | 110.0 | 147.1 | 158.0 | 192.4 | 120.0 | 88.1 | 140.6 | 159.4 | 68.5 | 29.8 | 1299.7 | 108.3 |
| Kpandu | 6.9 | 29.9 | 68.9 | 132.0 | 140.4 | 184.6 | 199.9 | 167.8 | 174.6 | 148.3 | 46.6 | 14.0 | 1314.0 | 109.5 |
| Navrongo | 0.0 | 2.3 | 11.8 | 52.6 | 104.1 | 141.5 | 182.7 | 274.3 | 166.7 | 48.5 | 2.5 | 2.1 | 989.2 | 82.4 |
| Salaga | 6.7 | 10.8 | 48.8 | 122.8 | 119.9 | 191.4 | 178.3 | 214.5 | 265.0 | 141.2 | 12.6 | 7.4 | 1319.5 | 110.0 |
| Sunyani | 8.3 | 41.0 | 101.5 | 150.1 | 144.6 | 192.7 | 97.1 | 68.9 | 161.6 | 165.2 | 45.1 | 17.1 | 1193.2 | 99.4 |
| Tamale | 3.1 | 10.0 | 32.6 | 87.5 | 118.0 | 149.4 | 173.3 | 192.3 | 215.4 | 93.5 | 8.1 | 4.2 | 1087.3 | 90.6 |
| Wa | 4.5 | 6.2 | 20.8 | 87.2 | 126.5 | 147.0 | 154.9 | 221.1 | 196.3 | 77.2 | 5.0 | 1.8 | 1048.4 | 87.4 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wenchi | 7.7 | 26.3 | 100.8 | 160.6 | 173.6 | 158.9 | 128.2 | 98.6 | 184.9 | 177.2 | 50.7 | 13.1 | 1280.7 | 106.7 |
| Yendi | 3.6 | 8.4 | 46.5 | 93.6 | 120.6 | 175.2 | 181.5 | 231.0 | 262.6 | 102.9 | 6.3 | 2.7 | 1234.8 | 102.9 |
| **Total** | 102.0 | 308.1 | 910.8 | 1706.3 | 2064.2 | 2624.5 | 2326.7 | 2523.7 | 3015.2 | 1936.9 | 411.9 | 166.2 | 18096.5 | 1508.0 |
| **Average** | 6.8 | 20.5 | 60.7 | 113.8 | 137.6 | 175.0 | 155.1 | 168.2 | 201.0 | 129.1 | 27.5 | 11.1 | 1206.4 | 100.5 |

Source: Ghana Meteorological Agency (2015)

## *Missing data*

Trace mean monthly rainfall amounts flagged as accumulation in a month were assumed missing or invalid as data values in the archived data. Stations included in the analysis were required to have records that spanned the period 1982–2012, with no year completely missing during this interval. Using this strategy, Bawku and Lawra, which have several years' rainfall data missing, were not included in the analysis. The available rainfall data at 15 rainfall stations were therefore collected for the analysis.

The location of the 15 stations did not follow any particular pattern. They appear to be dictated by the location of the meteorological stations that are cited in the regional capitals, such as Tamale, Wa, and Bolgatanga, and in other large settlements such as Ejura, Kintampo, Navrongo, and Bawku, which also serve as district capitals. As a result, the gauge network is very sparse. Much of the central and the northern parts do not have gauge coverage. Whereas most of the stations are found in the south, the rest of the catchment area is coarsely served. The number of rainfall stations located in the catchment area is shown in Table 2 and in Figure 3. Also presented in Table 2 are the altitudes (heights or locations of stations above sea level), the annual mean rainfalls for the 30-year period, and the coordinates of the stations.

**Table 2: Rainfall stations in the River Volta catchment area, their altitude above sea level, coordinates, and mean average rainfall for the period 1982-2012**

| Rainfall stations | Latitude | Longitude | Altitude (m) | Rainfall (mm) |
|---|---|---|---|---|
| **Abetifi** | 05°47'00"N | 000°38'00"W | 601 | 101.6 |
| **Bole** | 09°02'00"N | 002°29'00"W | 264 | 92.0 |
| **Bolgatanga** | 10°47'00"N | 000°51'00"W | 581 | 84.6 |
| **Ejura** | 07°23'00"N | 001°21'34"W | 228 | 107.4 |
| **Kete-Krachi** | 07°49'00"N | 000°02'00"W | 87 | 113.0 |
| **Kintampo** | 08°03'00"N | 001°43'00"W | 286 | 112.1 |
| **Koforidua** | 06°05'00"N | 000°15'00"W | 87 | 108.3 |
| **Kpandu** | 06°60'00"N | 000°17'00"E | 152 | 109.5 |
| **Navrongo** | 10°54'00"N | 001°06'00"W | 197 | 82.4 |
| **Salaga** | 08°33'00"N | 000°31'00"W | 163 | 110.0 |
| **Sunyani** | 07°20'00"N | 002°20'00"W | 308 | 99.4 |
| **Tamale** | 09°25'00"N | 000°51'00"W | 151 | 90.6 |
| **Wenchi** | 07°45'00"N | 002°06'00"W | 304 | 106.7 |
| **Wa** | 10°04'00"N | 002°31'00"W | 305 | 87.4 |
| **Yendi** | 09°27'00"N | 000°01'00"W | 157 | 102.9 |

Source: Ghana Meteorological Agency (2015)

N = north of equator, W = west of longitude 0, E = east of longitude 0

The ordinary rain gauges (Snowdon types) used to measure rainfall depths in Ghana are exposed, ground-levelled, and installed with their rims parallel to the slope. Rodda (1970) and Sevruk and Hammond (1984) have shown that ground-level gauges to be the most efficient collectors.

## Data processing

In order to meet the study objectives, some rainfall estimation model software programmes (McGuiness, 1963; Forest, 1980; Guillermo et al., 1985; McCuen & Snyder, 1986; Singh & Chowdhury, 1986; Majeed, 2002; Faisal & Gaffer, 2012) were reviewed, and some were considered as integrated solutions to the catchment rainfall estimation. In this work, the Thiessen polygon method described above was carried out by applying the nearest neighbour method in the Arc View GIS software (version 10.1) which was developed by the Environmental Systems Research Institute (2002) and used by Taesombat and Sriwongsitanon (2009). Input data consisted of the stations' coordinates, the monthly rainfall values from the 15 stations, and the names of the observed locations. The outputs from the Arc View GIS software were area rainfall surfaces which corresponded to the Thiessen polygon network.

Before presenting the full results of the analyses, however, details of the computer programmes that were used for the computations are provided in order to illustrate more fully the methods employed. The regression analysis is first described.

## Data analyses

### *Investigation of altitude effect on rainfall depths in the RVC*

A regression analysis (Equation 2) was performed to ascertain the effect of altitude on rainfall distribution in the RVC. The reason was that rainfall depths normally vary in space and in time (Goovaerts, 1997), and they tend to increase with increasing elevations, because of orographic effect of mountainous terrain, which causes air to be lifted vertically so that condensation occurs as a result of adiabatic cooling (Acheampong, 2009). Hevesi et al. (1992a) and Hevesi et al. (1992b), for example, obtained a significant correlation of about 0.75 between average annual precipitation and elevation in Nevada and in south-eastern California, in the United States.

To investigate whether this observation occurs in the RVC, the mean rainfall data of the stations were regressed against their altitudes above sea level using the equation:

$$Y = \alpha_o + \alpha_1 h_1 + \mathcal{E} \quad (2)$$

where Y is rainfall,

$\alpha_o$ is intercept,

$\alpha_1$ is the coefficient of altitude,

$h_1$ is the altitude (location of rainfall station above sea level),

and $\mathcal{E}$ is an error term.

In using this method it was assumed that a linkage between the two parameters would mean it is possible to increase the accuracy of area rainfall interpolation by applying a topographic parameter (ground elevation of rainfall station) (Hastings & Dunbar, 1998; Goovaerts, 2000; Gorokhovich & Voustianiouk, 2006).

## *Analysis of the RVC rainfall using the Thiessen polygon*

The Thiessen polygon (Equation 1), as noted already in this paper, is a method of using rain-gauge network (see Figure 1) for estimating watershed average rainfall depths, which is especially suitable for electronic computation (Diskin, 1969; Diskin, 1970). As in the hypothetical figure (Figure 1) taken from the US Department of Agriculture National Engineering Handbook (1993), the Volta basin was divided into sub-areas using the stations as hubs of polygons. The sub-areas were used to determine ratios that were multiplied by the sub-area rainfall and summed to get the watershed average rainfall depth. The ratios, as observed earlier in this paper, were therefore the percentages of areas in the basin presented by each station. Figure 4 shows a polygon diagram of the rainfall distribution in the RVC in Ghana.

## Results

### *Altitude effect on rainfall depths*

The results of the simple regression analysis of the annual totals from all the15 stations against their elevation are shown in Tables 3 and 4, and in Figure 4. Although the coefficient of determination is positive (0.139), the relationship is very weak. The implication is that elevation or height has very little influence on rainfall distribution in the catchment area, and hence did not feature in any subsequent computation.

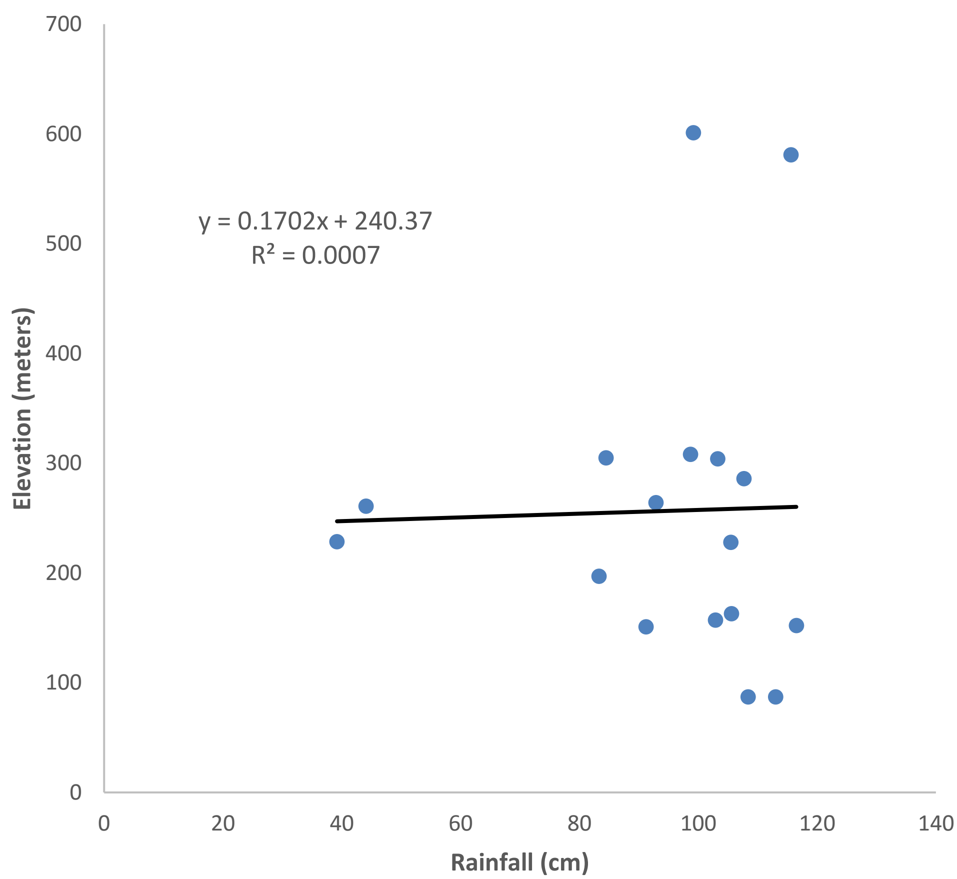


Figure 4: Altitude effect on rainfall distribution in the study area

Source: Result from regression analysis (2016)

Table 3: Residual output of regression analysis

| ***Observation*** | ***Predicted Y*** | ***Residuals*** | ***Standard residuals*** |
|---|---|---|---|
| 1 | 252.3462 | 348.6538 | 2.430821 |
| 2 | 304.8341 | -40.8341 | -0.2847 |
| 3 | 345.6687 | 235.3313 | 1.640734 |
| 4 | 220.0606 | 7.939445 | 0.055354 |
| 5 | 189.3591 | -102.359 | -0.71365 |
| 6 | 194.3648 | 91.63519 | 0.638882 |
| 7 | 215.2546 | -128.255 | -0.89419 |
| 8 | 208.6955 | -56.6955 | -0.39528 |
| 9 | 357.7291 | -160.729 | -1.12061 |
| 10 | 206.2049 | -43.2049 | -0.30123 |
| 11 | 264.1299 | 43.87013 | 0.305863 |
| 12 | 312.7328 | -161.733 | -1.1276 |
| 13 | 330.585 | -26.585 | -0.18535 |
| 14 | 223.9909 | 81.00908 | 0.564797 |
| 15 | 245.0439 | -88.0439 | -0.61384 |

Source: Computer-generated result (2016)

Table 4: Summary output of regression analyses

| *Regression Statistics* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Multiple R | 0.373268 | | | | | | | |
| R Square | 0.139329 | | | | | | | |
| Adjusted R Square | 0.073123 | | | | | | | |
| Standard Error | 148.8449 | | | | | | | |
| Observations | 15 | | | | | | | |
| ANOVA | | | | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* | | | |
| Regression | 1 | 46624.59 | 46624.59 | 2.104492 | 0.170566 | | | |
| Residual | 13 | 288012.3 | 22154.8 | | | | | |
| Total | 14 | 334636.9 | | | | | | |
| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
| Intercept | 811.5749 | 383.4797 | 2.116344 | 0.05418 | -16.8827 | 1640.033 | -16.8827 | 1640.033 |
| X Variable 1 | -5.50557 | 3.795151 | -1.45069 | 0.170566 | -13.7045 | 2.69335 | -13.7045 | 2.69335 |

Source: Computer-generated result (2016)

## ***Thiessen polygon map of the mean areal rainfall in the River Volta catchment***

As stated earlier in this paper, the Thiessen polygons were used to create initial territorial boundaries for each of the rainfall stations. The polygons so obtained involved the division of the catchment area into a number of separate territories, each of which focused on a separate or single station. The simple Thiessen polygons map (Figure 5) is therefore a territorial distribution of mean annual rainfall (MAR) that suggests lack of ranking. The polygons in the south and south-east are more clustered together and also have larger MAR values.

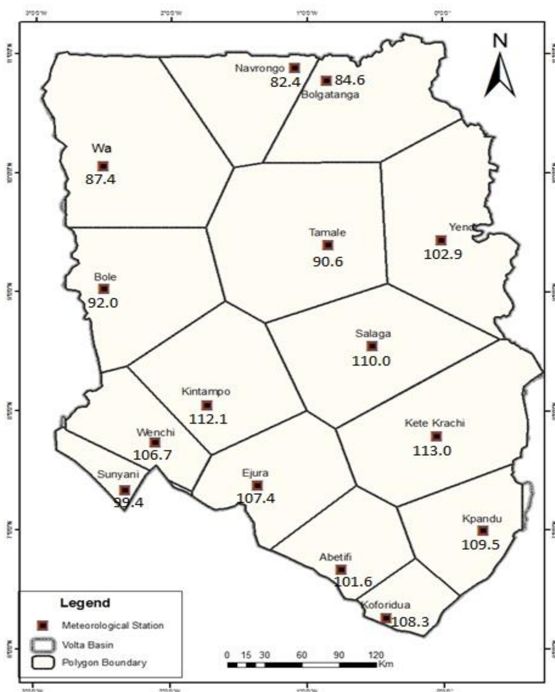


Figure 5: Thiessen polygon map showing mean annual rainfall depths in the River Volta catchment

Polygon mean of catchment = 93.0cm

Source: Computer-generated map, 2016

Those polygons in the rest of the catchment that have low MAR values are not clustered together. For example, Wa, Tamale, Salaga, and Yendi have low MAR values that are 87.4 cm, 91.6 cm, 110.0 cm, 102.9 cm, respectively, but because of their great distances from other stations, have large polygon sizes, which are 18,892.20 sq km, 17,770.90 sq km, 16,736.78 sq km, and 14,917.48 sq km, respectively. These polygons occupy 11.8%, 11.10%, 8.61%, and 9.31% of the catchment, respectively. On the other hand Sunyani (99.4 cm), Abetifi (101.6 cm), and Koforidua (108.3 cm) have high MAR values, but because of the proximity of several rainfall stations they have small Thiessen polygon sizes of 2,322.22 sq km, 6,736.78 sq km, and 3,385.03 sq km, respectively. The areas occupied by the three stations are 1.45%, 4.21%, and 2.11%, respectively. These findings suggest that a Thiessen polygon area alone is not sufficient to infer territorial importance. The catchment mean using this model is 93.0 cm.

## Summary conclusions and recommendations

The research sought to find the applicability of the Thiessen polygon method, as recommended by eminent hydro-meteorologists and climatologists, for the purpose of estimating area rainfall depths in the RVC in Ghana. The rationale behind the search was multi-faceted. One of the most important weather and climate elements in Ghana is rainfall, which is the source of water for most socio-economic activities. Not only is rainfall (water) essential for agriculture, it is also the driving force behind the generation of hydro-electricity at Akosombo and Bui. However, rainfall's variability and deficiency sometimes cause drought or floods, and not enough water in the Volta Lake to drive turbines to produce the needed electricity for domestic and industrial use. There was therefore a need to know, and also estimate, the mean rainfall amounts that are near the real values in those places in the catchment where rain-gauge networks are among the poorest in the country.

The RVC in Ghana was selected for the study because of its socio-economic importance to the country. The catchment covers more than half the surface area of the entire country. Economically, it is the least developed, but it has immense (economic) potentials. For example, much of the grain crops such as maize, millet, and sorghum, tuber-crops such as yam, and vegetables such as beans, onion, tomatoes, and groundnuts produced in Ghana come from the farmers in this area. Most importantly, the area has the Volta Lake, whose waters are used to generate hydro-electric power for Ghana and the neighbouring countries.

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In spite of the socio-economic potentials of the region, the RVC in Ghana is poorly served with rainfall stations; consequently, the actual quantities of rain that fall over the different locations in the catchment are unknown. There was therefore the need to search for efficient techniques that could be used to estimate the mean rainfall depths over the area. This was important because road or civil engineers, for example, need to know the minimum and maximum rains that fall at several other places in order to obtain the right measurements of culverts or drains that can efficiently carry flood waters into the Volta Lake, and eventually into the sea. The Ghana Electricity Company, for example, needs to know how much rain falls over every place in the catchment throughout the year. The return periods of extreme events such as meteorological drought and floods should be known so that the dams that are being proposed for future construction can be made large enough to have the capacities to hold large volumes of water for the generation of hydro-electric power even during the dry months.

A search through the studies that had been conducted on the estimation of rainfall depths at the earth's surface elsewhere revealed that though a few other techniques exist or are being used to estimate rainfall depths, the Thiessen polygon model is among the best, most popular, and most straightforward method for estimating rainfall depths. Although the literature acknowledges the fact that the method has certain weaknesses, its strength makes it ideal for estimating rainfall depths over different terrains, and especially in the RVC in Ghana.

Mean monthly rainfalls from the available 15 synoptic stations for a 30-year period (1982–2012) in the catchment area were employed. This period's mean values are accepted by the World Meteorological Organisation to represent the average falls over the area (Acheampong, 2009). The gauge network is considered very thin and poor, and suggestion is being made for the establishment of additional stations to make the gauge network dense in the region so that more readings can be taken at close intervals. This suggestion has been found necessary because the nature of tropical rainfall is such that a sudden copious rainfall, even in the dry season, may occur in a day at a non-recording location nearby and may cause severe flooding.

The height or altitude of the rain gauges above sea level and their coordinates were fed into a computer, and using some well-known computer programmes, the Thiessen polygon map was drawn. The results of the analyses, as has been noted, show that altitude has very little effect on rainfall distribution in the catchment, and that the Thiessen method is suitable, at least for the moment, for analysing rainfall data for the study area.

The map showing point values gives the rainfall at points that represent vast areas. Such a result is unacceptable, for example, for planning purposes. The Thiessen polygon method was therefore used to create territorial boundaries for each of the rainfall stations. The polygons so created involved the division of the catchment into a number of separate territories, each of which was focused on a single rainfall station.

The findings and conclusions from this particular area may be different from the findings from other regions in Ghana if the same methods are employed, because of the differences in terrain and in density of rain-gauge networks. For these and other reasons, it may be necessary for the research to be replicated in other catchments in the country that have potentials for irrigation projects and the harnessing of their rivers and streams for hydro-electric power. So far as the RVC study is concerned, the Thiessen polygon method is applicable. It appears that the method will become more accurate as the gauge distribution in the catchment becomes more nearly even.

Another area worth researching is the estimation of rainfall depths using other methods, such as radar, triangular facets, revised weighted polygons, and height-balanced polygons, which have been successfully used elsewhere, but so far have not been tried in Ghana.

Finally, the method could be used to estimate other climate elements such as humidity, evaporation, and potential-evaporation in river catchments in Ghana. Gauge network parameters should be included in such studies as significant factors, and such studies should make use of both simulated and real data sets. A product which can be envisioned from this type of research would be a rating system for all available areal rainfall assessment methods, in which the accuracy of each method is established on an either absolute or relative scale.

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