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# Relationship Between Rainfall And Sediment Yield in Gubi Dam Reservoir, Bauchi State, Nigeria

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**Abstract:** Gubi Dam in Bauchi state supplies the city and its environs with potable water for consumption. The catchment area of the reservoir is exposed to soil excavations, high runoff due to high rainfall, crop farming and overgrazing by livestock. This exposure leads to sediment accumulation in the reservoir and subsequent reduction in storage capacity and ultimately, flooding. A model reservoir was installed across Rafin Kira, which is one of the nine tributaries of the dam. Sediment depths were measured and the values of the yield were related to daily rainfall depth in order to establish a suitable relationship between the two variables. Three basic models were used to simulate the realationship viz: Linear model, Logarithmic model and the Polynomial model. The linear model gave a relationship of $Y= 3.251x + 791$ with $R^2$ of 85.6%, the polynomial model gave an equation of $Y= 0.000x^6 – 0.020x^5 + 0.395x^4 – 3.591x^3 + 14.84x^2 – 16.59x + 3.258$ with $R^2$ of 97.2% and the logarithmic model gave a relationship of $Y=20.72 \ln (x)-4.114$ with $R^2$ of 95.5%. The logarithmic relationship was found to be most suitable since it was the closest to the direct measurement estimate. A total sediment yield of $4.1x10^4$ $m^3$ (0.11% of reservoir capacity) was obtained per annum. It was found that the aforementioned causes only yielded a relatively insignificant quantity of sediment in the reservoir which was attributed to the large size of the catchment. Subsequent sediment studies in reservoirs and sophisticated equipments should be employed to enable a faster sediment investigation for proposed and existing reservoirs.

**Keywords:** Sediment, Rainfall, Dam, Reservoir, Catchment, Gubi

## I. INTRODUCTION

Dams have been used since ancient times to impound water in reservoirs for various uses in several communities. The easy accessibility of surface water makes it a preferable source of municipal water supply. The available surface runoff is about 0.05% of the total amount of water on earth with seawater acquiring the largest share of 97.2%. The rest are distributed between groundwater, ice sheets and soil moisture (Mustafa and Yusuf, 2012). These reservoirs are vital to the world's economy for their roles in electricity generation, flood control, water supply and irrigation (Kudamnya *et. al.*, 2013). The life expectancy of these reservoirs is however threatened by soil particles (sediment) that accumulate at the dam site which leads to a reduction of its storage capacity, quality of the stored water and consequently, collapse of the dam structure (Vulegbo, 2014). Many cases have been recorded where reservoir siltation rendered water storage structures useless in less than 25 years (Mama and Okafor, 2011).

High precipitation, which is the primary source of the accumulation, washes away easily erodible soil particles as surface runoff into streams and rivers. The absence of vegetal cover, flood frequencies, reservoir geometry and nature of topography impede the infiltration rates of catchments (Eze *et. al.*, 2012; Hirose and Sumi, 2005). In other instances, excessive farming activities which reflect an increase in population also enhance the yield of the sediments into watercourses (Liden *et. al.*, 2001). Most of these characteristics in addition to soil excavations are noticeable in Gubi reservoir catchment area. The river water further scours the bed and banks of the channel, then carries the sediment load towards the dam site (Mama and Okafor, 2011; Goel *et. al.*, 2002). As the flow approaches the reservoir, its velocity reduces and the sediments settle and accumulate. The settled sediment separates into two; the coarser particles settle at the very bottom as bed load, while the finer particles stay in suspension as suspended load (Hirose and Sumi, 2005; Jain and Singh, 2002).

Water users of rivers affected by sedimentation may have to remove suspended sediment from their water supplies or may suffer a reduction in the quantity of water (Ongley, 1996). Flooding is the aftermath of the reduction in channel capacity resulting from its incapacity to cope with its usual protracted rain river flow peaks. Sediment yield further degrades soil productivity as well as water quality causing detrimental effects and extinction to some aquatic lives (Betrie *et. al.*, 2014). Pollutants, for instance, pesticides, heavy metals and nutrients which are absorbed by the sediment load are also transported to the stream water and this is evidenced by their brown colours after rains (Eze *et. al.*, 2012; Liden, 2001).

The measurement of sediment yield can be a complex process and at most times very expensive. Researchers have developed physical methods of direct estimation with the aid of samplers. These samplers can be used to estimate both bed load and suspended load (Mama and Okafor, 2011). In more complex cases, such direct approaches can be cumbersome prompting the need for establishing relationships between variables that are closely related to sediment yield. Variables such as rainfall depth, river discharge, soil erosion and turbidity have been correlated and mathematical models derived for forecasting purposes (Chun and Gang, 2004).

An overview of the hydrologic cycle hints that all reservoirs carry some amounts of sediments no matter how little in quantity and the huge sums of money used in constructing structures such as dams justify its initial and periodic measurements. An understanding of the quantity of sediment deposition is necessary for an effective reservoir and watershed management (Onwuegbunam, 2013).

## II. MATERIALS AND METHODS

### 2.1 The Study Area

Gubi dam is located in Firo village, Ganjuwa Local Government Area of Bauchi State, Nigeria (See Fig. 1). The state's Southern and Northern limits are demarcated by latitudes 9° 45' North and longitude 12° 30' North respectively while its Western and Eastern limits are bounded by longitudes 8° 45' East and 11° 0' East respectively (Modibbo and Sumi, 2014). It lies within the tropical climatic zone with marked wet and dry season with Average Annual rainfall depth varying from 700mm to 1300mm. The state has two vegetative zones- Sahel Savannah in the north and Sudan Savannah in the southern part (Akinsanola and Ogunjobi, 2014; Furo and Suleiman, 2010). Bauchi is basically composed of crystalline rocks in Nigeria basement complex. The source of water in Gubi dam is mainly coming from three tributaries, namely Gubi River, Tagwaye River link with Shadawanka, Ran River and six (6) other tributaries of which Rafin Kira is inclusive. The function of the dam is to supply the state capital and its environs with potable water (Abdullahi et. al., 2014).

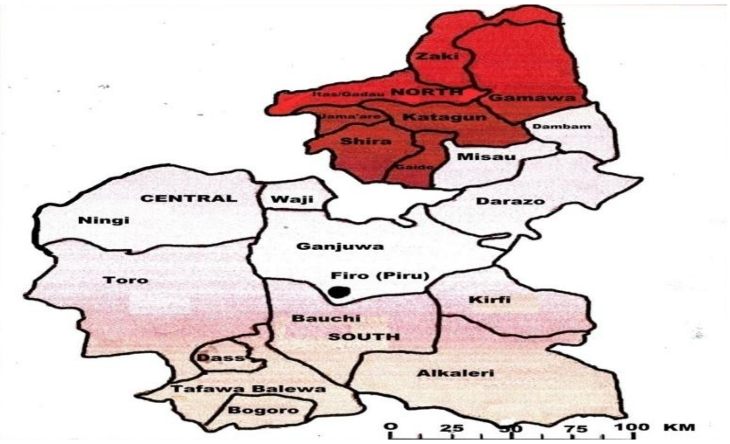


**Figure 1** Map of Bauchi State (Sadiq et. al., 2014)

Gubi dam is classified as a large, zoned earth filled dam with catchment area of 179km² and average annual runoff of 39.4 million m³.The embankment of the dam has a length of 3.86km and volume of bottom earth-fill of 2,315,000m³ with a reservoir area of 590 hectares (FMAWR, 2007). The crest has an elevation of 560m above mean sea level (msl) with top width, maximum height and maximum base width of 10m, 27m and 190m respectively (See Fig. 2). The dam has a Full Supply Level of 557m and Dead Storage Level of 545m above mean sea level. The total storage capacity is 38.4 x $10^6$m³ while the Dead Storage and Active Storage Capacities are 3.25 million m³ and 35.15 million m³ respectively. The spillway has a length of 70m at an elevation of 557m above mean sea level. The Emergency Crest Level is 559 above mean sea level (BSWB, 2014).


**Figure 2:** Map of Gubi dam

**2.2 Measurement of Rainfall**

The rainfall depth after each rainfall occurrence was obtained from the Bauchi State Water Board from 11th August, 2015 to 23rd October, 2015. This represented the peak period of rainfall in the study area. The mean yearly rainfall depths were obtained for the catchment area for 30 years (NIMET, 2015).

**2.3 Measurement of Sediments**

One of the nine tributaries of Gubi dam, *Rafin Kira* was chosen because of its accessibility and proximity to borrow pits, farming activities and overgrazing. A hole of size 1m x 1m x 1m dimension was dug as practiced by Mama and Okafor (2011). The hole was located at midstream of the river about 150m upstream of the confluence of the reservoir tributaries. A metallic model reservoir of the same dimensions was placed in the hole to avoid cave- in. The top of the reservoir was leveled with the bed of the stream. The model reservoir has a 0.6m projection at the top of one of the sides of the reservoir for the purpose of reducing the velocity of the flowing water. The model reservoir was placed at the early days of the rainy season. The depth remaining or depth covered by sediments after each rainfall was measured until the frequency of the rainfall occurrence had reduced. The depth of sediment accumulation was measured with a 3m metal rod and a piece of slipper that was carved and lined within the rod. After the rod and slipper were removed, the depth was measured with the aid of a measuring tape. The depth was measured at nine (9) points of the model reservoir for the purpose of precision. The average of the nine (9) points was then computed to represent the depth of sediment accumulation for that day. The results of the field work were tabulated. A graph was plotted for sediment accumulation in mm/m$^2$ on the Y- axis against cumulative rainfall depth in mm on the X- axis using Microsoft Excel for the purpose of forecasting. The plots gave the linear, logarithmic and polynomial mathematical relationships and confidence levels ($R^2$). The total rainfall depths of the 30 years were computed and inserted into the relationship. The percentage sediment accumulation rate was computed by dividing the total reservoir capacity by the average yearly sediment yield multiplied in percentage (Chun and Gang, 2004; Liden *et. al.*, 2001).

## III. RESULTS

**3.1 Sediment Yield**

The results over the study period confirmed a high initial sediment yield while the subsequent yields decreased as the rainy season came to an end (BSWB, 2015). The cumulative rainfall depths and sediment yields were computed and presented in Table 1

**Table 1 Values of Cumulative Rainfall depths and Cumulative Sediment yields**

S/N Date of Rainfall Cum. Rain. Sediment Cum. Sediment Record Depth (mm) Depth (mm) Yield (mm/m²) Yield (mm/m²)

| | | | | | |
|---|---|---|---|---|---|
| 1 | 11/8/2015 | 0 | 0 | 0 | 0 |
| 2 | 12/8/2015 | 0 | 0 | 0 | 0 |
| 3 | 14/8/2015 | 34.59 | 34.59 | 24.4 | 24.4 |
| 4 | 17/8/2015 | 34.63 | 69.22 | 1.16 | 25.56 |
| 5 | 21/8/2015 | 23.04 | 92.26 | 5.55 | 31.11 |
| 6 | 24/8/2015 | 53.57 | 145.83 | 2.22 | 33.33 |
| 7 | 27/8/2015 | 51.78 | 197.61 | 0.00 | 33.33 |
| 8 | 31/8/2015 | 51.96 | 249.57 | 5.00 | 38.33 |
| 9 | 8/9/2015 | 69.15 | 318.72 | 2.23 | 40.56 |
| 10 | 14/9/2015 | 24.40 | 343.12 | 0.00 | 40.56 |
| 11 | 15/9/2015 | 101.38 | 444.5 | 6.55 | 47.11 |
| 12 | 17/9/2015 | 103.80 | 548.3 | 2.45 | 49.56 |
| 13 | 22/9/2015 | 115.23 | 663.53 | 0.00 | 49.56 |
| 14 | 26/9/2015 | 116.35 | 779.88 | 0.33 | 49.89 |
| 15 | 5/10/2015 | 104.00 | 883.88 | 2.11 | 52.00 |
| 16 | 23/10/2015 | 106.45 | 990.33 | 2.44 | 54.44 |

It can be deduced from Table 1 that the first rainfall depth of 34.59mm gave the maximum sediment yield of 24.4mm/m$^2$. A rainfall depth of 51.78mm and 24.4 have produced no sediment yield. The highest depth of rainfall which was 106.45mm produced a sediment yield of 2.44mm/m$^2$. It is obvious that a linear relationship hardly exists between the cumulative rainfall and sediment accumulation.

The depth of sediment yield in mm/m$^2$ was plotted against Rainfall Depth in mm and the linear, logarithmic and polynomial relationships are illustrated thus;

**3.2 Relationship between Sediment accumulation and cumulative rainfall**

### 3.2.1 Linear Relationship

The two variables subjected to Linear testing in gave the relationship in Figure 3;

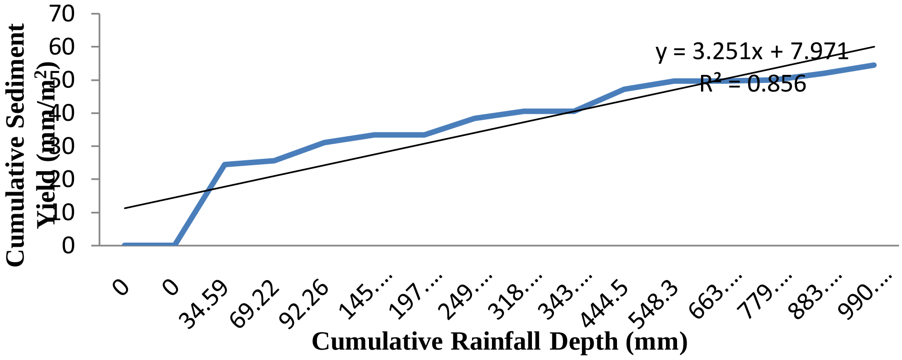


**Figure 3:** Linear Relationship between Sediment Accumulation and Cumulative Rainfall Depth

From figure 1 the relationship gave a coefficient of determination of **85.6%** and an equation of

**Y = 3.251x +7.971**…………………….. (1)

The equation can be simplified into
Y = ax + b, where; x is the cumulative rainfall depth in mm,
Y is the sediment accumulation in mm/$m^2$ and,
a and b are 3.251 and 7.971 respectively and are the catchment coefficients.

### 3.2.2 Logarithmic Relationship

The data were also tested to determine their logarithmic relationship in Figure 2;

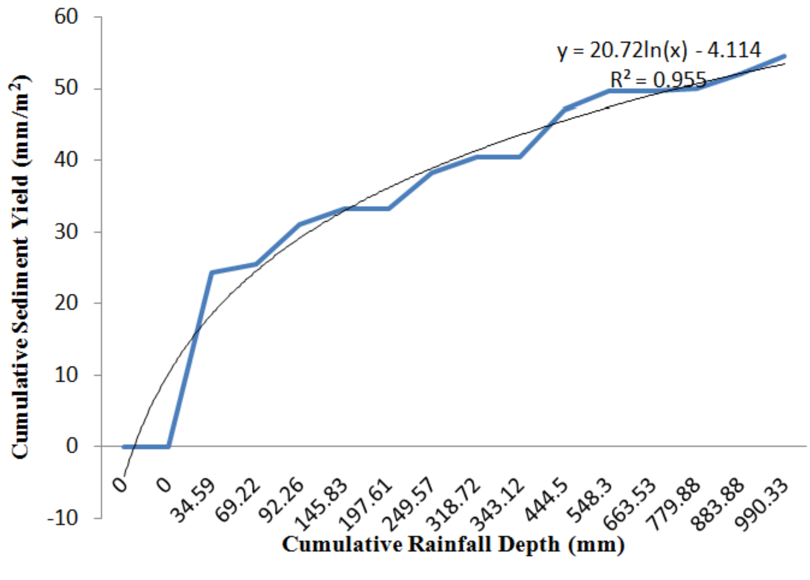


**Figure 4:** Logarithmic Relationship between Sediment Accumulation and Cumulative Rainfall Depth

From Figure 4, the relationship gave a coefficient of determination ($R^2$) of **95.5%** and an equation of
**Y = 20.72 In (x) – 4.114**…………………………………(2)

The equation can be re-written as
**Y = a In (x) – b** where a and b are 20.72 and 4.114 respectively.

### *3.2.3 Polynomial Relationship*

The data were also subjected to a polynomial relationship to the $6^{th}$ order. This is illustrated in figure 5;

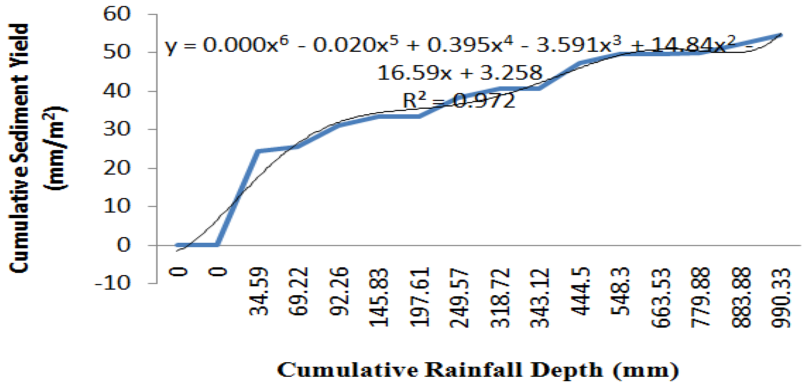


**Figure 5:** Polynomial relationship between Sediment accumulation and Cumulative Rainfall Depth

From figure 5, the relationship gave a coefficient of determination ($R^2$) of 97.2% and an equation of $Y= 0.000x^6 – 0.020x^5 + 0.395x^4 – 3.591x^3 + 14.84x^2 – 16.59x + 3.258$…………………..(3)
The equation can be simplified as
$Y = ax^6 – bx^5 + cx^4 – dx^3 + ex^2 – fx + g$. where a, b, c, d, e, f and g represent the catchment coefficients.

### 3.3 Rate of Sediment Yield

#### *3.3.1 Sediment Yield from Direct Measurement*

Given that the sediment yield estimated for this year at *Rafin Kira* is 54mm/m$^2$ For a reservoir area of 590 hectares, the average annual sediment yield is

$0.054 \times 5.9 \times 10^6 = 31.86 \times 10^4 m^3$ yearly

The capacity of the reservoir is $38 \times 10^6 m^3$. This indicates siltation at a rate of 0.84% yearly.

#### *3.3.2 Sediment Yield from Linear Model*

Given that x is 29,744.5mm, a = 3.251 and b= 7.971, the sediment yield Y is;
Y = 3.251 (29,744.5) + 7.971 = 96,707.34mm/m$^2$ divided by 30 is 3,223.5mm/m$^2$ yearly.
For a reservoir area of 590 hectares, the average annual sediment yield is

$3.225 \times 5.9 \times 10^6 = 19 \times 10^6 m^3$ yearly

The capacity of the reservoir is $38 \times 10^6 m^3$. This indicates siltation at a rate of 50% yearly.

#### *3.3.3 Sediment Yield from Logarithmic Model*

Given that x is 29,744.5mm, a = 20.72 and b= 4.114, the sediment yield is;
Y = 20.72 ln (29,744.5) – 4.114= 209.3 mm/m$^2$ divided by 30 is 6.977mm/m$^2$ yearly
For a reservoir area of 590 hectares, the average annual sediment yield is

$0.00698 \times 5.9 \times 10^6 = 4.1 \times 10^4 m^3$ yearly

The capacity of the reservoir is $38 \times 10^6 m^3$. This indicates siltation at a rate of 0.11% yearly.

#### *3.3.4 Sediment Yield from Polynomial Model*

Given that x is 29,744.5mm, a= 0.00, b= -0.020, c= 0.395, d= -3.591, e=14.84 and f= -16.59 and g= 3.258

$Y= 0.000(29,744.5)^6 – 0.020(29,744.5)^5 + 0.395(29,744.5)^4 – 3.591(29,744.5)^3 + 14.84(29,744.5)^2 – 16.59(29,744.5) + 3.258 = -4.7 \times 10^{20}$ mm/m$^2$

This value is out of range since sediment accumulation cannot be a negative value. The Logarithmic value has given a more rational value since the dam was completed in 1980 in which the linear relationship indicates that the dam would have been silted in 1982. The Polynomial model gave a negative value which is out of range since sediment yield cannot be a negative value.

## III. DISCUSSION

Gubi dam which has an area of 17,900 ha had an annual siltation rate of $31.86 \times 10^4 m^3$ per annum estimated from the direct measurement and $4.1 \times 10^4 m^3$ per annum estimated from the logarithmic relationship. This sedimentation rate in *Gubi* dam reservoir is less than the sediment rate of $1.26 \times 10^6$ m$^3$ per annum of Kubanni dam reservoir in Kaduna State, Nigeria which has a catchment area of 5.75 ha as assessed by Adeogun and Otun (2012). Although Kaduna State lies in the Sudan Savannah region of the country which is characterized by similar vegetation features with that of Bauchi State, the sedimentation in Gubi dam reservoir may therefore be attributed to its higher catchment area.

In terms of climate and vegetation on the other hand, the Tagwai river basin in Niger State has an average sediment yield of 404.3$m^3$ per annum (Vulegbo *et. al.*, 2014). The reservoir has a total storage of 28 x $10^6 m^3$ and catchment area of 110,000 ha. The catchment area also has an average annual rainfall of 1270mm which is similar to that of Gubi dam reservoir with sediment rate of 4.1 x $10^4 m^3$ per annum, catchment area of 17,900ha and average annual rainfall of 1000mm. The sediment rate from Gubi dam reservoir is far higher than that of Tagwai river basin and can be attributed to differences in vegetation. The Tagwai river basin falls under the Guinea Savannah region of Nigeria which is characterized by grasses, shrubs and trees which reduce the amount of sediment into the rivers and streams (Adwubi, 2009).

## IV. CONCLUSION

The logarithmic model of Y= 20.72 ln (x) – 4.114 with $R^2$ of 95.5% gave a value which was closer to the direct measurement value. The sediment yields from the direct measurement and logarithmic model of 31.86 x $10^4 m^3$ per annum and 4.1 x $10^4 m^3$ per annum respectively do not necessarily reflect a low sediment yield in the basin. The relative volumes of 0.84% and 0.11% for the direct measurement and logarithmic model respectively simply reflect the greater magnitude of the dam in relation to the sediment yield. Furthermore, the aforementioned causes of the yield in Gubi dam reservoir have little sediment conveyance into the reservoir. It was concluded that the size of the catchment area was the reason for the low siltation rate.

## RECOMMENDATIONS

**1)** Sophisticated equipments for sediment yield measurement should be obtained for a faster sediment yield investigation. The equipment should be constructed with a stronger material toavoid deformation during backfilling.
**2)** Further research should be made to develop a technique to account for the disturbed sediment.
**3)** The Mama and Okafor (2011) method of sediment measurement should be employed where previous sediment data is not available.
**4)** For similar catchments, a similar equipment with a smaller geometry should be used since the yield was minimal.
**5)** The study of the relationship between rainfall and yield in Gubi dam reservoir needs to be carried out from time to time to validate the model developed in this study.

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**Appendix A:** Mean Average Annual Rainfall

| S/n | Year | Depth (mm) | S/n | Year | Depth (mm) |
|---|---|---|---|---|---|
| 1. | 1978 | 1151.00 | 16. | 1993 | 1141.90 |
| 2. | 1979 | 1000.30 | 17. | 1994 | 1174.30 |
| 3. | 1980 | 988.20 | 18. | 1995 | 961.40 |
| 4. | 1981 | 1244.80 | 19. | 1996 | 1180.80 |
| 5. | 1982 | 900.00 | 20. | 1997 | 770.00 |
| 6. | 1983 | 779.00 | 21. | 1998 | 1156.50 |
| 7. | 1984 | 893.70 | 22. | 1999 | 1403.80 |
| 8. | 1985 | 742.20 | 23. | 2000 | 937.00 |
| 9. | 1986 | 946.20 | 24. | 2001 | 1307.20 |
| 10. | 1987 | 790.90 | 25. | 2002 | 781.00 |
| 11. | 1988 | 920.70 | 26. | 2003 | 744.00 |
| 12. | 1989 | 909.70 | 27. | 2004 | 672.10 |
| 13. | 1990 | 879.60 | 28. | 2005 | 1078.50 |
| 14. | 1991 | 949.60 | 29. | 2006 | 1007.20 |
| 15. | 1992 | 1226.00 | 30. | 2007 | 1136.90 |

**Source:** Nigerian Meteorological Services, Bauchi State, 2015.

**Appendix B: Values of Rainfall after each rainfall event**

| S/D | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R(mm) | 0.00 | 0.00 | 34.59 | 34.63 | 23.04 | 53.57 | 51.78 | 51.96 | 69.15 | 24.40 | 101.38 | 103.80 | 115.23 | 116.35 | 104.00 | 106.45 |

**Source:** Bauchi State Water Board, 2015