HYDROGEOLOGICAL DEEP PERCOLATION MODELLING OF GROUNDWATER RECHARGE IN VOINJAMA REGION, LIBERIA

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Abstract

Indirect physical methods of assess groundwater recharge rely on the measurement or estimation of soil physical parameters, which along with soil physical principles; can be used to estimate the potential or actual recharge. However, the deep percolation method uses a daily water- budget approach to simulate deep percolation. In this method, the model computes daily fluxes of water into and out of a volume extending from the top of foliage to the bottom of the root zone and accounts for changes in water content. In most environments, deep percolation is destined to recharge the saturated systems that are tapped by wells. Deep percolation technique was deployed to determine the rate of ground water recharge in the Voinjama region of Liberia, and also establish points of lineaments where wells can be dug for water supply. The perimeter of the hypothesized basin is about 28.9km while the length of the thalweg of the mainstream is about 11km. the average width of the basin area is 5.9km while the circumference of the equivalent circular area is 25.33km and compactness coefficient (R) of the basin is computed at 1.14. The elongation ratio (E_r) is computed at 0.73km. The diurnal recharge computed from Deep Percolation was 6712.21 cm^3 /km^2 per annum. In conclusion, this study aids the restoration of water supply system destroyed during the war periods emphasizing the abundant water in the hydrological system and viable ground water recharge adequate for exploitation in a near uniform geology. Several faults and crevices scattered abroad the area were recorded indicating good lineament distribution and abundant aquifer recharge.

Key Words: *Hydrogeology, Deep Percolation Method, Groundwater, Recharge*

Introduction

Liberia, recovering from a 14 year civil war is currently turning from a state of emergency to one of development, as such; much of the population which hitherto has had no access to improved drinking water sources is being targeted for portable water supply. Today, safe water supply depends on boreholes and hand dug wells particularly in the Lofa

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county capital, Voinjama city (26,594 inhabitants), since the communal pipe network got destroyed during the war (Williams, 2002; Herbert, 2014). Whereas, finding water requires appropriate site selection to increase success rates and enhance water point performance based on deeper understanding of the hydrogeological environment, such knowledge is limited, thus leading to high failure rates up to 40% or higher among groundwater project implementers.

Groundwater recharge, also called deep drainage or deep percolation, is a hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface.

Groundwater is recharged naturally by rain and to a smaller extent by surface water (rivers and lakes). Recharge may be impeded somewhat by human activities including paving, development, or logging. These activities can result in loss of topsoil resulting in reduced water infiltration, enhanced surface runoff and reduction in recharge. Use of groundwaters, especially for irrigation, may also lower the water tables. Groundwater recharge is an important process for sustainable groundwater management, since the volume-rate abstracted from an aquifer in the long term should be less than or equal to the volume-rate that is recharged. Recharge can help move excess salts that

accumulate in the root zone to deeper soil layers, or into the groundwater system. Tree roots increase water saturation into groundwater reducing water runoff (Fisher, 2008).

Groundwater occurrence has been well described by various authors and a well-established conceptual hydrogeological model for groundwater occurrence exists. Aquifers can develop within the weathered overburden and fractured bedrock but groundwater found in the fresh bedrock is negligible (Acworth, 1987; Wright and Burgess, 1992; Chilton and Foster, 1995; Taylor and Howard, 2000; MacDonald et al., 2005). The development of the weathering profile is controlled by chemical degradation of fresh bedrock (Acworth, 1987). Weathering processes depend on presence of water, oxygen and carbon dioxide. Amount of precipitation, groundwater flow (permeability of material and hydraulic gradient) and vegetation cover (hydrolysis reactions) are therefore drivers for the rate of weathering. Evolutionary cycles of weathering and stripping (fluvial and colluvial erosion) over geological time caused heterogeneities in vertical and horizontal extent of the weathering profile (Taylor and Howard, 2000). Deeper fractures within the bedrock are of tectonic origin (Acworth, 1987).

The British Geological Society classification of the weathering profile describes three main lithological sequences that can be further considered as framework of the conceptual hydrogeological model for groundwater occurrence (Wright and Burgess, 1992). Depth to bedrock, thickness of sequences and additional lithological specifications (e.g. soil type) are variable parameters

depending on local conditions. The base of the saprolite is promising for groundwater development because of less clay minerals and coarser grain size fractions (even rock fragments). Moderate to low yields between 0.1-1 l/s can be expected if an extensive saprolite zone is present (MacDonald *et al*., 2005). It is questionable if higher borehole yields correlate with thicker water saturated saprolite (Wurzel, 2001). For instance, Wright and Burgess (1992) didn't observe a correlation from analysing 929 borehole logs in Zimbabwe but Agyekum and Dapaah-Siakwan (2008) examined 2458 borehole logs in north-eastern Ghana and found a strong tendency of higher yield versus deeper weathering. Many factors of uncertainty like the hydraulic gradient and technical borehole aspects might make analysis difficult. Taylor and Howard (2000) suggest based on pumping test results to target only the regolith extent (T= 5-20 m2/day), since transmissivities of the saprock (T= approximately 1m2/day) are much lower.

However, MacDonald *et al*. (2005) recommend targeting the saprock by identifying deeper tectonic fractures is undoubted required for successful siting in areas of poor weathering. Appropriate siting increases drilling success rates and improves borehole yield performance. A wide range of methods are used in Africa from unscientific divining to expensive exploratory drilling (MacDonald et al., 2005). The UNDP guideline for site selection subdivides specific methods in the following categories: geophysical investigations, remote sensing interpretation, hydrogeological fieldwork, and reconnaissance of existing hydrogeological data, local knowledge and exploratory drilling (van Dongen and Woodhouse, 1994). However, all methods are only suited to answer specific questions and a promising prospection strategy should involve an integrated method approach to meet the challenges of siting (MacDonald et al., 2005). This study attempts an analysis of the hydrogeological recharge capacity of the Voinjama region by employing the deep percolation method.

Study Area

The Voinjama region in Liberia is an extremely rugged hilly topography with rounded and elongated tops up to 300m above the surrounding terrain and dense rainforest except when cleared characterize the landscape of Voinjama city, like most of the Lofa county (Seitz, 1974). The average terrain of the area lies on approximately 400m above sea level and only the Wologizi mountain range to the west of Voinjama city, rises up to 1400m. Annual precipitation ranges between 2000-3000mm, much less than at the 5000mm along the coastline of Liberia (De Boer et al., 1982). Still, rainfall is high compared to most other areas of sub-Saharan Africa (MacDonald et al., 2005). The rainy season lasts from May to October with peak values in July and August. A period from December to April is the driest and it is important to notice that a mid-dry phenomenon is absent. The temperature remains relatively stable around 26°C throughout the year with extreme values between 10-37°C (Reed, 1951).
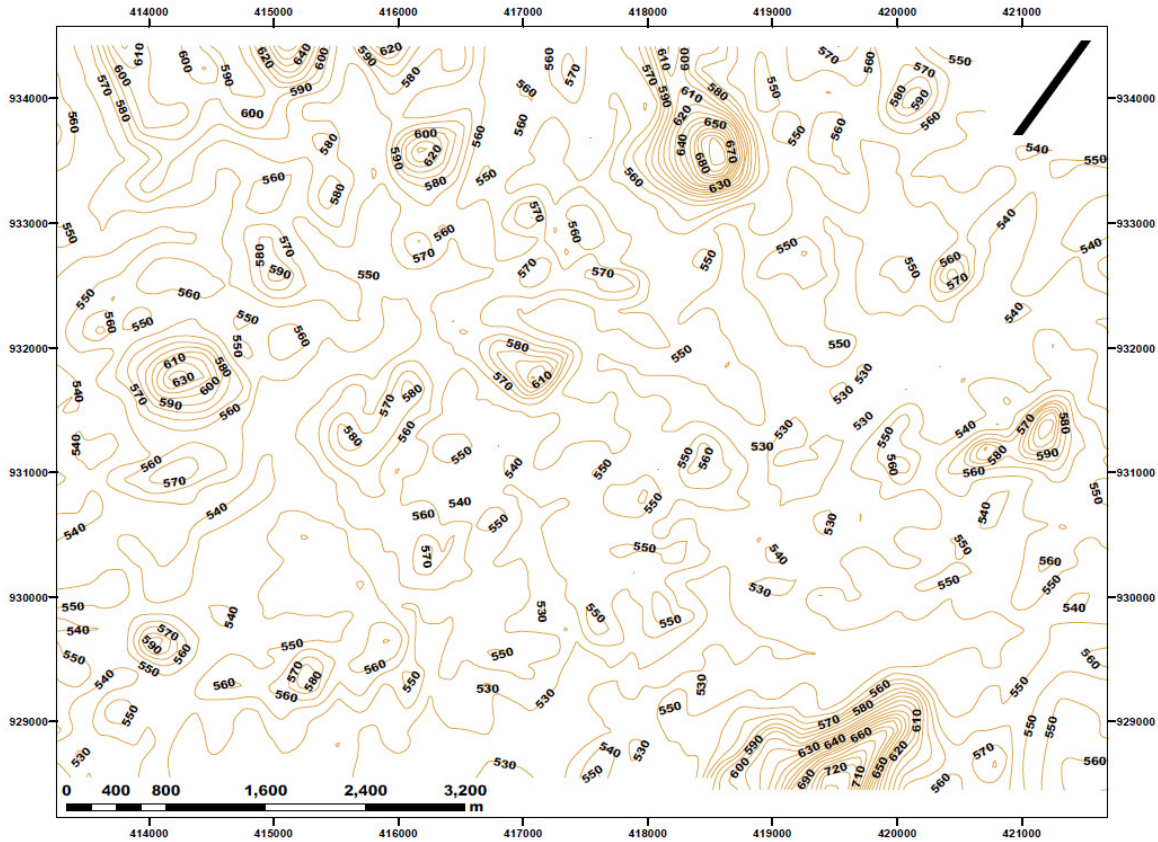
Figure 1 Topographic map of the Voinjama city generated from SRTM

The area is part of the West African Craton (Leo or Man terrane) and crystalline rocks are dominant unlike at the coastline where unconsolidated sediments are found (Schlüter, 2008). Voinjama city lies upon the Precambrian Guinean Shield (Seitz, 1974). Granitic gneiss and granite (gradual transition) make up 85% of the dominant rock types besides ultramafic rocks, amphibolite, dolerite dikes, schists and iron formations (Beherent and Wotorson, 1974). Intensive weathering of rocks causes outcrops of bedrocks only to be exposed at road cuts, stream channels and rounded Inselbergs (granitic domes) with steep flanks (Seitz, 1974). Thermotectonic activity taking place 2.7 billion years ago (Liberian Age Province) was responsible for major folding, faulting and shearing with a general structural north east trend (White, 1970). Dolerite dikes are estimated to be 1.2-2.8 billion years old in the entire Lofa region. That is much older than in other parts of Liberia where Jurassic Age was determined with radioactivity methods (Grommé and Dalrymple, 1972).

Lateritic soil is usually the top sequence of the weathering profile (Reed, 1951). Approximately 40% of sub-Saharan Africa is underlain by Precambrian crystalline bedrock (MacDonald *et al.*, 2005).

Method

The primary method adopted for estimating ground-water recharge from precipitation for this study is the near surface water-balance method, a deep-percolation model (DPM), developed for eastern Washington (Bauer and Vaccaro, 1987) and modified for western Washington (Bauer and Mastin, 1997), was selected to estimate deep percolation from precipitation for this study. The DPM uses a daily water- budget approach to simulate deep percolation. In this method, the model computes daily fluxes of water into and out of a volume extending from the top of foliage to the bottom of the root zone and accounts for changes in water content.

Time-series data required for this application of the DPM include daily values of precipitation, precipitation throughfall, minimum and maximum air temperature, solar shortwave radiation, and "direct runoff." Direct runoff is herein defined as surface-water runoff plus water that drains from temporarily saturated soils to local drainage features. Spatial data required for the DPM include land-surface altitude, properties of soils, and land cover (vegetation type, surface water, or impervious surfaces). Areal variation in soils, vegetation, and land cover is accounted for in the DPM by dividing a drainage area into cells or polygons of any size and shape. Each cell is characterized by a single altitude (and optionally, surface slope and aspect), land cover, soil type, subsoil infiltration capacity, and climate regime. Areal variation in precipitation, air temperature, and solar shortwave radiation are accounted for by interpolation of data to each cell from data collected in or near the study basins.

Evapotranspiration depletes soil moisture and depends on soil-moisture content and meteorological conditions. Therefore, evapotranspiration and soil moisture must be calculated at sufficiently frequent intervals to accurately simulate changes. The DPM uses a daily time step, primarily because daily meteorological data generally are available. A daily time step is sufficiently short to ensure that soil moisture variations are small enough to avoid significant error in the evapotranspiration calculations. For each day of a DPM simulation, deep percolation for each cell is computed as the residual of precipitation minus evapotranspiration minus direct runoff minus the change in soil moisture in the root zone.

Direct runoff for each cell is difficult to determine. Although the total direct runoff for the drainage basin can be readily estimated from streamflow measurements, the contributions from individual cells in the basin can vary greatly, depending on the soil and subsoil properties. For example, during a storm, a cell with a thick soil underlain by a permeable sand-and-gravel glacial outwash deposit may not contribute direct runoff, whereas a cell with thin soil overlying poorly permeable glacial till will contribute a large quantity of direct runoff. The DPM disaggregates the daily total measured direct runoff to the cells in proportion to a simulated daily direct runoff for each cell (for details, see Bauer and Mastin, 1997). A specified infiltration capacity beneath the root zone for each cell, based on the soil and subsoil properties, is incorporated into these calculations. By adjusting this parameter, a water balance (or calibration) is achieved. If the infiltration

capacities are set mostly too large, too little water will be available to support the measured total direct runoff. This is indicated as a "negative deficit" in the DPM output; conversely, a "positive deficit" results when the infiltration capacities are mostly set too small.

Three steps were used to estimate recharge for the area at basin scale using the DPM in this study: (1) the spatial data needed for applying the DPM to the entire study area were assembled, checked for accuracy, and divided into uniform cells; (2) the DPM was calibrated for the study basin; and (3) the DPM was applied to the entire basin using surface meteorological data collected from the NASA Goddard Earth Observing System satellite.

In step 3, island-wide direct runoff data were not available. The DPM was, therefore, operated in a mode in which the simulated direct runoff for each cell is used in place of the disaggregated measured runoff.

DPM includes both energy and water-budget components that are represented as physical processes. The process components are represented in the following mass-balance equation:

$$R = P - SE - PT - SRO - EI - (\pm SM \pm IS) \pm DS$$

where
R	is recharge (deep percolation),
P	is precipitation,
SE	is soil evaporation,
PT	is plant transpiration,
SRO	is surface runoff,
EI	is evaporation of intercepted water,
±*SM*	is change in soil water in the root or soil zone,
±*IS*	is change in intercepted moisture storage, and
±*DS*	is deficit or surplus.

The sum of *SE, PT,* and *EI* in the equation is the model calculated actual evapotranspiration (AET). The calculated deficit/surplus term (*DS*) in the equation accounts for direct surface runoff, if input, that the surplus water (water in excess of field capacity) cannot account for or is over accounted for. Either case indicates that:

1) the daily estimates of baseflow made by a user may be either too large or small (even after user adjustments),
2) hydrologic phenomena, such as macropore flow, that are not included in the model can be locally important, or

3) there may be errors in either the soil information or the interpolated weather data. Although deficit/surplus is considered a separate term in DPM's output that is not part of the error term, it reflects an error due to one or more of the above three factors.

Result and Discussion

Only one perennial stream was identified within the boundaries surrounding Voinjama city as specified for this study (8.452N, -9.789W and 8.399) about 51.08 km^2. The stream which flows south-westward takes its

source from around the base of the neighboring Guinean highlands to the north of Voinjama, and discharges into the Gbeya River further south-westwards. Only about 11 km of the nearly 120 km entire stretch is bounded in the area of study, hence of significance to the water condition of Voinjama city. In all, about ten (10) different flow systems (referred to as sub basins in this report) were encountered within the study area, although it is certain that such flows occur year round.

The area of the basin is estimated as 51.08km^2 since the boundary of the study was has been specified as such. Even though the entire basin covering

Voinjama City is much larger, the boundary area specified for this study covers the entire City and its outskirts. Thus, this hydrological analysis is based on the urban area assessed. The perimeter of the hypothesized basin is about 28.9km while the length of the thalweg of the mainstream is about 11km. the average width of the basin area is 5.9km while the circumference of the equivalent circular area is 25.33km and compactness coefficient (R) of the basin is computed at 1.14. The elongation ratio (E_r) is computed at 0.73km. The remaining estimated basin characteristics are presented in Table 1.

Table 1: Voinjama Basin Characteristics

	Length of water course (m)	Average channel width (m)	Average bankfull channel depth (m)	Estimated bankfull volume (m^3)
Perennial Stream	11000	10	3.5	385000
Sub-Watershed 1	2900	7.2	3.1	64728
Sub-Watershed 2	4600	5.1	2.8	65688
Sub-Watershed 3	8300	6.2	2.5	128650
Sub-Watershed 4	2150	4.4	1.8	17028
Sub-Watershed 5	700	3.3	1.2	2772
Sub-Watershed 6	400	3.1	1.1	1364
Sub-Watershed 7	3500	4.9	1.3	22295
Sub-Watershed 8	3020	4.6	1.5	20838
Sub-Watershed 9	800	3.2	0.8	2048
Sub-Watershed 10	200	2.8	0.6	336

Table 2: Monthly Basin scale water balance parameters

	Basin scale precipitation (cm/km^2)	Estimated soil evaporation (cm/km^2)	Estimated plant transpiration (cm/km^2)	Basin scale total surface runoff (cm3/km^2)	Evaporation of intercepted water (cm/km^2)	Change in soil water in the root or soil zone (cm/km^2)	Change in intercepted moisture storage (cm/km^2)
January	14.3024	0.530881	0.4256	409	2.66	0.16	0.010384
February	33.202	0.562694	0.5083	950	2.99	0.17	0.012517
March	78.6632	0.63403	0.6534	2251	3.63	0.18	0.015151
April	185.9312	0.709186	0.7486	5320	3.94	0.19	0.016459
May	275.3212	0.81312	0.8736	7878	4.16	0.21	0.016877
June	421.41	0.927699	1.012	12058	4.4	0.23	0.016584
July	422.9424	1.010749	1.0824	12102	4.51	0.24	0.015932
August	546.556	1.021867	1.1184	15639	4.66	0.24	0.015948
September	486.2816	0.948627	1.0534	13914	4.58	0.23	0.016279
October	314.142	0.846151	0.8778	8989	4.18	0.21	0.016119
November	114.93	0.784167	0.722	3289	3.61	0.2	0.015311
December	20.9428	0.648	0.5112	599	2.84	0.18	0.011941
Annual Average	242.8854	0.786431	0.798892	6950	3.846667	0.203333	0.014959

The water balance of the basin as computed using the deep percolation model shows that the amount of rainfall input to the basin is barely sufficient given the daily mean annual average of 4.78mm per day. Evaporation was assessed as a total column precipitable water of 3.85cm mean annual average while the vegetation of the area was estimated as 18m broad leaf savanna with about 30% ground cover. The basin scale water balance parameters are summarized in the table 2.

The groundwater recharge of the area holding geology and soil condition constant as described above, for the entire Voinjama City is modeled at diurnal scale considering total amounts of water in the hydrological cycle within the closed boundary of Voinjama City is presented in Table 3.

Table 3: Monthly Diurnal Recharge computed from Deep Percolation cm^3/km^2

	Diurnal Recharge computed from Deep Percolation cm^3/km^2
January	398.39
February	920.71
March	2176.92
April	5139.47
May	7608.30
June	11642.85
July	11685.42
August	15099.06
September	13434.44
October	8680.35
November	3178.56
December	582.12
Annual Average	6712.21

The diurnal recharge computed from deep percolation method gives the above values for the estimate of the basin area,

as such for every square kilometer and for a given day in the particular month of assessment, the modeled value is recommended. However, further assessment based on actual field study can be taken to validate the models.

The rainfall pattern in most of the sub-Saharan region of Africa is highly variable, especially the Sahel zone where increased desiccation has resulted in recent times due to the intense nature of rainfall variability. The same is the case with Voinjama city and most of Liberia, particularly the northern half with its proximity to the Guinea highlands. The long term (1983 – 2012) rainfall condition is summarized in the figure 2.

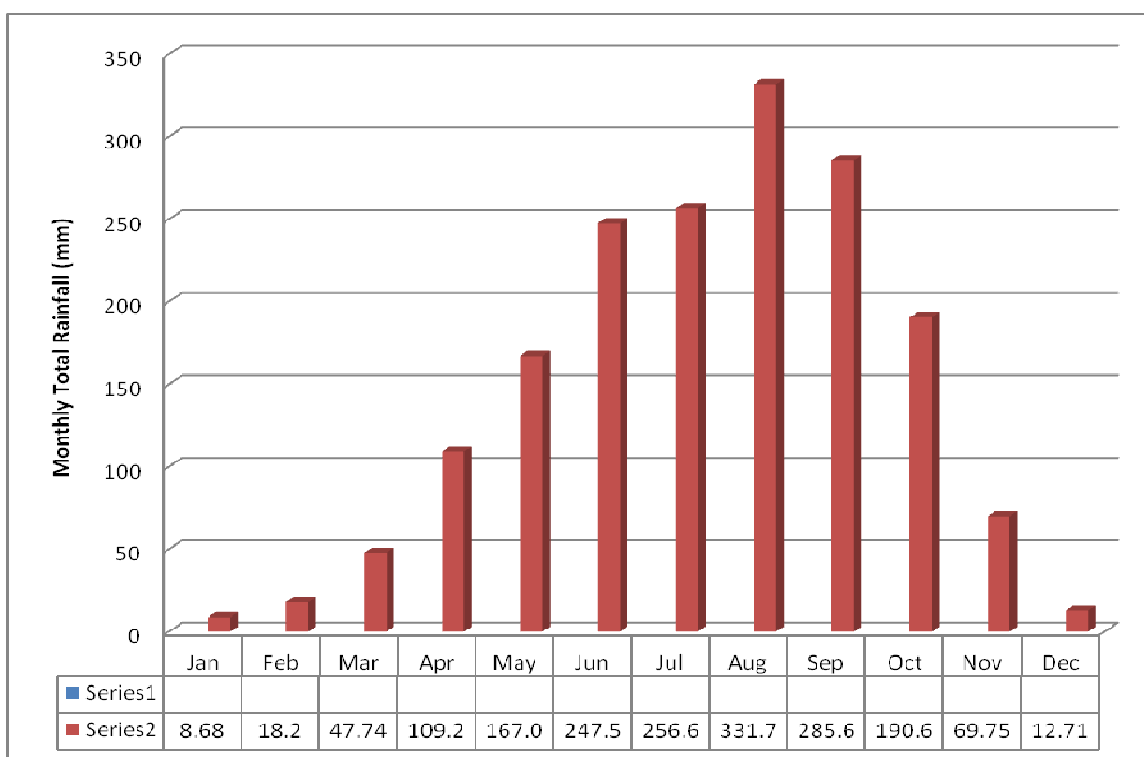|	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Series1												
Series2	8.68	18.2	47.74	109.2	167.0	247.5	256.6	331.7	285.6	190.6	69.75	12.71

Figure 2: Monthly Rainfall in Voinjama Region

Based on the rainfall summary, Voinjama City experiences rainfall all year round. Although the rainfall pattern varies significantly from year to year, the dry months are mostly dry (December to February). On the average, the onset of rains begins in March when the total rainfall experienced is nearly 50 mm, while the retreat is usually around November with a mean total rainfall of about 70 mm. The highest rainfall is usually experienced in August when total amounts of rain exceeds 300 mm as shown in the above figure. The rainfall pattern shows a significant single peak rising from about 110 mm of rain in April and declining to about the same amounts between October and November. As such bankfull condition usually occurs in September after the great floods resulting

usually from the thunderstorms in August. For most of the year, the perennial water courses are bound to have water, although some of the runoff paths most of which flow through the populated areas of Voinjama city, which have resulted from faults, joints and topographic crevices have water episodes regulated by rain amounts.

The rainfall variability in Voinjama city shows a trend averaging about 2654mm per annum. Quite significantly, the rainfall has barely dropped below 2000 mm since 1983 as shown in the figure 3.
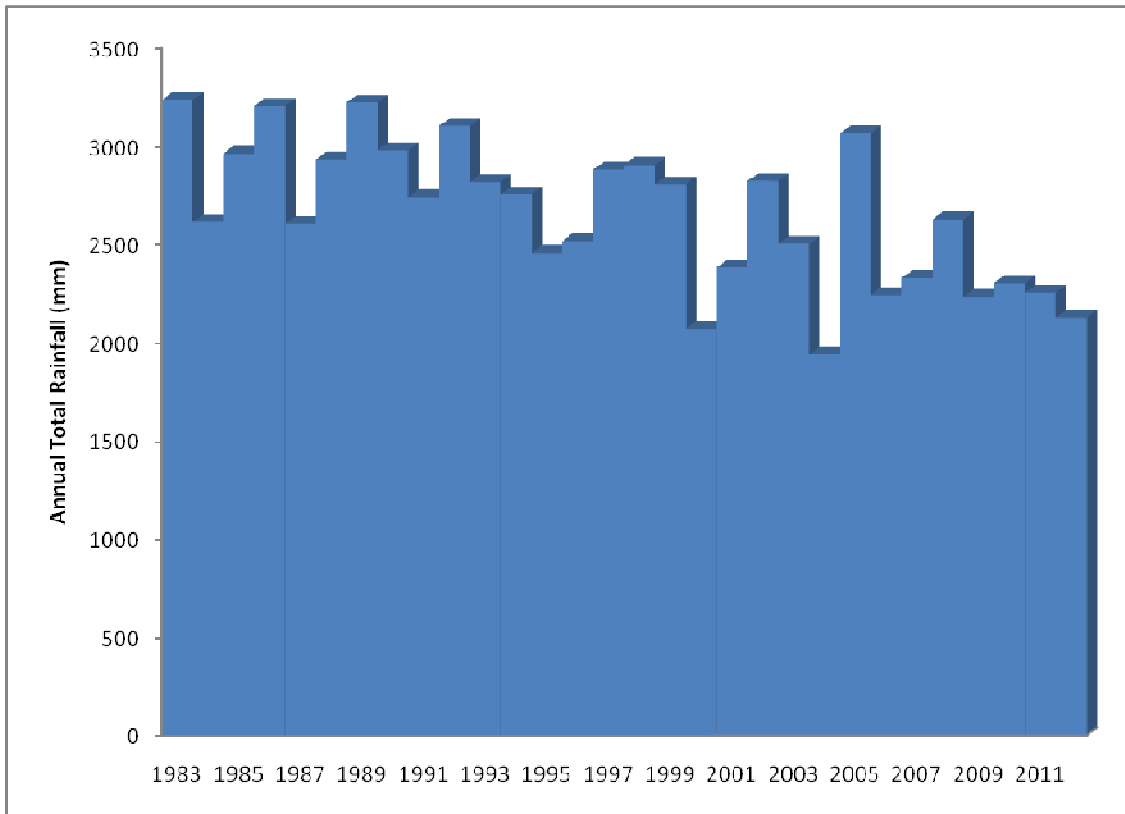

Figure 3: Annual Total Rainfall Amounts in the Voinjama Region

However, over the space of 30 years, the pattern of rainfall over Voinjama City is one of a declining trend. The highest annual total rainfall amount experienced is about 3200mm (1983, 1985, 1989, 1992,), while the lowest annual total rainfall experienced is about 1800mm (2004). Before the turn of the century the pattern of rainfall has been fairly consistent without no year experiencing not less than 2400mm amount to total annual rainfall (1983-1999). Immediately after the turn of the century, the annual total amount of rainfall declined and experienced the lowest record ever in 2004 (1800m), while its maximum annual total is about 3100mm in 2005. The reason for this could be tied to changing climates and this has significant impact on the total water available within the City.
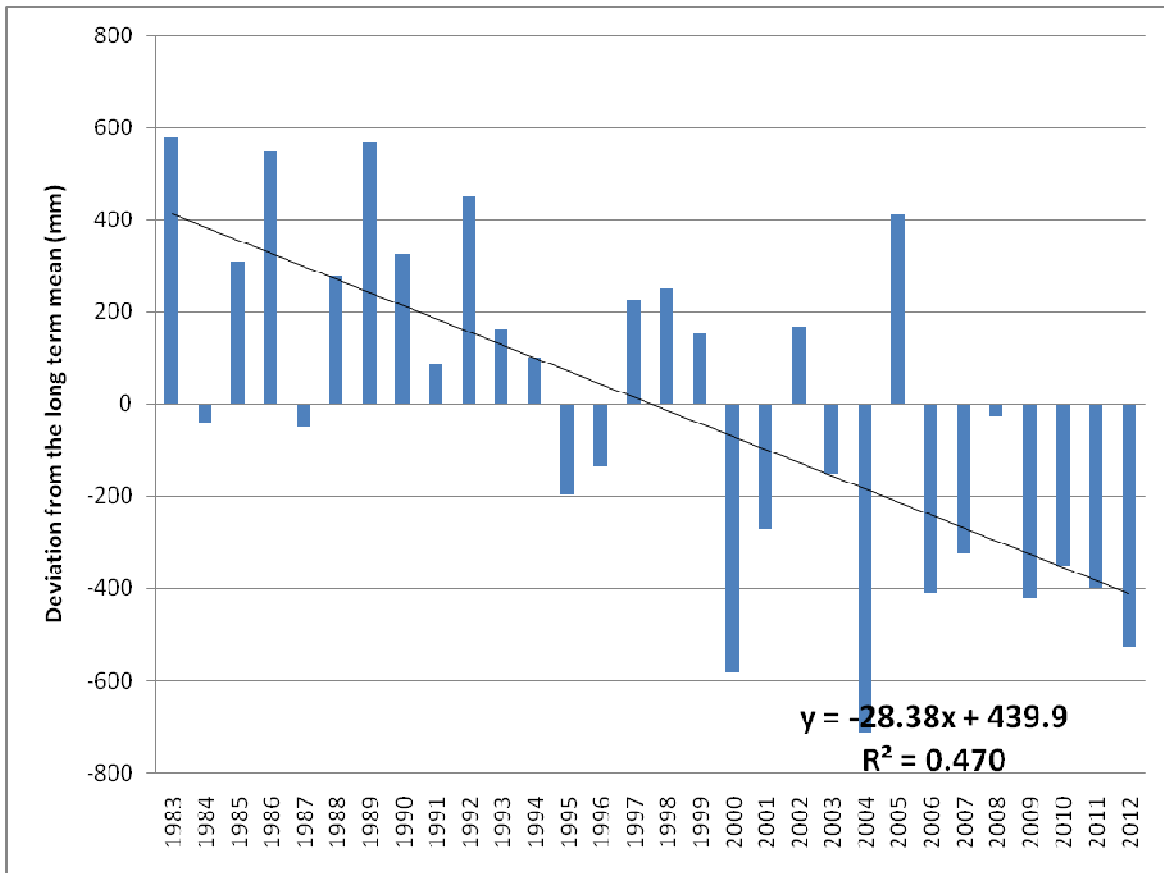
Figure 4: Annual Rainfall Deviations from the long term mean in the Voinjama Region

In tandem with the discussion above, the deviation from the long term mean over the past 30 years shows significant decline after the turn of the century by recording the highest number of years (11 years) having rainfall amount lower than the observed mean over the time period with a deviation of about 700mm in 2004 while only two years had rainfall amount greater than the observed 30-year average. Before the turn of the century, only four years experienced rainfall amounts less than the 30-year average with the highest deviation in 1995 (200mm).

To this end, the trend line shows a weak relationship between rainfall amount and the mean average, suggesting that the 30-year average cannot be taken as an approximate of the rainfall amount in a year within Voinjama City, hence implying that each year is unique in its rainfall amount observed and the pattern varies significantly.

Conversely, the regression equation $y = -28.38x + 439.9$ is indicative of the increasing decline of water input from precipitation to feed the recharge of the hydrological cycle. A deficit of about 28.38 mm rainfall is consistently experienced on an annual basis indicating a dangerous trend towards increasing water shortage. Should the trend continue the implication for water resources and ground water recharge in the region may be that of severe drought which may not

be found interesting. Although, the R^2 value of 0.47 indicates that the rate of declining water availability may leave some time for respite, which may require increased ground water exploitation.

Conclusion

Although, the rainfall trend in the Voinjama city tells a story of decline, the past water years indicates significant amounts of water input from rainfall in the region. Interestingly, Liberia has received quite a humongous input of water over the years, especially, relative to most of the neighboring countries. This blessing is to the effect that the water supply system destroyed during the war periods may not pose too much problem for redemption in the post war rebuilding process. With abundant water in the hydrological system, stored over the years, it is positive that the ground water recharge is adequate and exploitation may not be limited.

Also, the near uniform geology of the vast region underlain by Pre-Cambrian undifferentiated rocks which is overlain with ferrasols, strongly weathered soils of the humid tropics, though bearing generally low fertility, is a plausible prospect for easy access to water. Moreover, many faults and crevices occur scattered abroad the area indicating good lineament distribution and abundant aquifer recharge. However, field study is requisite to consider the details of the water bearing capacities of the aquifers and the ease of exploitation for water use for the population. Furthermore, the declining trend in precipitation input to the area may be examined with climate change projections to determine exact sustainable water management strategies for Voinjama city.

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