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APPLICATION AND COMPARISON OF GROUNDWATER RECHARGE ESTIMATION METHODS FOR THE SEMIARID YOLA AREA, NORTHEAST, NIGERIA

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ABSTRACT

Then Bima Sandstone aquifer is the main water resource in the semi-arid Yola area of Northeastern, Nigeria. The rapid increase in water demand in this area has prompted the need to estimate available groundwater recharge for sustainable utilization. Groundwater recharge estimation methods and results are compared: chloride mass balance method (5.81 to 9.65 mm/year); water budget method (52.45 to 86.20 mm/year); Darcian method (16.38 to 104.04 mm/year) and hydrograph separation method (133.6 to 645.81 mm/year).

The Chloride mass balance and the Darcian methods are well suited to identify the existence of recharge and enable one to determine good estimates of aerial and point values. A major limitation of the chloride mass balance is that there may be other sources of chloride in the soil (eg halites) other than the chloride contained in the rainwater. On the other hand in the Darcian method the hydraulic conductivity of the soil is poorly known due to heterogeneities and its variation with saturation.

The water budget method is bedeviled by a number of limitations which include lack of lysimeter for measuring evapotranspiration but is simple and can be estimated as a residual in a continuity equation.

A major drawback of the hydrograph separation method is that it estimates baseflow at lower elevations in a watershed which is assumed to be equal to recharge that occurred at higher elevation. It is however one of the few integrative measurement of recharge.

The merits and demerits of each recharge method in terms of accuracy and applicability were also highlighted in this study.

This study has shown that recharge occurs to some extent in even the most arid regions, though increasing aridity are characterized by a decreasing net downward flux and greater time variability. Thus as aridity increases, direct recharge is likely to become less important and indirect recharge more important in terms of total recharge to an aquifer.

It is therefore concluded that estimates of direct recharge are likely to be more reliable than those of indirect recharge.

KEYWORDS Groundwater recharge/water budget, evapotranspiration. Yola, variability.

INTRODUCTION

Background to work

Recharge is the downward flow of water reaching the water table and groundwater reservoir. For a sufficiently long period of years, and in aquifers not subjected to pumped extractions, the mean annual value of the recharge is equivalent to the rate of discharge. It follows that groundwater recharge over an area is normally equal to infiltration excess. Lerner et al (1990) recognized the existence of three mechanisms of recharge namely: direct recharge by percolation through the unsaturated zone, indirect recharge through the beds of surface water courses, and localized or concentrated recharge at points.

Accordingly aquifer recharge can be expressed as an annual mean volume, which is normally termed the mean annual resources or entry, or as a percentage of precipitation, that is, the rate of recharge or effective infiltration.

Groundwater recharge can be measured by means of diverse methods, none of which are free from uncertainty (Scanlon et al 2002; Flint et al 2002). Estimating recharge in arid to semi-arid regions involve a large degree of relative uncertainty due to low precipitation and high evapotranspiration. This task is particularly challenging in semi-arid Yola Area of Northeastern Nigeria because of its fundamental importance to water resources assessment and management as well as the assessment of groundwater contamination from point sources. Estimation of groundwater recharge may vary from days (for recharge of dynamic karst aquifers and for contaminant transport) to thousands of years (for identifying sites appropriate for disposal of radioactive wastes). As aquifers are depleted, recharge estimates have become more essential in determining appropriate levels of groundwater withdrawal. Estimation of recharge is also becoming more important for contaminant transport; as aquifer management expands from clean up of existing contamination to aquifer protection by delineation of areas of high recharge.

Both physical and chemical methods have been employed to estimate recharge in arid and semiarid areas. A review by Alison et al (1994) indicates that indirect, physical approaches, such as water balance and Darcy flux measurements, are the least successful

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while methods using tracers (eg Cl, ^{3}H and ^{36}Cl) have been successfully applied methods/techniques in estimating groundwater recharge in dry regions. Lysimeters, which can directly measure root-zone drainage, have been useful in quantifying recharge, particularly for coarse soils, but are costly to construct and operate. Of the tracer techniques available, chloride balance techniques appear to be the simplest, least expensive, and most universal for recharge estimation (Alison et al 1994). Unfortunately, given the current state of the science, it is extremely difficult to assess the accuracy of any method. For this reason, it is highly beneficial to apply multiple independent methods of recharge estimation and hope for some consistency in results.

Objectives

The main objectives of this research are, first to report on the application of different methods (tracer and physical methods) to estimate recharge rates in the semi-arid Yola area of Northeastern Nigeria. And secondly, to compare the recharge estimation results obtained from these methods highlighting their merits and demerits with regard to the accuracy and applicability of the methods based on UNDP (2002) report.

This study is relevant due to the fact that groundwater demand is growing in this area and determination of recharge rate is crucial for the groundwater management in this region. Furthermore the amount of recharge received by aquifers is far more critical to the sustainable use of water than it is in humid regions. Despite this fact, little remains known about the quantities of water that are required to sustainably recharge aquifers in semi-arid and arid regions.

Literature Review

Many studies have been done on the recharge over extended areas using field data from different methods (numerical models, chemical and isotopic techniques, direct measure of flow rate). Previous studies on regional recharge assessment permits identification of some international examples (Leaney and Herczeg 1995; Sukhija et al 1996; Birkle et al 1998; Rangarajan and Athavale 2000; Nolan et al 2006; Anuraga et al 2006). Recent advances on distributed methods of recharge calculation have been done by Heathcote et al (2004) and Hughes et al (2006) to estimate the recharge and runoff components at regional scale. Subsequently, Brito et al (2006) identified maximum infiltration by means of GIS whereas Zagana et al (2007) described the groundwater recharge in three hydro-climatic environments in the eastern Meditarranean region.

Study Area

The study area occur at an elevation varying from 152m to 455m above mean sea level and falls within the Upper Benue Basin which has a catchment area of about 203,000km^2. It is located within longitudes 12°24'E and 12°34'E and Latitudes 9°11'N and 9°24'N and lies about 50km south of the Hawal Massifs. It is bounded to the east by the Republic of Cameroun and to the west by Ngurore town. The northern boundary is demarcated by Gokra town and the southern boundary by the Mandarara town (see Figures 1).

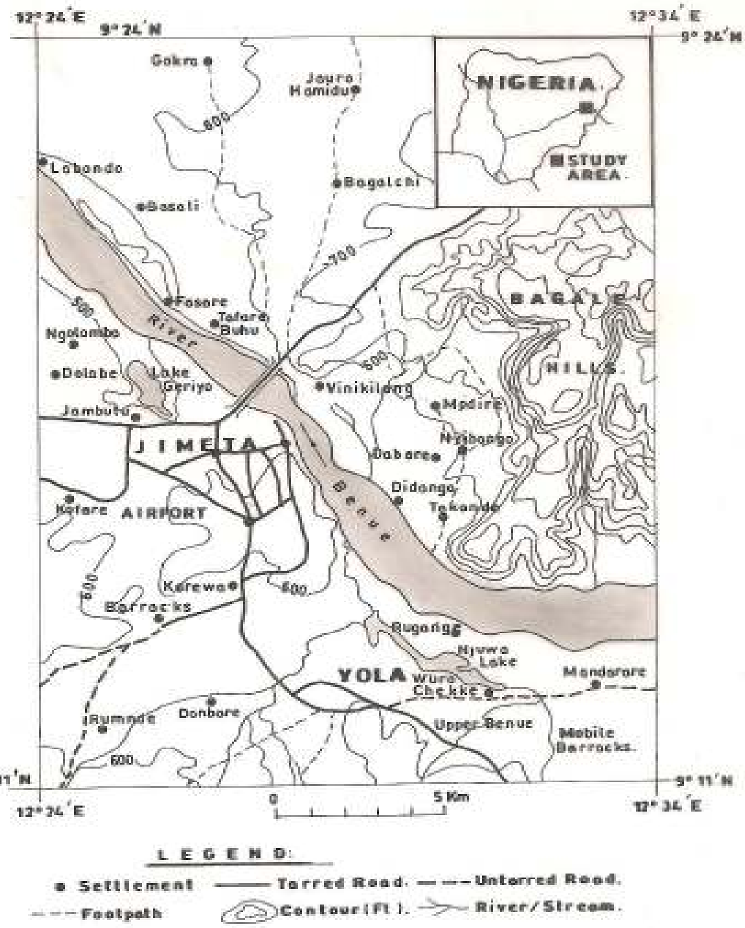

Fig. 1: Location map of the study area.

The study area falls within the semi-arid climatic zone of Nigeria in sub-Saharan Africa is characterized by two distinct seasons; a hot dry season lasting from November to April and a cool rainy season lasting from April to October. The study area receives summer rainfall from the south-western monsoon derived from the Gulf of Guinea. Rainfall during 1963/64-2006/2007 water years averaged 827.7mm per annum while the mean annual evapotranspiration is about 2384.6 mm (Obiefuna in Preparation Tables 1a to 1f).

Table: 1 a Average Meteorological Data in Jimeta Area (Latitude 9.233°N, Longitude 12.467°E, Altitude188.5m)

Month	Tm(maximum air temperature)	Relative Humidity %	Rainfall(mm)	Piche Evapora -tion	Sunshine Hours	Wind Run	Solar Radiation	Actual Vapour Pressure(KP A)	Saturate Vapour pressure (KPA)
April	35.2	43	45.6	344	216.1	3170.9	15.82	2.32	5.4
May	31.1	62.12	103.1	227.7	243.9	3109.7	18.2	2.77	4.46
June	28.6	72.4	126.9	127.1	221.2	2544.3	18.4	2.82	3.9
July	27.3	78.3	184.2	95.3	194.85	2039.6	18.31	2.82	3.6
Aug	26.7	81.1	201.2	78.3	184.3	1848.8	16.6	2.84	3.5
Sept	27.2	77.4	218.3	80	224.7	1704.2	15.52	2.84	3.67
Oct	28.9	71.6	57.2	119.9	237.1	1544.3	13.5	2.81	3.92
Nov	28	42.1	-	216.6	269.2	1527.6	12.99	1.74	4.13
Dec	27.5	29.7	-	127.5	254.9	1924.2	15.11	1.1	3.7
Jan	27	25.4	-	353.6	227.8	2110.6	16.73	0.91	3.58
Feb	28.6	21.1	-	353.5	206.1	2147.9	17.17	0.92	4.36
March	36.1	31.36	4	438.94	207.5	2549.5	16.1	1.43	4.56
Total	352.2	635.58	940.5	2562.44	2687.65	26221.6	194.45	25.32	48.78
Mean	29.35	52.965	117.56	213.536 67	223.9708 3	2185.13 3	16.20417	2.11	4.065
Dates of Record s	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years

Source: Federal Meteorological Station, Yola

Table: 1b Average Meteorological Data in FUTY Area(Latitude 9.346° N, Longitude 12.503°E, Altitude 244.8m)

Month	Tm(maximum air temperature)◦	Tm(minimum air temperature	Tm(average)	Difference b/w Tmax and Tmin	Relative Humidity%	Rainfall (mm)	Piche Evaporation	Sunshine Hours	Wind Run	Solar Radiation
April	40	27.1	33.5	12.9	57.9		-	268.5	2773	15.8
May	37	26.2	31.5	10.8	66.7	73.2	-	219.5	2666	16.6
June	33	24.8	28.9	8.2	76.6	81.5	-	169.7	2447	16.3
July	31.6	23.9	27.8	7.7	71.6	121.1	-	189.8	2347	13.2
Aug	30.4	23.3	26.4	7.1	74.9	143.4	-	183	2094	13
Sept	31.1	23	27.1	8.1	74.3	121.2	-	205.7	2241	14.2
Oct	32.9	22.8	27.9	10.1	68.9	58.1	-	212.7	2003	15.6
Nov	34.4	23.1	28.7	11.3	54.4	-	-	235.6	1531	15.4
Dec	33.9	21.8	28	12.1	44.1	-	-	293.5	1725	13.4
Jan	35.1	22.6	28.2	12.5	46	-	-	183.4	2485	15.2
Feb	36.8	23.3	30.1	13.5	45	-	-	160.2	2215	15
March	40.3	26.3	33.2	14	51	5.7	-	227.7	2658	17.2
Total	416.5	288.2	351.3	128.3	731.4	629.2	-	2549.3	27184	180.9
Mean	34.708333	24.01667	29.275	10.691667	60.95	78.65	-	212.44167	2265	15.075
Dates of Records	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years	1997/98 to 2007/08 Water Years

Source: Department of Geography, Federal University of Technology, Yola Meteorological Station

Table: 1c Average Meteorological Data in Yola Area(Latitude 9.198° N, Longitude 12.512°E, Altitude 192.1m)

Month	Tm(maximum air temperature)◦	Tm(minimum air temperature	Tm(average)	Difference b/w Tmax and Tmin	Relative Humidity %	Rainfall(mm)	Piche Evaporation	Sunshine Hours	Wind Run
April	42.6	21.8	32.3	20.8	46	37.6	269.5	226.9	2767
May	40	21.5	30.8	18.5	58	115.6	221.3	223.3	2606
June	37.3	20.7	27.7	16.6	71.6	131.7	155.3	204.1	1965
July	35.2	20.5	27.8	14.7	73.4	182.9	133.8	184.6	2200
Aug	34.5	20.3	28.4	14.2	80.1	198.3	123.5	167.4	1373
Sept	34.4	20.9	27.6	13.5	76.5	182.2	126.4	183.9	1394
Oct	36	20.9	28.5	15.1	66.2	58	153.4	118.2	1301
Nov	37.5	17.5	26.6	20	40	6.2	183.8	255.9	1441
Dec	37.1	14.2	25.6	22.9	32.4	-	189.4	398.6	1535
Jan	37.4	14.4	25.9	23	30.6	-	219.99	241.2	1790
Feb	40.5	16.7	28.1	23.8	26.9	-	250.3	324.3	2034
March	42.2	20.1	31	22.1	34.2	5.3	194.1	212	2319
Total	454.7	229.5	340.3	225.2	635.9	917.8	2220.79	2740.4	22725
Mean	69.953846	35.30769	52.354	34.646154	97.830769	183.56	341.66	421.6	3496
Dates of Records	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years	1982/83 to 2006/07 Water Years

Source: Upper Benue River Basin Development Authority Yol

Table 1d: Average Monthly values of Actual evapotranspiration for Yola Area (Latitude 9.198°N,Longitude12.512° E,Altitude192.1m)

Month	Penman 1948 Method (mm)	FAO Penman Monteith Method(mm)	Blaney Criddle Method (mm)	Hargreaves Models(mm)	USDA Method (mm)	Wright Penman Method (mm)	Radiation Balance Method	Hargraves (1968) Epan Method	Mean Value (mm)
April	188.7	218.2	190.5	288.4	190.5	231.5	217.9	234.5	220.03
May	250.6	255.9	188.8	281.3	177.7	294.5	241.5	192.5	235.35
June	214.5	251.6	156.6	211.1	152.9	295.2	213.7	135.1	203.84
July	220.1	260.5	153.7	207.9	153.7	298.3	215.7	116.4	203.29
Aug	199.3	236.5	245.4	230.9	158.6	259.7	221.7	107.4	207.44
Sept	180.9	214	156.6	188.7	152.4	223.9	186.1	109.9	176.56
Oct	163.2	191.8	161.8	230.3	159.4	191.8	183	133.5	176.85
Nov	154.5	176.9	143.6	252.9	144.6	173	174.3	159.9	172.46
Dec	183.4	214.9	137.5	256.6	137.3	204.2	190.1	164.8	186.1
Jan	204.9	237.9	140.2	267.3	137.3	224.9	202.5	191.4	200.8
Feb	191.2	218.9	158.3	258.2	159.3	198	197.4	217.8	199.89
March	198.2	225.7	180.7	295.3	179.4	228.7	218	168.9	211.86
Total	2349.5	2702.8	2013.7	2968.9	1903.1	2823.7	2461.9	1932.1	2394.5
Mean	195.7917	225.23333	167.8083	247.4083	158.59	235.31	205.1583	161.008	199.54

Table 1e: Average monthly values of actual evapotranspiration for Futy area (Latitude 9.346° N,Longitude12.503°E,Altitude244.8m)

Month	Penman 1948 Method(mm)	FAO Penman Monteith Method(mm)	Blaney Criddle Method(mm)	Hargreaves Models(mm)	USDA Method (mm)	Wright Penman Method(mm)	Radiation Balance Method	Mean Value (mm)
April	188.4	217.7	234	255.8	201	236.7	222.5	222.3
May	201.5	233	207.7	226.5	183.7	274.3	221.1	221.11
June	190.2	222.1	177.5	177.5	162.3	267	199.5	199.44
July	159.1	186.4	164.5	188.8	153.7	220.9	178.9	178.9
August	156.6	184.7	156.4	172.6	143.2	207.4	170.2	170.16
Sept	165.6	194.7	161.8	174.9	148.5	204.6	175	175.01
October	188.2	221.2	175.3	178	154.5	219.5	189.4	189.44
November	182.4	212.5	187.9	232.3	160.8	201.8	196.3	196.29
December	164.9	190.7	183.4	267	155.3	180.7	190.4	190.34
January	194.7	214.9	194.2	242.7	157	207.4	201.8	201.81
February	167.7	189.8	207.1	231.4	172	188.5	192.8	192.76
March	211.4	241.1	237.3	275.1	198.2	249.5	235.8	235.49
Total	2170.7	2508.8	2287.1	2622.6	1990	2658	2373.7	2373.1

(After Obiefuna in Preparation)

Table 1f:Average Monthly values of actual evapotranspiration for Jimeta Area(Latitude 9.233° N,Longitude12.467° E,Altitude188.5m)

Month	Penman 1948 Method(mm)	FAO Penman Monteith Method(mm)	Blaney Criddle Method(mm)	Hargreaves Models(mm)	USDA Method(mm)	Wright Penman Method(mm)	Radiation Balance Method	Hargraves (1968) Epan Method	Mean Value (mm)
April	165.5	216.1	190.5	288.4	216.1	234.6	218.5	299.3	228.6
May	170.7	254.3	175.3	263.8	180.2	270	219	198.1	216.4
June	165.2	251.1	153.9	209.3	160	270.4	201.7	110.6	190.3
July	170.5	259.5	154	194.5	150	276.4	200.7	82.9	186.1
Aug	170.5	236.5	196.9	227.1	145.4	249.5	204.3	68.1	187.3
Sept	165	212.5	151.4	186.4	149.3	224.7	181.5	69.6	167.6
Oct	170.7	191.8	159.1	217.4	162.4	231.6	183.8	104.3	177.6
Nov	165.2	178.3	143.6	253.2	155.3	224	186.6	188.4	186.8
Dec	170.7	215.8	134.9	265.1	151.6	204.4	190.4	110.9	180.5
Jan	171	237.6	137.5	267	147.8	228.4	198.2	307.6	211.9
Feb	154.4	214.9	158.3	258.2	160	215.3	193.5	307.5	207.8
Mar	171	224.4	199.6	293.9	224.4	224.4	233	381.9	244.1
Total	2010.4	2692.8	1955	2924.3	2003	2854	2411.2	2229.2	2385
Mean	167.53	224.4	162.91	243.69	166.9	237.8	200.9	185.7	198.7

Geological and hydrogeological setting

Geology

The study area is underlain by the upper member of the Bima Sandstone (B3) which is a cretaceous sedimentary unit of the Yola Arm of the Upper Benue Trough. The Upper Bima Sandstone (B3) was marked by the deposition, during the Cenomanian? Of fluvio-deltaic sandstones and arkoses, which commenced in the south and extended progressively northwards? Several episodes of transgressions and regressions (often linked with sedimentary disturbances) are registered in the Bima Sandstone (Abubakar2006). The surface geologic units of the study area are the fine-medium grained sandstone to the north and south and the coarse grained sandstone to the northeast (see Figure 2). The depth to the bedrock varies from 30 meters to more than 45 meters. Stratigraphically, the Bima Sandstone consist of alternating layers of poorly to moderately consolidated fine to coarse grained sandstones, clay-shales, siltstone and mudstone with an average thickness of more than 250 meters as seen from their outcrops in the field. This geologic formation which reaches several hundred meters in thickness is of significant hydrogeologic interest. From field observations, exposures of Bima Sandstone in the study area is light brown to reddish brown in colour, feldspathic and fine to coarse grained in texture. It is highly crystalline and cemented in places especially north of Jimeta and Yola around Girei area.

The grain-sizes range from 0.43mm to 2.2mm indicating a fine to coarse grained sandstone that is poorly to moderately sorted. The mineralogical composition of the Bima Sandstone consist essentially of 50-60% quartz, 26-28% plagioclase feldspar, 4% microcline feldspar 8% clay matrix, 8% iron oxide and 3% calcite and are thus classified as arkosic sandstone.

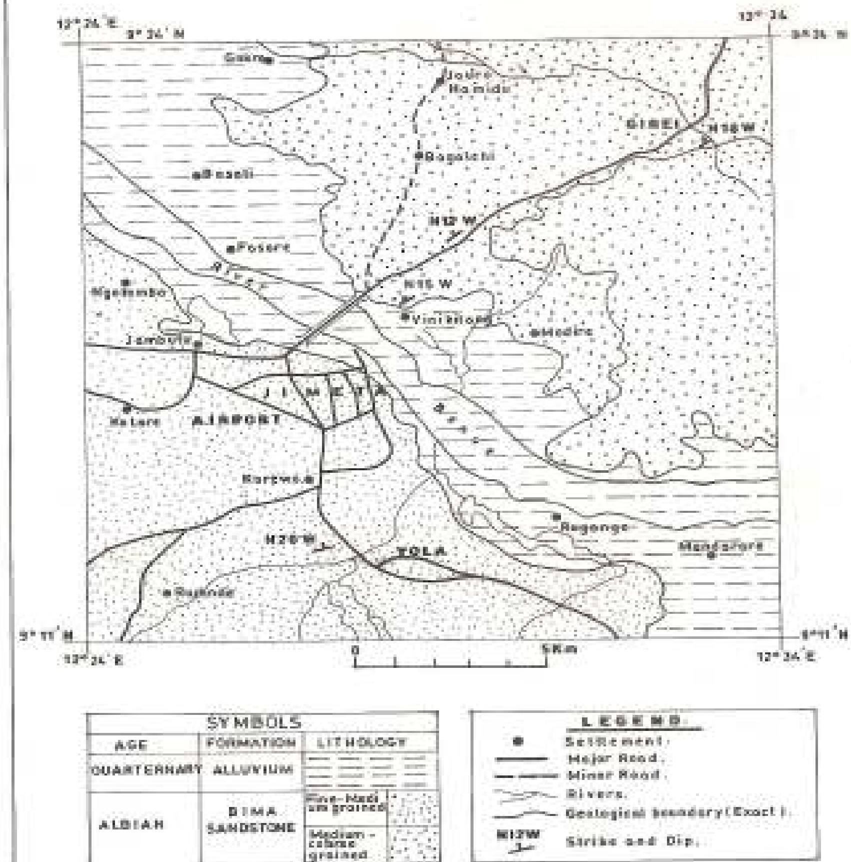

Fig.2: Geological map of the study area.

In thin section, the quartz is sub-angular to sub-rounded and rimed by reddish brown colouration indicating iron-oxide. The feldspars are largely plagioclase and microcline parts of which have been altered to clay matrix. It is thus both texturally and mineralogically immature and hence competent. The predominance of quartz grains could be due to diagenetic effect of compaction and pressure solution at greater depths. Hence the quartz grains responded by shifting into more dense packing arrangements during the middle to later stages of diagenesis lending to reduction in porosity of the sandstone. The sandstone is thus highly indurated and has reduced porosity probably due to increased siliceous cementation especially adjacent to lineaments. The Bima Sandstone has abundant soft-sediment deformation structures that include cusps, droplets, convolute bedding, deformed cross-bedding and sand volcanoes (Abubakar et al 2006). The structures in most outcrops are sandwiched between undeformed cross-bedded strata that have no major textural differences with the sediments hosting them. The cusps are both simple internal cusps and interpenetrative cusps and are formed by post-depositional fluidization triggered by seismic shocks, where the interpenetrative cusps serve as conduits through which sands rose to the surface to form volcanoes. The droplets are the discrete type associated mostly with complex deformed cross-beddings while the convolute bedding forms concentric antiforms and synforms without any evidence of faulting and gradually die out vertically upward. The deformed cross-bedding is represented by both simple and complex recumbent folds of flood and seismically induced origin respectively. The source of the seismic shocks may be episodic syndepositional Mesozoic Volcanism of Jurassic to Albian times within the Upper Benue Trough (Abubakar et al 2006). Overlying the Bima Sandstone in the study area is the river course alluvium which is composed of sands, silts, shales and clays and is confined mainly along the course of the River Benue and its tributaries. Field studies have shown that there is hydraulic connection between the river course alluvium and the underlying Bima Sandstone Formation.

Groundwater Occurrence

The main aquifer systems in the study area are defined based on data from borehole logs and Field work. The study area is divided diagonally into two nearly equal halves by the River Benue and is limited by the Bagale hills to the east, Gongola Sub-basin to the West and rocks of the Hawal Massif and Precambrian Basement Complex to the north and south respectively.

The Bima Sandstone which underlies the area represents alluvial fan and braided river complexes deposited in an uneven topography created during the folding and lifting of the Upper Benue Trough along the west coast prior to the Cretaceous? The lithology is characterized by mottled sublitharenite and quartzarenites with a 100m thick conglomerate at the base followed by fine to coarse grained sandstone and siltstones; altogether the maximum thickness of the Bima Formation in the study area exceed 240 meters based on borehole logs (Peters 1982). It is characterized by minor sandwiched iron-rich clay-shale, silty-clay and mudstones which affect the groundwater quality in terms of colour and smell and serve as semi-confining medium for the sandstone aquifers in the study area

The accurate definition of the limits and types of aquifers in the study area is not simple because of the heterogeneity of the Bima sedimentary sequence and the different criteria used in the lithological description of the well records. However, based on available borehole lithologic logs an unconfined to confined aquifer systems exist in areas underlain by the recent quaternary river coarse alluvial stratigraphic unit which laterally changes to upper unconfined aquifer system in areas underlain by the cretaceous sandstone. This is subsequently underlain by the lower semi-continued to confined aquifer systems.

Thus the recent quaternary sediments constitute the shallow upper alluvial aquifer whereas the older cretaceous sediments constitute the lower semi-confined to confined aquifer system.

Groundwater within the alluvial aquifer occur largely under water table conditions at outcrops and in places it is confined by interstitial clays especially in areas close to the banks of the River Benue. Thus River Benue waters recharge both aquifer systems.

Aquifer Properties

The hydraulic conductivity, K, values for the upper alluvial (largely unconfined) aquifer were determined employing both the pumping test and the granulometric methods (See Tables 1, 2).

Hazen (1893) method indicates k, values ranging from $9.03* 10^{-3}$ m/s to $3.36* 10^{-1}$m/s with a mean value of about $7.53*10^{-2}$ m/s.

TABLE 2: HYDRAULIC properties of some samples of the bima sandstone (upper unconfined alluvial aquifer) from the study area determined from granulometric methods

Location	Hydraulic conductivity values (m/s)						Transmissivity values (M^2/S)					
	Hazen (1893)	Harlemanet al (1963)	Masch and Denny (1966)	Uma et al (1989)	Uma and Leohnert (1992)	Average	Hazen (1893)	Harleman et al (1963)	Masch and Denny (1966)	Uma et al (1989)	Uma and Leohnert (1994)	Average
HW9 Bagalchi thickness=6m	2.25×10^{-2}	1.46×10^{-1}	2.13×10^{-4}	9.55×10^{-5}	1.33×10^{-5}	3.38×10^{-2}	13.5×10^{-2}	8.76×10^{-1}	12.78×10^{-4}	5.73×10^{-4}	7.95×10^{-5}	2.03×10^{-1}
HW1 Lainde thickness=15m	3.55×10^{-2}	2.42×10^{-3}	1.80×10^{-5}	1.46×10^{-5}	3.04×10^{-7}	7.98×10^{-3}	5.63×10^{-1}	3.63×10^{-2}	2.70×10^{-4}	2.19×10^{-4}	4.56×10^{-6}	1.20×10^{-1}
HW7 Wuro Alhaji thickness=7.9m	4.0×10^{-3}	2.56×10^{-3}	1.78×10^{-1}	3.42×10^{-2}	1.14×10^{-5}	4.38×10^{-2}	3.16×10^{-2}	2.02×10^{-2}	1.41	2.70×10^{-1}	9.01×10^{-4}	3.47×10^{-1}
HW 19 Yolde pate thickness=4.3m	4.9×10^{-3}	2.25×10^{-3}	2.46×10^{-5}	1.36×10^{-2}	3.13×10^{-5}	4.14×10^{-3}	2.11×10^{-2}	9.68×10^{-3}	1.06×10^{-4}	5.85×10^{-2}	1.35×10^{-4}	1.79×10^{-2}
HW34 Girei thickness=9m	3.36×10^{-1}	2.16×10^{-1}	2.83×10^{-1}	1.28×10^{-2}	1.13×10^{-5}	1.70×10^{-1}	3.20	1.94	2.55	1.15×10^{-1}	1.12×10^{-4}	1.53
HW 40 Gokra thickness=12.6m	2.03×10^{-3}	3.30×10^{-3}	2.56×10^{-5}	1.96×10^{-5}	6.05×10^{-7}	1.08×10^{-3}	2.56×10^{-2}	3.96×10^{-2}	3.23×10^{-4}	2.47×10^{-4}	7.62×10^{-6}	1.32×10^{-2}
HW 33 Bajabure thickness=9.1m	3.52×10^{-3}	1.30×10^{-1}	2.69×10^{-2}	8.65×10^{-2}	2.45×10^{-5}	4.94×10^{-2}	3.18×10^{-2}	1.18	2.45×10^{-1}	7.87×10^{-1}	2.23×10^{-4}	4.49×10^{-1}
HW 24 Jimeta thickness=1.4m	8.64×10^{-3}	2.60×10^{-3}	1.96×10^{-5}	1.82×10^{-5}	1.40×10^{-7}	2.26×10^{-3}	12.10×10^{-3}	3.63×10^{-3}	2.74×10^{-5}	2.55×10^{-5}	1.96×10^{-7}	2.49×10^{-2}
HW27 Demsawo thickness=5m	6.72×10^{-3}	3.18×10^{-3}	5.08×10^{-5}	2.05×10^{-5}	4.21×10^{-7}	1.99×10^{-3}	3.36×10^{-2}	1.59×10^{-2}	2.54×10^{-4}	10.25×10^{-5}	2.11×10^{-6}	9.97×10^{-3}
HW48 Jambutu thickness=6.1m	9.03×10^{-3}	1.60×10^{-3}	3.77×10^{-5}	9.50×10^{-5}	6.80×10^{-7}	2.15×10^{-3}	5.51×10^{-2}	9.76×10^{-3}	2.30×10^{-4}	5.80×10^{-4}	4.15×10^{-6}	1.31×10^{-2}

(After Obiefuna In Preparation)

TABLE 3: Estimated Hydraulic Conductivity, K And Specific Storage Ss Values In Multi-Aquifer Test

S/N	BOREHOLE PROJECT NUMBER	LAYER(AQUIFER)	THICKNESS (m)	HYDRAULIC CONDUCTIVITY K(m/d)	SPECIFIC STORAGE(Ss1/m)	TOTAL DEPTH (M)
1	BH13	UNCONFINED (UPPER)	SL =15	0.67	0.1417535181c	55
2	BH24	UNCONFINED (UPPER)	6	2.35	0.324441427c	41
3	BH37	UPPER UNCONFINED	12	0.27	0.018379445c	47
4	BH40	UPPER UNCONFINED	12	0.62	0.14646106c	37.5
5	BH79	UPPER UNCONFINED	15	3.13	0.54830150c	55
6	BH81	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	24 112	6.05 1.3	0.045732025 56.24906289	240
7	BH82	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	12 18.06	13.16 8.75	0.4807757086c	148
8	BH83	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	9.3 24.3	9.17 3.51	0.4065118244 2.061098340	140
9	BH84	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	12.3 15.56	8.53 6.75	2.075301130c	148
10	BH85	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	21.64 27.76	4.28 3.33	2.448773013c	164
11	BH86	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	6.12 12.24	1.5 0.75	0.004059515917c	165
12	BH87	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	15.48 27.72	7.05 3.94	2.792598592c	140
13	BH88	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	6.14 33.39	56.98 10.48	0.00972855	187
14	BH89	UPPER UNCONFINED	41	0.096	0.00972855	48
15	BH91	UPPER UNCONFINED	10.2	1.047	0.00972855	75
16	BH92	UPPER UNCONFINED	15	0.34	0.00972855	56
17	BH93	UPPER UNCONFINED	15	0.17	0.00972855	55
18	BH94	UPPER UNCONFINED	15	0.1	0.00972855	57
19	BH95	UPPER UNCONFINED	15	0.6	0.00972855	57
S/N	BOREHOLE PROJECT NUMBER	LAYER(AQUIFER)	THICKNESS (m)	HYDRAULIC CONDUCTIVITY K(m/d)	SPECIFIC STORAGE(Ss1/m)	TOTAL DEPTH (M)
20	BH104	UPPER UNCONFINED	33	0.051	0.00972855	45
21	BH105	UPPER UNCONFINED	27	0.152	0.00972855	36
22	BH106	UPPER UNCONFINED	6	0.27	0.00972855	39
23	BH107	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	15	0.29	0.00972855	56
24	BH118	UPPER UNCONFINED LOWER SEMI CONF-CONFINED	34 82.7	0.47 0.22	0.00972855	245
25	BH119	UNCONFINED (UPPER)	15	0.56	0.00972855	56
26	CHIKITO FUFORE	UPPER UNCONFINED	15	3.49	0.00972855	

(After Obiefuna in Preparation)

Harleman et al (1963) method gave k values that range between $1.60*10^{-3}$m/s to $2.16*10^{-1}$m/s with a mean value of about $4.83*10^{-2}$m/s.

Masch and Denny (1966) gave k values that varies from $3.77*10^{-5}$m/s to $2.83*10^{-4}$ with a mean value of about $1.20*10^{-4}$m/s

Uma et al (1989) method is similar to other statistical methods, except that the empirical coefficient, A, varies with the degree of consolidation of the porous medium. The value, A, varies from 6.0 for poorly consolidated sediments, 3.8 for moderately consolidated sediments and 2.0 for well consolidated sediments (example is the aquifers of the Bima Sandstone).

.Uma et al (1989) indicate k values that range from $9.50*10^{-5}$m/s to $1.28*10^{-2}$m/s with a mean value of about $2.86*10^{-3}$m/s. Finally Uma and Leohnert (1994) gave k values ranging from $6.8*10^{-7}$m/s to $1.13*10^{-5}$m/s with a mean value of about $3.46*10^{-6}$. It was observed that only Masch and Denny (1966) and Uma et al (1989) methods gave the results that matched the aquifer samples of the study area when compared with other statistical grain-size methods and were therefore adopted. The values of hydraulic conductivity, k, obtained from the various pumping test methods for the upper unconfined aquifer are shown in tables 1 and 2. The values obtained from the Cooper-Jacob (1946) vary from 0.021m/day to 152.17m/day whereas those obtained from the Theis (1935) Recovery method varies from0.052m/day to 19.28m/day.

The Logan (1964) method gave k values that vary from 0.081m/day to 23.28m/day as against values of 0.072m/day to 3.50m/day obtained from the step-drawdown method. The k values generally fall within the range (10^{-2} m/day to 10^{2}m/day) which indicate moderate to good aquifers. The values obtained from the statistical grain-size (granulometric) methods are essentially uniform and compare favorably with values got from the pumping test methods. This is expected in view of the fact that the upper alluvial aquifer occurs at a relatively shallow depth (less than 80m) and are composed of recent sediments. It has been observed by Uma and Leohnert (1994) that both methods generally give similar values in recent sediments that have not been subjected to significant diagenetic alteration.

A summary of the hydraulic conductivity, k, values obtained from both the pumping test and the statistical grain size methods for the upper unconfined alluvial aquifer indicate values ranging from 0.051m/day to 56.98m/day with a mean value of 2.54m/day. The hydraulic conductivity, K, values for the lower semi – confined to confined aquifer was determined employing the pumping test methods. These are the Cooper- Jacob (1946) method, the Theis (1935) Recovery technique, the Step-draw-down method and the Logan (1964) Approximation method. The values obtained from the Cooper- Jacob (1946) method vary from 0.59m/day to 27.98m/day whereas those obtained from the Theis (1935) Recovery Technique varies from 0.99m/day to 12.81m/day.

The Logan (1964) method gave values that varies from 1.11m/day to 15.47m/day as against values of 0.08m/day to 2.33m/day got from the Step-drawdown method.

A summary of hydraulic conductivity values obtained for the lower semi-confined to confined aquifer employing the pumping test and the statistical grain-size methods indicate values ranging from 0.22m/day to 10.48m/day with a mean value of 3.81m/day.

The k,values obtained for this aquifer falls within the range of 10^{-2}m/day to 10^{2}m/day which indicate an aquifer system of moderate to good performance (Todd, 1995). The k values obtained from pumping test method for the lower semi-confined to confined aquifer which is composed of older and diagenetically altered sediments is much lower than those of statistical grain-size methods. This is thus due to a long burial history resulting in increased compaction and cementation undergone by the sediments of this aquifer system (Uma and Leohnert, 1994).

Transmisssivity is defined as the ease with which a saturated aquifer transmits water through its entire thickness. It is represented mathematically as;

$$T = kb \ (m^2/s) \qquad (1)$$

Where;

k = hydraulic conductivity (m/s)

b = saturated thickness of the confined aquifer or the height of the water table above the top of the underlying aquitards that bounds the aquifer from the unconfined aquifer (Freeze and Cherry, 1979).

The saturated thickness of the upper unconfined alluvial aquifer was estimated from borehole lithological analyses and surface exposures of the aquifer whereas those of the lower semi-

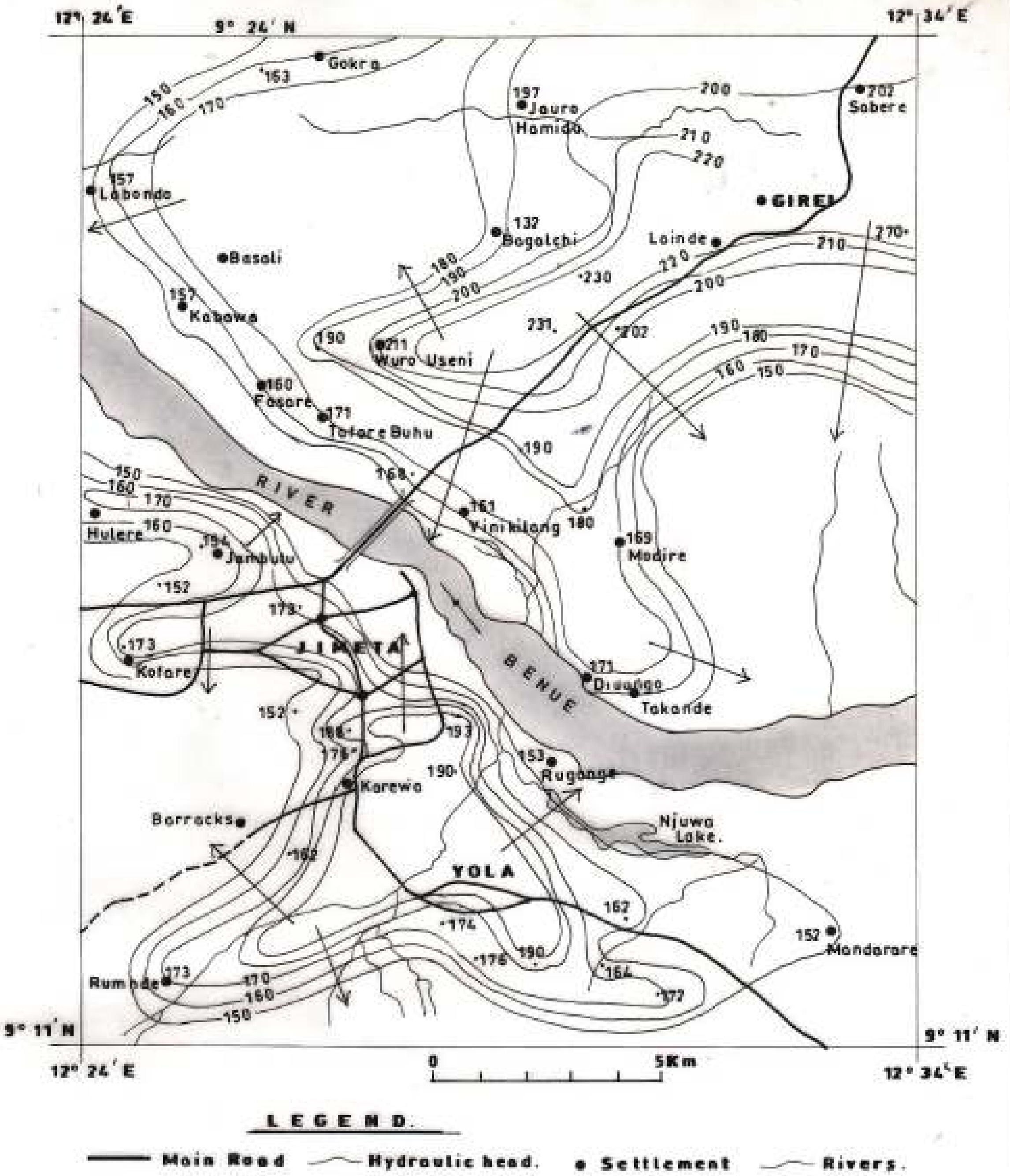

Fig. 3: Hydraulic head distribuition and ground water flow direction in the upper unconfined (alluvial) aquifer systems.

confined to confined aquifer was estimated from screen length and borehole logs. The transmissivity values for the upper unconfined alluvial aquifer ranges from $1.52m^2$/day to $349.86m^2$/day with a mean value of 37.99m2/day whereas those obtained from granulometric methods vary from 9.97×10^{-3} m^2/s to $1.53m^2/s$.

The transmissivity values for the lower semi-confined to confined aquifer varies from $9.18m^2$/day to $349.93m^2$/day with a mean value of about $103.51m^2$/day. The variation in transmissivity values in the two aquifer systems are because of variations in the thickness of the aquifer rather than in hydraulic conductivity.

The pumping test indicates that the phreatic aquifer has an average hydraulic conductivity of 2.54 m/d, a transmissivity value of 37.99 m^2/d and a specific yield of 27% (obtained from pumping test method). The recharge area on either side of the study area is about $337.5km^2$ and the expected average net abstraction rate

is172800 m^3/day by the year 2020. This would yield an infiltration rate of 0.000512 m/d on average.
The coefficient of storage values indicate that confining conditions exists in the two aquifer systems.

Groundwater Levels

The hydraulic head distribution in the study area are displayed in Figure 3 as well as Tables 4 and 5 respectively. Two groundwater flow systems are recognized namely the shallow upper largely unconfined alluvial aquifer (see figure 3) and the deeper lower semi-confined to confined aquifer systems of the Bima Sandstone Formation. The flow directions in the two aquifer systems in the same direction due to similar depth to static water levels (Obiefuna in Preparation). The upper unconfined groundwater flow system receives direct recharge from rainfall over its permeable soil cover and flow is from areas of higher elevation such as hills or undulating ridges (Bagale hills) to areas of lower elevation such as river or stream valleys (River Benue Valley).
It is therefore mainly structurally controlled and occurs at a depth of less than 80meters and at average hydraulic gradients of 0.008 and 0.0231 to the northeast and southwest respectively. Figure 3 indicates that to the northeast a localized recharge area of the aquifer occurred to the west whereas to the southwest it is northeastwards towards the Benue River. It discharges

TABLE 4 :Hydraulic Head Values For The Hand-Dug Wells In The Study Area

S/N	LOCATION	HAND-DUG WELL PROJECT NUMBER	COORDINATE IN DEGREE	ELEVATION ABOVE MEAN SEA LEVEL	SWL(m)	HYDRAULIC HEAD (m)
1	LAINDE	HW1	N09◦21'6.3 " E012◦308.22"	179m	24.2	154.8
2	DAMARE	HW2	N09◦10'4.62" E012◦26'41.82"	174.545m	9.09	165.46
3	NJOBBORE	HW3	N09◦17'1.02" E012◦29'22.92"	150.91m	1.21	149.7
4	MODIRE	HW4	N09◦17'24.6" E012◦30'35.16"	192.72m	23.33	169.39
5	VINIKILANG	HW5	N09◦17'24.6" E012◦30'35.22"	191.82m	1.52	190.3
6	BAJABURE	HW6	N09◦20'54.66" E012◦29'3.54"	207.58m	2.12	205.37
7	WURO ALHAJI	HW7	N09◦19'44.4" E012◦28'37.62"	218.79m	7.88	210.91
8	KOFARE BAGALCHI (JAURO HAMIDU)	HW8	N09◦20'54.66" E012◦29'3.42"	205.15m	23.33	181.82
9	BAGALCHI	HW9	N09◦21'25.38" E012◦28'52.98"	203m	6.06	196.94
10	SABON GARI	HW10	N09◦20'24.28" E012◦30'25.8"	237.88m	2.42	235.46
11	SANGEREI	HW11	N09◦20'56.84" E012◦30'50.58"	233.94m	3.64	230.3
12	GIREI	HW12	N09◦21'28.38" E012◦32'20.7"	233.03m	7.27	225.76
13	TASHA MAITARARE	HW13	N09◦22'22.26" E012◦33'11.04"	255.76m	27.27	228.49
14	SABERE	HW14	N09◦23'17.22" E012◦33'17.52"	238.18m	36.36	201.82
15	DIGINO	HW15	N09◦23'17.82" E012◦33'16.62"	238.18m	21.21	216.97
16	NYIBANGO	HW16	N09◦16'35.7" E012◦30'37.26"	183.33m	2.12	181.21
17	DIDANGO	HW17	N09◦15'47.52" E012◦30'37.26"	172.73m	2.12	170.61
18	TAKWANDE	HW18	N09◦16'22.14" E012◦29'53.22"	165.76m	3.94	161.82
19	YOLDE PATE	HW19	N09◦16'50.88" E012◦27'3.24"	163.64m	4.3	159.34
20	RUMDE	HW20	N09◦10'36.3'' E012◦32'46.44''	190.3m	17.8	172.5
21	MBAMBA R WAZIRI	HW21	N09◦10'36.24" E012◦32'46.26"	186.97m	7.6	179.37
22	WUROCHEKKE	HW22	N09◦12'32.22" E012◦30'34.38"	167.27m	8	159.27
23	YOLA TOWN	HW23	N09◦12'35.58" E012◦29'42.12"	167.27m	2.7	164.57
24	JIMETA	HW24	N09◦12'43.38" E012◦28'53.34"	178.48m	1.40	177.08
25	BACHURE	HW25	N09◦14'46.86" E012◦25'33.12"	192.12m	5.2	186.92
26	KAREWA	HW26	N09◦15'16.5" E012◦26'36.42"	189.39m		
27	DEMSAWO	HW27	N09◦16'50.46" E012◦25'50.94"	167.88m	1	166.88
28	JEKPEDEDE	HW28	N09◦17'43.02" E012◦24'41.64"	166.97m	9.09	157.88
29	HULERE	HW29	N09◦17'53.7" E012◦24'13.86"	175.45m	8.48	166.97
30	DAMILU	HW30	N09◦16'14.76" E012◦25'17.64"	183.33m	6.27	177.06

31	KOFARE BAGALCHI (JAURO HAMIDU)	HW31	N09°16'43.5" E012°24'41.58"	165.76m	6.36	159.4
32	KOFARE BAGALCHI (JAURO HAMIDU)	HW32	N09°16'5.64" E012°24'19.32"	179.09m	6.06	173.03
S/N	**OCATION**	**HAND-DUG WELL PROJECT NUMBER**	**COORDINATE IN DEGREE**	**ELEVATION ABOVE MEAN SEA LEVEL**	**SWL(m)**	**HYDRAULIC HEAD (m)**
33	BAJABURE	HW33	N09°19'1.86" E012°28'34.56"	221.82m	9.09	212.73
34	GIREI	HW34	N09°22'22.38" E012°33'10.68"	260m	8.48	251.52
35	GIREI	HW35	N09°21'23.28" E012°32'10.68"	262.72m	3.64	259.08
36	TAFARE BUHU	HW36	33P0220165 UTM1030847	173m	2.12	170.88
37	LABONDO	HW37	N09°22'50.94" E012°23'57.0"	165.15m	10.9	154.25
38	KABAWA	HW38	N09°21'12.48" E012°25'14.82"	163.64m	6.7	156.94
39	FASARE	HW39	N09°19'41.1" E012°26'40.2"	166.67m	7.1	159.57
40	GOKRA	HW40	N09°23'35.52" E012°26'18.60"	175.76m	12.6	163.16
41	BATARE	HW41	N09°23'56.46" E012°29'7.32"	193.94m	4.2	189.74
42	SEBORE	HW42	33P0233679 UTM1009347	164.55m	12	152.55
43	RUGANGE	HW43	33P0226421 UTM1021166	164.55m	12	152.55
44	MANDARARE	HW44	33P0230594 UTM1019157	164.55m	13	151.55
45	YOLDE PATE11	HW45	33P0210050 UTM1018823	179.09m	7.88	171.21
46	KAREWA	HW46	N09°15'24" E012°26'57.18"	172m	62	110
47	KAREWA	HW47	N09°15'25.26" E012°26'56.7"	203m	58	145
48	JAMBUTU	HW48	N09°17'24.42" E012°25'38.16"	154m	6.06	147.94

(After Obiefuna in Preparation)

Table 5: Hydraulic head values calculated for the boreholes in the study area

S/N	LOCATION	BOREHOLE LOCAL NUMBER	BOREHOLE PROJECT NUMBER	COORDINATES	ELEVATION ABOVE SEA LEVEL(M)	DEPTH TO STATIC WATER LEVEL(M)	HYDRAULIC HEAD(M)
1	Yolde Pate		BH133	N09^{0}12' E012^{0}26'	170.91m	10.64	160.27
2	Mbamba		BH98	N09^{0}11'33.96" E012^{0}30'11.76"	187.9	12	175.90
3	Mbamba Corner		BH99	N09^{0}1'10.24" E012^{0}31'43.26"	182.4	9.8	172.60
4	Wuro-Dole		BH92	N09^{0}12'15.24" E012^{0}30'23.46"	173.3	8.12	165.18
5	Bako Primary School Yola Town		BH93	N09^{0}12'10.68" E012^{0}28'21.84"	176.7	18.27	158.43
6	Rabeh		BH94	N09^{0}12' E012^{0}28'	175.5	12.35	163.15
7	Army Barracks Road Jimeta		BH75	N09^{0}1'44.62" E012^{0}26'30.6"	167.27	8.00	159.27
8	Army Barracks Road Jimeta		BH88	N09^{0}14' E012^{0}26'	170	9.60	160.4
9	Karewa Extention		BH48	N09^{0}15' E012^{0}26'	187.88	45	142.88
10	Jimeta		BH84	N09^{0}16' E012^{0}26'	175.8	4.04	171.76
11	Demsawo		BH87	N09^{0}17' E012^{0}25'	163.64m	5.07	158.57
12	State Poly Jambutu		BH36	N09^{0}17' E012^{0}25'	156.36	4.5	151.86
13	Damilu		BH81	N09^{0}16' E012^{0}25'	177.58	6.10	171.58
14	Modire		BH120	N09^{0}17' E012^{0}30'	178.79m	25	153.79
15	Njobbore		BH124	N09^{0}17' E012^{0}29'	172.73	5.25	167.48

16	Bajabure Phase1		BH20	N09^{0}19' E012^{0}28'	228.48	10.25	218.23
17	Kofare		BH136	N09^{0}15'57.5" E012^{0}27'13.14"	196.7	6.5	190.2
18	Futy		BH10	N09^{0}20 ' E012^{0}30'	241.21m	25	216.21
19	Sabere		BH121	N09^{0}23' E012^{0}33'	234.55m	38	196.55
20	Girei		BH7	N09^{0}21'54" E012^{0}33'10.4"	261.21m	51.28	209.93
21	Girei		BH6	N09^{0}21' E012^{0}3245"	258.48	18.5	239.98
22	Wuro Alhaji		BH122	33p0220616 Utm1032699	199m	5.15m	193.85
23	Bajabure Phase11		BH21	33p0219118 Utm1025141	196m	6.42	189.58
24	Lainde		BH123	33p0221223 Utm1030050	188m	25.50	162.50
25	Damare		BH24	33p0210200 Utm1030724	173m	9.4	163.6
26	DABARE		BH125	33p0210005 Utm1030860	178m	8.60	169.40
27	Badarisa		BH18	33p0221014 Utm1029845	207m	28	179
28	Labondo		BH126	N09^{0}22'5" E012^{0}2'45.52"	170.91m	12	158.91
29	Kabawa		BH127	N09^{0}21'11.34" E012^{0}25'16.14"	169.7m	7.10	162.60
S/N	**LOCATION**	**BOREHOLE LOCAL NUMBER**	**BOREHOLE PROJECT NUMBER**	**COORDINATES**	**ELEVATION ABOVE SEA LEVEL(M)**	**DEPTH TO STATIC WATER LEVEL(M)**	**HYDRAULIC HEAD(M)**
30	DEGRIBATA		BH128	N09^{0}20'44.28" E012^{0}25'44.76"	168.79	8.75	160.04
31	GORKA		BH25	N09^{0}23'35.64" E012^{0}26'18.18"	176.36m	13.36	163
32	BATARE		BH129	N09^{0}23'56.46" E012^{0}29'7.32"	195.45m	16.40	179.04
33	RUMNDE ALKALI		BH134	33P0231173 UTM1016312	186.67m	6.87	179.80
34	SEBORE		BH100	33P0233729 UTM1009394	215.76	45.76	170
35	RUGANGE		BH135	33P0226769 UTM1021045	169.09	15.60	153.49
36	NJOBOLI KAREWA GADA	ADA/TH10/987/98	BH117	33P0234938 UTM1018369	197.88m	32.50	165.38
37	WURO-HAUSA YOLA TOWN		BH110	33P0226106 UTM1018942	167.88	15.30	152.58
38	TOUNGO-A YOLA TOWN		BH106	33P0220000 UTM1018886	187.27	13.00	174.27
39	GERIYO		BH57	33P0210747 UTM1029146	137.27	6.27	131
40	ABATTOIR ALONG YOLA ROAD		BH132	33P0220105 UTM1020937	138.18	8.20	129.98
41	YOLDE PATE 11		BH137	33P0210417 UTM1018917	176.06	8.96	167.10
42	(RUMDE WARD) CHINKO JIMETA		BH60	N09^{0}171'86 " E012^{0}27'4632"	162.42	7.52	154.90
43	DOUGIREI		BH66	33P0222380 UTM1023387	200.3	20.30	180
44	WATER TREATMENT PLANT ALONG RIVER BENUE JIMETA		BH130	33P0221809 UTM1026712	172.73	9.31	163.42
45	MAKURDI STREET, JIMETA ALHERI JIMETA		BH131	33P0219953 UTM1026474	171.82	7.65	164.17
46	JAMBUTU		BH37	N09^{0}17'20.04" E012^{0}25'35.46"	168	5.10	162.9
47	BAGALCHI		BH17	N09^{0}20'0.3" E012^{0}29'23.4'	221	8.20	212.8
48	KAREWA GRA		BH51	N09^{0}15'24.72" E012^{0}26'57.36"	203	15.00	188

(After Obiefuna in Preparation)

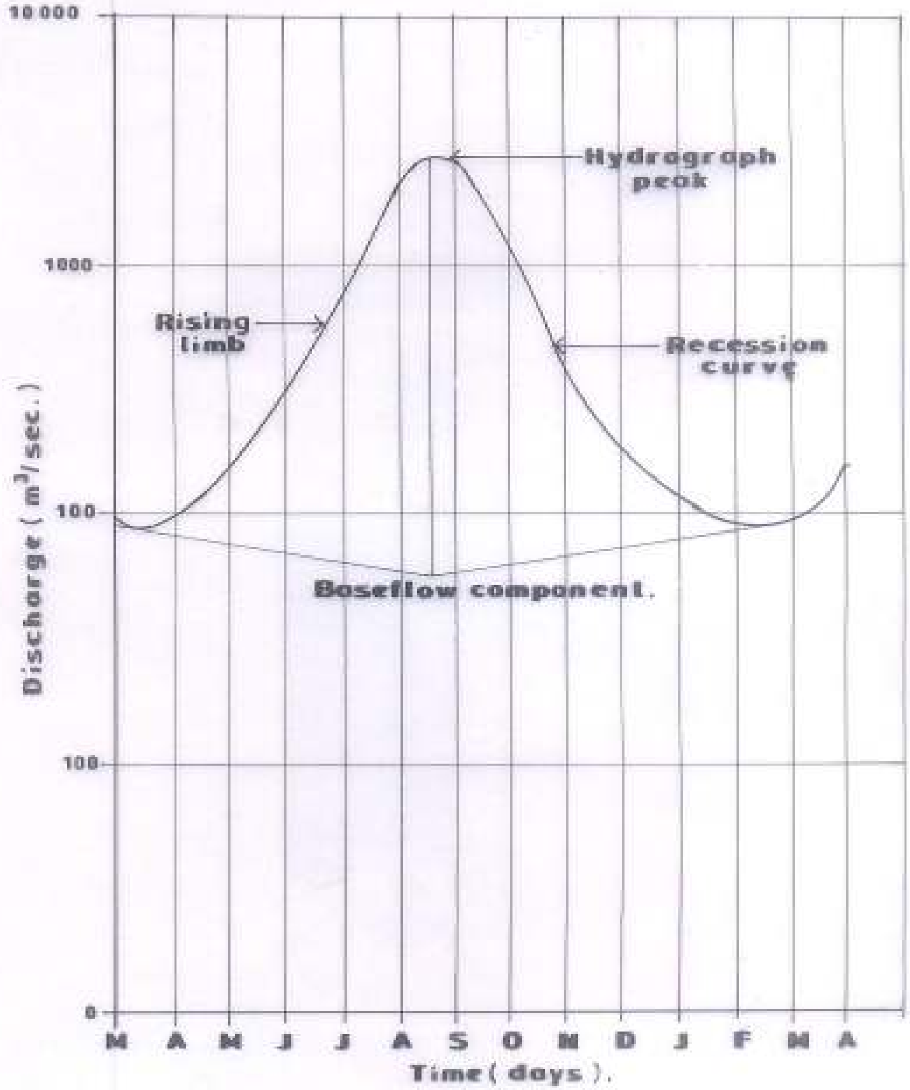

Fig. 4a: Hydrograph Recession curve for River Benue at Jimeta for 1994/95 to 1997/98 water years.

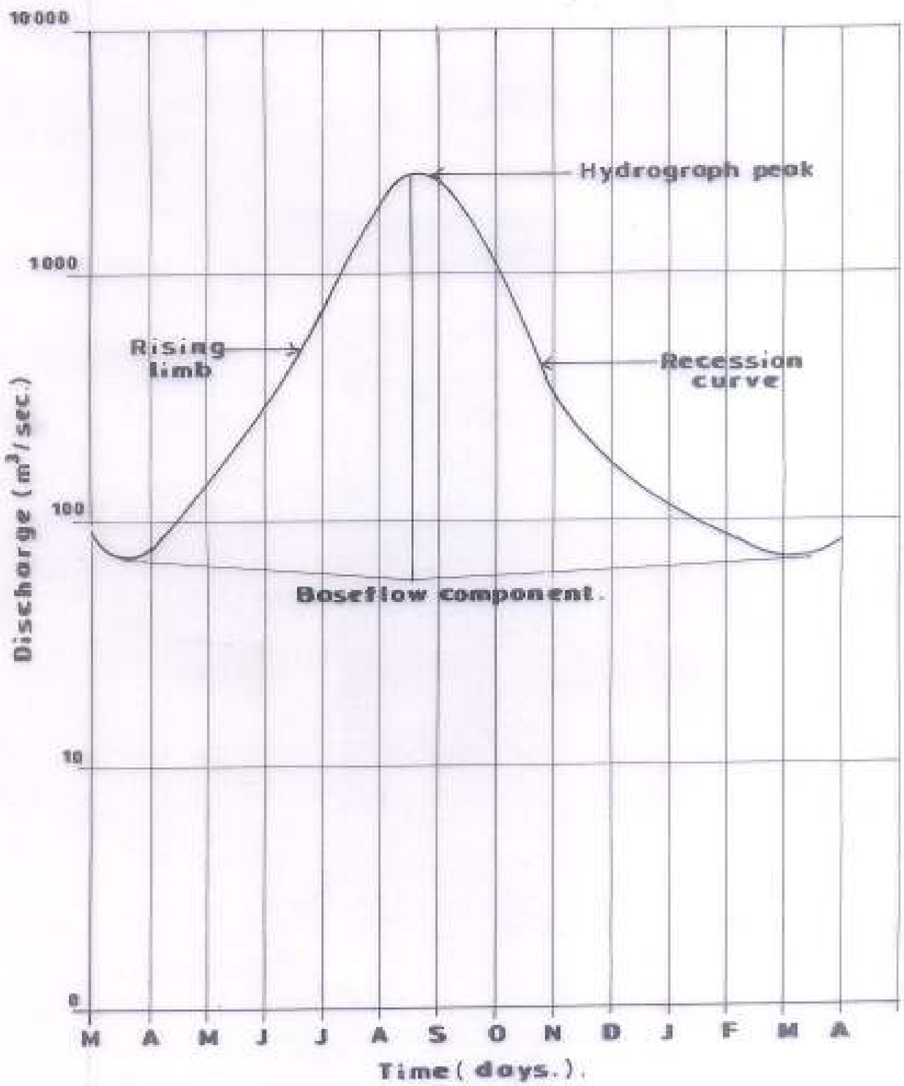

Fig. 4b: Hydrograph Recession curve for River Benue at Jimeta for the 1963/64 to 2006/07 water years.

naturally at points or areas where the aquifer with its underlying relatively impermeable alluvial units such as clay-shales and mudstone intercepts the ground surface in river or stream valleys. Two groundwater mounds occur within the study area. A snake-like shaped groundwater mound exist to the northeast around Girei where groundwater flows radially away from it discharging naturally into the Benue River and as seasonal streams and Rivers within the study area. Another one occurred to the south around Yola town and Karewa area and again flowing radially away from the mound discharges naturally into the Benue River as well as into some seasonal streams and rivers within the study area.

The regional groundwater flow system in the area occurs at a depth of about 80meters below the ground surface and is assumed to be recharged by the Benue River. To the northeast of the study area the regional groundwater flow direction is to the southwest while to the southwest it is northeastwards. The recharge areas of this flow system probably occurred to the northeast and to the southwest and discharges naturally towards the Benue River. The two groundwater flow systems thus converges and discharges as baseflow into the Benue River which flow diagonally along the southeastern-northwestern directions dividing the study area into two equal halves. Hence the relationship between the two flow systems depends largely on the relative depth to static water level in the two flow systems and the gauge height of the Benue River. The Benue River will be influent or effluent depending on the depth to static water level and the gauge height of the Benue River which is largely dependent on the vagaries of seasonal climatic variations. The water table in the bedrock is typically 0-6m below the ground surface in low-lying areas and 10-50m below the ground surface at hill slopes and the hills. The amplitude of the annual variation of the water table is about 3-5m. Thus depending on the local topography and the soil cover thickness, there is groundwater in the soil, with a water table that differs from that in the bedrock.

According to Meyboom (1966), Toth (1966) and Brassington (1988), recharge and discharge areas can be delineated on the basis of topography, piezometric patterns, hydrogeochemical trends, the use of environmental isotopes and soil and land surface features.

The soil type in the study area is variable. Along the Benue River valley which coincide with the local and regional discharge area they consist of alluvial deposits made up of fine sands, silts, clay-shales and mudrock. To the northeast and southwest which probably constitute the recharge area the soil type ranges from deep porous brown soils to weathered red earth and coarse acid sands. They are thus relatively porous and permeable which encourages infiltration. The depth to static water level in areas close to discharge areas are less than 10 meters whereas towards the recharge area it may be up to 50 meters. The Benue River Valley conforms to a topographic low where groundwater flow is directed downward away from the water table and displays depressed groundwater troughs. The water fluctuations are thus comparatively small with groundwater head increasing with depth. The groundwater quality is comparatively older and more mineralized and thus relatively more saline (with larger TDS Values).

However, the above characteristics of discharge area changes as we move towards the recharge area to the northeast and to the southwest across the Benue River. The recharge area in the study area is characterized by generally influent or losing stream, relatively deep water table and generally coarse textured residual soils.

MATERIALS AND METHODS

The key to the successful estimation of groundwater recharge lies in the utilization of a variety of independent methods. Every method has its strengths and weaknesses, but combined they become much stronger. Thus by bringing together chloride mass balance method, the Darcian method, the hydrologic balance method and the hydrograph separation method in a comprehensive groundwater model, the study of the groundwater hydrology of arid and semi-arid environments can enter a new era (UNDP2002).

Accuracy ratings are given in three classes, according to regional recharge estimates (UNDP2002):

*Class 1: Within a factor of 2

*Class 2: Within a factor of 5 (of the same order of magnitude)

*Class 3: Within a factor of 10 or more (with large errors likely)

Recharge was investigated in the study area using the following independent approaches: hydrograph recession analyses, hydrologic balance equation, chloride mass balance method and Darcy's law.

Hydrograph Recession Analyses

Stream flow data was analyzed employing the hydrograph recession method. In this method a plot was made of stream discharge data (during and after rainfall) versus time to produce a flow hydrograph for 1963/64 to 2006/2007 water year period.

In those hydrograph (see Figures 4a and 4b) the following different parts are defined namely rising limbs; hydrograph peak; recession curve; and depletion curve (Lancaster and France 1984). The rising limb corresponds to the growth referring to the increase of discharge occurring as a result of rainfall.

The hydrograph curve peak occurs at the maximum discharge value. The depletion curve corresponds to the decrease in the discharge resulting only from the base flow discharge. The rising time plus the recession time define the base time of the hydrograph and correspond to the period in which the direct discharge occurs. The recession curve corresponds to the progressive reduction of direct discharge until its annulment. The two main components of total discharge (both direct and base) can be individualized in the hydrograph. The slope of the recession curve flattens over time from its initial steepness as the quick flow components passes and base flow becomes dominant. Hence, recession curves are the parts of the hydrograph that is dominated by the release of water from natural storages, typically assumed to be groundwater discharge. Recession segments are selected from the hydrograph and can be individually or collectively analyzed to gain an understanding of these discharge processes that make up baseflow. Graphical approaches have traditionally been taken but more recently analysis has focused on defining an analytical solution or mathematical model that can adequately fit the recession segments. Each recession segments is often considered as a classic exponential decay function as applied in other fields such as heat flow, diffusion or radioactivity and expressed according to (Smaktin 2001) as:

$$Q_t = Q_o e^{-at} \quad (2)$$

Or

$$Q_t = Q_o e^{-k}$$

Where

Q_t is the stream flow at time t,

Q_o is the initial stream flow at the start of the recession segment, a is a constant also known as the cut-off frequency (fc) and T_c is the residence time or turnover time of the groundwater system defined as the ratio of storage to flow. The term e^{-a} in this equation can be replaced by K called the recession constant or depletion factor, which is commonly used as an indicator of the extent of base flow(Nathan and McMahon,1990).

The typical ranges of daily recession constants for stream flow components are given by Nathan and McMahon (1990).

Another parameter interpreted from the recession segment is the recession index (K) which is the time (in days) required for base flow to recede by one log-cycle i.e. Q_o to 0.1 Q_o. A similar index called the half-flow period or half-life, which is the time (in days) for flow to halve, can also be calculated. For streams with low base flow inputs the half-life may be in the range of 7-21 days, while discharge from large stable natural storages can result in a half-life exceeding 120 days (Smaktin, 2001).

The integrated form of the classic recession function of the above equation is

$$Q_t = aS_t \quad (3)$$

Where

S_t is the storage in the reservoir that is discharging into the stream at time t. This relationship is called a linear storage-outflow model and implies that the recession will plot as a straight line on a semi-logarithmic scale.

However, semi-logarithmic plots of individual recessions are commonly curved rather than linear indicating that the storage-outflow relationship is non-linear. The change of recession behavior with time is a reflection in variations in the shape of the recession segments found in a stream hydrograph. An excellent review of the reasons for and the different approaches used in addressing this non-linearity and variability in recession are given (Langbein 1938, Barnes 1940, Meyboom 1961, Rutledge and Daniel1994, Rutledge 1998, Smakhtin 2001, Sujono et al 2004).

A major drawback of the surface-water methods including Stream-hydrograph analyses is that it estimate baseflow (groundwater discharge) at lower elevations in a watershed, which is taken to equal the recharge that occurred at higher elevations. The method is not feasible for ephemeral rivers where low flow reaches zero. There is also some ambiguity about the point in time when the discharge curve of a river has reached the base flow.

Accuracy: Problems may arise when recharge to aquifers deeper than the one draining to the observed river are considered. The base flow then has no relation to the recharge of the deeper aquifer, the discharge of which is not contained in the measured flux.

Rating: Class 3

Hydrologic balance equation

The generalized hydrologic equilibrium equation which is given below expresses a balance between the total water gains and losses within a basin during a defined time period usually a mean water year. It takes into consideration of all waters whether surface or subsurface applied to (or entering) and lost from (or leaving) from a particular container, basin, area or type of surface. In the study area precipitation is overwhelmingly in the form of rainfall (dew is insignificant) and this rainfall is lost mainly by evapotranspiration, surface runoff and infiltration occurs only after the soil moisture deficit is met.

The generalized hydrologic balance or equilibrium equation is therefore given as follows;

$$P = I + R + E \quad (4)$$

Where,

P= Precipitation
I=Infiltration
R=Surface runoff
E=Evapotranspiration

In other words, the average rate of inflow minus the average rate of outflow must equal the average rate of change in storage over the specified time interval.

Furthermore, this equation state specifically that all water in a region must be accounted for either as inputs or outputs where the net value describes either an increase in storage volume (+ surplus) or decrease in storage volume (-deficit).

Thus even though the above equation is essential in evaluating the water losses and water gains in a particular watershed, area or type of surface, it is an approximate equation. It is however bedeviled by a number of limitations which include lack of lysimeter for measuring evapotranspiration. Thus potential evapotranspiration and actual evapotranspiration were calculated from empirical equations, infiltration (or recharge) and surface run-off was estimated from hydrograph recession analysis of stream flow data whereas precipitation was measured for the study area by the meteorological stations involved.

Water budget methods however estimate all terms in the continuity equation except recharge which is calculated as the residual. The calculation from standard data is simple and can be done in a spreadsheet.

The major limitation is that all methods of this type are basically very inaccurate when applied to recharge estimation. The reason is that recharge is the difference between two inaccurately known large quantities (precipitation and evapotranspiration) with inaccuracies being particularly large under conditions of weak infrastructure and the peculiarities of the arid environment. The difference between two such quantities is prone to error and is often insignificant.

Accuracy: Accuracy is low. At best some sensitivity analyses are possible which could be used for the estimation of recharge contrasts.

Rating: Class 3.

An excellent review of the various methods for measurement and estimation of meteorological/hydrological parameter and problems likely to be encountered when measuring them under field conditions is given in (Meinzer1942; Ward 1975; Todd 1980; Doorenhos and Pruitt 1977 and Wilson 1984; UNDP2002).

Chloride Mass Balance Method

Recently, Herczeg and Edmunds (2000) demonstrated the use of a chloride mass-balance technique for estimating recharge, which was first developed by Anderson (1945). Many others have utilized the technique to estimate recharge (Kitching et al 1980; Sharma and Hughes 1985; and Cook and Herczeg 1998). In this technique, firstly a steady-state water balance for a catchment is written as:

$$P = E + R + Q \quad (5)$$

Where

P is precipitation
E is evapotranspiration
R is recharge
Q is discharge to surface water bodies and runoff

If we assume that Chloride within the groundwater is only deposited by precipitation or dust particles within the precipitation then, under steady state conditions, the chloride mass balance can be included in equation 1 as

$$P[cl]_p = E[Cl]_e + R[cl]_r + Q[cl]_q \quad (6)$$

Where

$[cl]_p$, $[cl]_e$, $[cl]_r$ and $[cl]_q$ are the concentration of chloride within the precipitation, water removed via surface run-off respectively. If significant quantities of Chloride are not removed by evapotranspiration (i.e. this term tends to zero) and sites are selected such that surfaces run-off is minimal (i.e. areas of low surface gradients such as like the topographic divides within the study area)

Equation 6 can be simplified to solve for recharge as:

$$R = P[cl]_p/[cl]_r \quad (7)$$

However, Sukhija et al (2003) indicates that the error attributed to this method could be as high as 25% of the true values.

The method is cheap and can be carried out in less sophisticated laboratories. It follows the chloride profile in the unsaturated zone, but can also be applied more readily to concentrations in the top layer of the saturated zone. It directly estimates the recharge flux.

There are however several instances in which this method can fail. This is especially the case if there are sources of chloride in the soil (e.g. halites) other than the chloride contained in the rainwater. Recycling of dried salt by wind, unaccounted runoff and uptake by harvested plants may also distort the results.

Accuracy: In the unsaturated zone, the method again yields a very local recharge value. The input function is difficult to obtain, as a local time series of chloride in precipitation as well as dry deposition is required. Such data are still rarely available and where they are, the time series is not yet long. It will take another decade to establish such data for West Africa. Finally the area associated with the recharge rate has to be determined.

Rating: Class 2 to 3.

Darcy's Law

The Darcian method applied to steady flow conditions in the unsaturated zone (Nimmo et al 1994) can produce high quality local recharge estimates at diverse locations to provide a standard of comparison, for example between humid regions where streamguaging data are useful for recharge estimation and drier regions where they are not. This method is based on knowledge of the unsaturated hydraulic conductivity (K) at a point (usually deep) in the unsaturated zone where flow is downward and steady.

If flow under field conditions is steady and driven by gravity alone, then, according to Darcy's Law, downward percolation rate will be numerically equal to the hydraulic conductivity of the material at the measured in-situ water content.

The Darcian unit-gradient method (Nimmo et al 1994) was originally used to estimate long-term average recharge rates in arid regions with thick unsaturated zones where, below some depth, flow is considered to be steady and driven by gravity alone. In shallow unsaturated zones in some environments, some form of this method may be applicable if changes in water content are slight and recharge rates may vary little over the course of the year or may exhibit a seasonal, repetitive pattern of variability. The Darcian method does not necessarily indicate total recharge as it only accounts for diffuse, matrix flow. Recharge due to preferential flow is inherently non-Darcian and if significant, must be determined separately. In the unsaturated zone, Darcy's Law may be represented in head units by the equation:

$$q= k(q)[dy/dz +1] \qquad (8)$$

Where

q= flow rate $[LT^{-1}]$

k= hydraulic conductivity $[LT^{-1}]$

q= volumetric water content [dimensionless]

dy/dz= matric potential gradient [dimentionless] and

$dz/dz=1$= gravitational potential gradient [dimentionless]

Under the unit-gradient assumption, matric potential is constant with depth (ie dy/dz=0) and gravity is the only driving force, therefore q numerically equals the hydraulic conductivity of the medium at the water content of the depth interval where the dy/dz=0 conditions holds. If the K corresponding to the in-situ content is known, that K may be interpreted as a recharge rate.

The major advantage is that all quantities involved on the right hand side of the Darcy's equation are measurable. A major drawback is that the hydraulic conductivity of a soil is poorly known due to heterogeneity and variation with saturation. The functional relationship between the two quantities is hard to obtain and the values of water flux determined are very local. Furthermore water suction pressure is very hard to measure in arid climates.

Accuracy: The accuracy is poor due to the inaccuracy of unsaturated hydraulic conductivity.

Rating: Class 3

RESULTS AND DISCUSSION

Application and comparison of results

Four basic methods of groundwater modeling to estimate groundwater recharge from precipitation and surface water bodies in yola area showed results that differ slightly to considerably from each other.

Tables 6a, 6b and 6c summarize the recharge rates obtained through the different methods applied in the study area. Despite the similarity there are differences in the results that can be explained as follows. The chloride mass balance method which is often recommended in semi-arid regions may have under-estimated recharge rates in the underlying Bima Sandstone Formation. The method determines point recharge which is supposed to be diffuse recharge originating from the porous parts of the rock at or 'upstream' of the observation wells where chloride samples have been taken. In these areas, the recharge estimation appeared to be relatively small with recharge ranging from 5.78 mm/yr to 9.65mm/yr with an average of 7.42mm/yr. It is thus considered too small for the typical recharge area covering the underlying relatively porous and permeable fine to medium grained Bima Sandstone.

The method is cheap and can be carried out in less sophisticated laboratories. It follows the chloride profile in the unsaturated zone, but can also be applied more readily to concentrations in the top layer of the saturated zone. It directly estimates the recharge flux.

There are however several instances in which this method can fail. This is especially the case if there are sources of chloride in the soil (e.g. halites) other than the chloride contained in the rainwater. Recycling of dried salt by wind, unaccounted runoff and uptake by harvested plants may also distort the results.

The water budget method which determines diffuse recharge with relatively variable precipitation and high evapotranspiration were determined at three locations. These have resulted in relatively high value of recharge estimates ranging from 52.45 to 86.20 mm/yr with an average of about 73.13 mm/yr. The application of the water budget method in the study area allow the estimation of aerial recharge rates but is useful in the sense that it provides wide limits of the recharge values which can be compared with the results of other methods (Sibanda et al 2009). The major limitation is that all methods of this type are basically very inaccurate when applied to recharge estimation. The reason is that recharge is the difference between two inaccurately known large quantities (precipitation and evapotranspiration) with inaccuracies being particularly large under conditions of weak infrastructure and the peculiarities of the arid

Table 6a:Discharge characteristics of the River Benue

River Guaging Station	Water Year	Base Flow in m^3/s	Base Flow Index	Direct Runoff in m^3/s	Total Runoff m^3/s	Recharge Rate in mm/yr
Upper Benue River Basin Development Authority Guaging Jimeta Bridge Yola	1963/64 To 1967/68	11279	0.23	4330	5609	198.69
	1968/69 to 1972/73	4157	0.66	2100	6257	645.81
	1973/74 to 1977/78	3345	0.66	1750	5095	519.66
	1978/79 to 1981/82	2603	0.51	2531	5134	404.38
	1982/83 to 1985/86	860	0.3	2047	2907	133.6
	1986/87 to 1989/90	860	0.28	2265	3125	133.6
	1990/91 to 1993/94	1700	0.52	1540	3240	254.24
	1994/95 to 1997/98	2003	0.43	2644	4647	311.17
	1998/99 to 2001/02	2459	0.34	4671	7130	382
	2002/03 to 2006/07	2105	0.52	1960	4065	327
	1963/64 to 2006/07	1594	0.33	3245	4839	247.63

(After Obiefuna in Preparation)

Table 6b Comparison of recharge estimate for Yola area from different methods

Well Location	Geology	Average Depth (M)	Number of samples	Rainfall (mm/yr)	Chloride mass balance method (Mm/yr)	Water budget method (Mm/yr)	Darien Method (mm/yr)	Mean annual recharge (Mm/yr)	Remark
Girei	Fine-medium grained sandstone	15.77	5	629.20	5.81	86.20	16.38	36.13	
Fut. Yola	Fine-medium grained sandstone	9.16	14	629.20	7.27	86.20	34.32	45.60	
Vinikilang	Alluvium	9.96	22	940.50	9.17	70.40	40.46	40.01	
Jimeta-Yola	Fine-medium grained sandstone	9.21	31	940.50	5.78	70.40	53.22	43.17	
Yola town	Fine-medium grained sandstone	13.74	22	917.80	9.65	52.45	104.04	55.38	

After Obiefuna (In Preparation)

Table 6c: Recharge estimations of Yola area using different recharge methods

Method	Recharge rate (mm/year)	Limitations
Chloride mass balance	5.81-9.65	Long-term atmospheric chloride deposition unknown
Water budget	52.45-86.20	Evapotranspiration difficult to determine
Darcian computations	16.38-104.04	Poorly known transmissivities and contour lines
Hydrograph Separation	133.6-645.81	Baseflow at lower elevations in a watershed assumed to be equal to the recharge at higher elevations

After Obiefuna (In Preparation)

environment. The difference between two such quantities is prone to error and is often insignificant.

The darcian method does not determine point recharge but it integrates recharge over a larger area. Large variations or lack of information regarding transmissivity values and groundwater level contour lines may limit the application of the method. However for the study area, these values fall within fairly well-defined ranges allowing the estimation of recharge rates on the order of 16.38 to 104.04 mm/yr. Thus as an integrating method, the computed rates give an idea on the average recharge for the study area.

The hydrograph separation method to estimate recharge determines channel recharge. A major drawback of this method is that it estimate baseflow (groundwater discharge) at lower elevations in a watershed which is taken to equal the recharge rate that occurred at higher elevations. It is however an integrative method because observations of heads can be used.

The recharge rate estimations on the order of 133.6 to 645.81 mm/yr with an average of 331.02mm/yr obtained from this method are largely close to the results of the other methods.

The mean annual recharge provide a check on the other recharge estimation methods. The mean annual recharge estimates of the order of 36.13 mm/yr to 55.38 mm/yr with an average of 44.06 mm/yr gives a fairly reasonable estimate of the recharge rates of the study area.

The above mean annual recharge rates gives confidence in the recharge values estimated from both the water budget and the darcian methods.

It is therefore important to note that the confidence in recharge estimation improves when applying several methods as reported by other authors (Beekman et al 1996; De Vries and Simmers 2002)

These results has testified that there is no doubt that recharge occurs to some extent in even the most arid regions, though increasing aridity will be characterized by a decreasing net downward flux and greater time variability. Thus as aridity increases, direct recharge is likely to become less important and indirect recharge more important in terms of total recharge to an aquifer.

Evaluation of methods

The confidence in recharge estimation improves when applying several methods (Beekman et al 1996; De Vries and Simmers 2002). Nevertheless, the different methods of estimating recharge was rated in terms of accuracy and the ratings was based on a survey of methods for groundwater recharge in arid and semi-arid regions by UNDP (2002).

The chloride mass balance method rates relatively high (Class 2 to 3: within a factor of 5 to 10 or more), as it is considered as one of the best point recharge estimation methods in terms of ease of application and costs (UNDP 2002). However in the unsaturated zone, the method again yields a very local recharge value. The input function is difficult to obtain, as a local time series of chloride in precipitation as well as dry deposition is required. Such data are still rarely available and where they are, the time series is not yet long. It will take another decade to establish such data for West Africa. Finally the area associated with the recharge rate has to be determined.

The water budget method also rates low (Class 3: within a factor of 10 or more). At best some sensitivity analyses are possible, which could be used for the estimation of recharge contrasts.

The darcian method was rated low (Class 3: within a factor of 10 or more) largely because of inaccuracy of unsaturated hydraulic conductivity.

Finally the hydrograph separation techniques are rated high (Class 1: within a factor of 2) for the humid environment but low (Class 3: within a factor of 10 or more) for the arid region. The low ratings in arid region are considered to be due to the problems that may arise when recharging to aquifers deeper than the one draining to the observed river that are considered. The base flow then will have no relation to the recharge of the deeper aquifer, the discharge of which is not contained in the measured flux. The method is also largely not applicable in the arid region.

CONCLUSIONS

The hydrogeological conceptualization with regard to recharge is confimed by the results of the recharge estimation methods.

Recharge to the aquifers underlying the study area is dominated by both direct and localized percolation from precipitation during the rainy season as well as influent flow from the River Benue. The channel recharge from the River Benue appears to be the dominant recharge process.

The unconfined nature of the upper alluvial aquifer of the underlying Bima Sandstone encourages direct recharge from precipitation into this unit.

Furthermore hydraulic connectivity between the underlying aquifers and the River Benue also encourage influent from the river.

This study has also shown that each of the different recharge estimation methods has its own individual merit sand demerits. The chloride mass balance methods and darcian method are well suited to identify the existence of recharge and enable one to determine good estimates of aerial and point recharge values. . A major limitation of the chloride mass balance is that there are other sources of chloride in the soil (eg halites) other than the chloride contained in the rainwater. On the other hand in the Darcian method the hydraulic conductivity of the soil is poorly known due to heterogeneities and it also varies with saturation.

The water budget method is bedeviled by a number of limitations which include lack of lysimeter for measuring evapotranspiration. This method however estimates all terms in a continuity equation except recharge which is calculated as the residual.

A major drawback of the hydrograph separation method is that it estimates baseflow at lower elevations in a watershed which is assumed to be equal to recharge that occurred at higher elevation. It is however one of the few integrative measurement of recharge.

The estimation of recharge from precipitation using the chloride mass balance method and the darcian approach range from 5.81mm/yr to 9.65mm/yr and from 16.38mm/yr to 104.04 mm/yr respectively. Since the transmissivity values and groundwater level contour lines used for the darcian method were obtained from standard pumping test methods the approach is considered more reliable.

However the estimation of recharge obtained using the water budget method and the hydrograph separation indicate values ranging from 52.45 mm/yr to 86.20 mm/yr and from 133.60 to 645.81 mm/yr respectively. They are relatively higher than the mean annual recharge obtained for the study area. The relatively high recharge values obtained from the hydrograph method is largely expected since it is a channel recharge.

The range of recharge rates obtained in this study largely agrees with the findings of similar studies of other researchers (Larsen et al 2002; Obakeng 2007), Beekman et al 1996, Martinelli and Hubbert 1996, Beasley 1983)

Larsen et al (2002) predicted a value of 20 to 25 mm/yr for Zambezi Basin whereas Beekman et al (1996) adopted recharge values for Botswana in the range of 10-25 mm/yr.

Martinelli and Hubbert(19996) gave values ranging from 14 to 28 mm/yr whereas Beasley(1983) adopted estimates of 125mm/yr for the Nyamandhlovu area of Zambabwe respectively.

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