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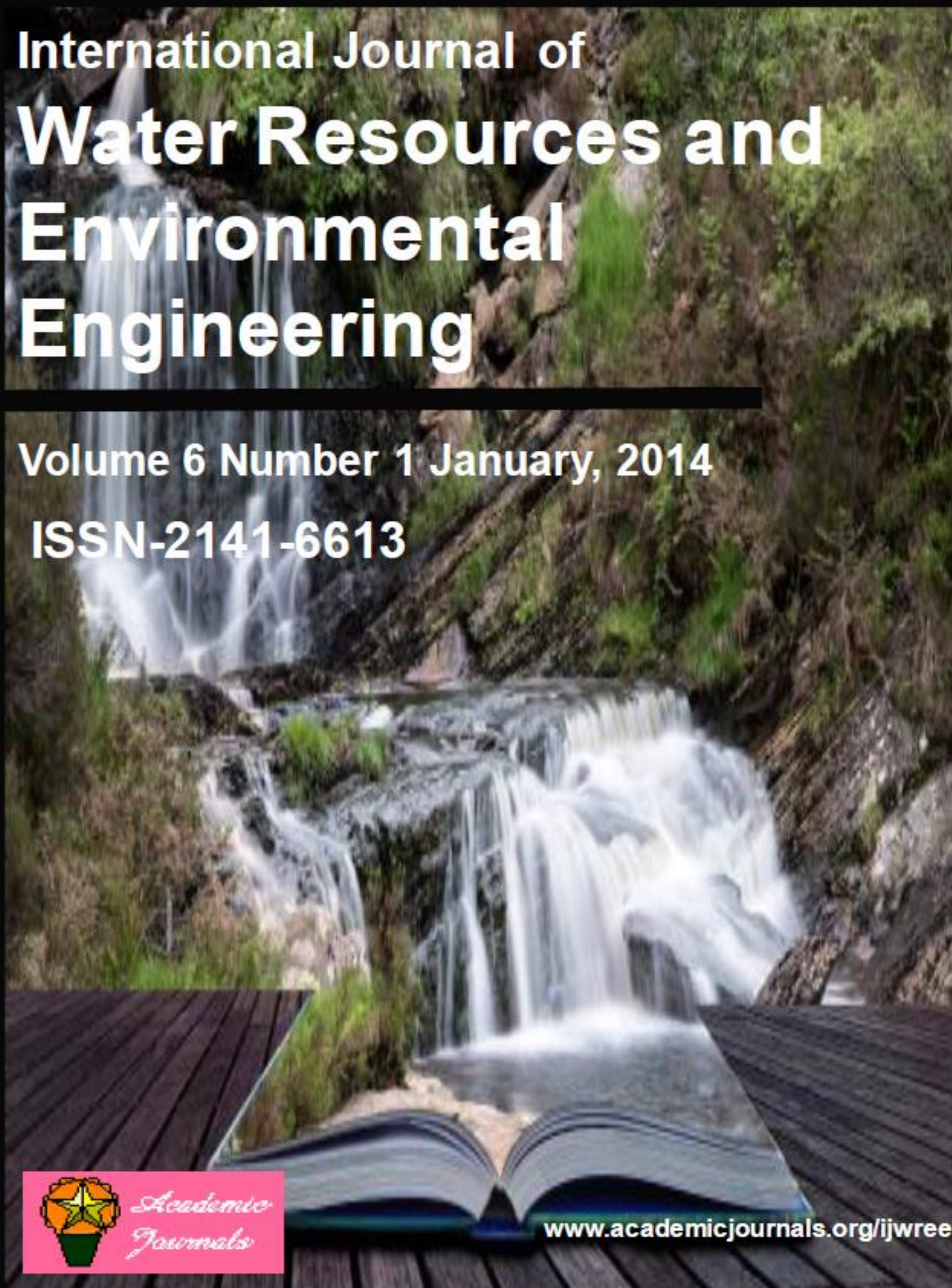

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Pitout JDD, Church DL, Gregson DB, Chow BL, McCracken M, Mulvey M, Laupland KB (2007). Molecular epidemiology of CTXM-producing Escherichia coli in the Calgary Health Region: emergence of CTX-M-15-producing isolates. Antimicrob. Agents Chemother. 51: 1281-1286.

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International Journal of Water Resources and Environmental Engineering

Full Length Research Paper

Determination of rainfall-recharge relationship in River Ona basin using soil moisture balance and water fluctuation methods

Oke, M. O., Martins, O. and Idowu, O. A.

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A quantitative evaluation of spatial and temporal distribution of groundwater recharge is a pre-requisite for the management of ground water resources system in an optimal manner. The amount of groundwater recharge depends upon the rate and duration of rainfall, as rainfall is the principal means for replenishment of moisture in the soil water system and recharge to ground water. This paper investigated the relationship between rainfalls and groundwater recharge within Ona River basin, southwest Nigeria, using soil moisture balance and water table fluctuation. Analysis of rainfall trends within the Ona River basin suggests that there is considerable high annual rainfall occurrence, with a mean of 1623.48. It must be noted that the mean annual lost due to evapotranspiration of 1361.68 mm is very high when compared to the rainfall (83.9%). The results obtained from the soil moisture balance when considering the three dominant soil types within the basin, that is, sandy loam, clay and find sand, having water capacity of root zone value of 70, 70, and 50 respectively, suggests that groundwater recharge follows a positive trend as the corresponding rainfalls. However, empirical relationships of: $y = 0.540x – 606.2$, with a coefficient of determination (r^2) value of 0.719, for sandy loam and clay; and $y = 0.552x – 621$, with a coefficient of determination (r^2) value of 0.726 for fine sand was established for the basin area. On the other hand, recharge ranging from 220.25 to 40.50 mm was computed from the water table fluctuation method.

Key words: Rainfall–recharge relationship, soil types, soil moisture balance, Ona River basin, water table fluctuation.

INTRODUCTION

The need to determine local rainfall recharge relationship through the use of locally determined empirical formula as a viable option for prediction of groundwater recharge is the main focus of this paper. Groundwater recharge is understood as the downward flow of water recharging the water table, forming an addition to the groundwater reservoir (Backundukize et al., 2011). But Kumar (1973) asserted that the quantification of the rate of natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management. The case study happens to be in the humid region where the amount of recharge in wet season is usually high because such region receive large amount of rainfall and the relative proportion of these components fluctuate according to the

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climatic conditions, geology, and geomorphology. Although in the humid tropics region, the most important mechanisms of ground recharge are considered to be indirect recharge by infiltration from floods through the beds of ephemeral streams (Marechal et al., 2008), there are several methods for estimating groundwater recharge, which are being used until date. The use of methods depends on the temporal and spatial resolutions of required estimates. Estimation of groundwater recharge is normally with errors and uncertainties (Dages et al., 2009; Sophocleous, 2004; Fitzsimons and Misstear, 2006). The best way to minimize these uncertainties is to use a combination of several methods (Scanlon et al., 2002). However, the Food and Agricultural Organization of the United Nation (FAO) recommends the use of Penman-Monteith equation as the standard for estimating reference evapotranspiration because it approximates better with lysimeters (Jabloun and Sahli; 2008; Trajkovic, 2001). Thus, in this paper, reference evapotranspiration was calculated using Penman-Monteith equation. This is useful for estimation of recharge using the soil moisture balance. A water table fluctuation method was also used to estimate groundwater recharge in the Ona River basin.

The aim of this paper is to estimate groundwater recharge within Ona River basin using both soil moisture balance and the water table fluctuation methods; and to establish an empirical relationship between recharge and rainfall. In other to carry out the main objective, the following sub-objective is considered: estimation of monthly and annual evapotranspiration using Penman-Monteith equation; estimation of annual groundwater recharge using soil moisture balance, and water table function methods; and establishment of empirical relationship between the groundwater recharge and rainfall.

Justification

Two major cities in Nigeria are located within Ona River Basins with other smaller urban settlements. They are Ibadan and Ijebu Ode. These cities are with considerable high population. For example, the population of Ibadan city is hovering around 6 million people and Ijebu Ode around 1 million. Equally, major industries are located within the drainage basin in question. However, there exist challenges in water sourcing in these cities. Although the cities are blessed with various rivers, streams and rivulet, they are often polluted and the State Government is finding it difficult in satisfying the water provision using surface water. Also, lots of buildings, both surface and underground were observed in these cities; so also asphalt overlay and pavement construction capable of preventing recharge into the water table is eminent in the study area. Whereas the majority of the people rely on groundwater for domestic, industrial and irrigational purposes, the activities in the cities is preventing recharge into the groundwater. But natural recharge by downward flows of water through the unsaturated zone is generally the most important mode of groundwater recharge. It is therefore crucial to estimate groundwater recharge for safe and efficient management of groundwater resource (Fitzsmons and Misstera, 2006).

As a result of possible excess withdrawals from groundwater reservoirs against natural replenishment which lead to regular lowering of water table, detailed study of groundwater recharge within Ona basin is essential.

Study area

River Ona is located in Southwestern part of Nigeria, an area whose boundaries are approximately latitudes 6° 34' N and 7° 38' N, and longitudes 3° 26' E and 3° 59' E (Figure 1). The basin occupies an area of 6,800 km^2 with its greater part in Ogun State before it terminates in the Lagos lagoon. The Ona basin is located west of the Oshun River basin as well as the Owa, Ibu and Omi rivers.

The climate of the Ona basin is similar to what obtained in the southwestern Nigeria. It is influenced by the movement of the inter-tropical convergence zone (the ITCZ), a quasi-stationary boundary zone which separates the sub-tropical continental air mass over the Sahara and the equatorial maritime air mass over the Atlantic Ocean. The former air mass is characterized by the dry northeasterly winds known as Harmatan, the latter by the rain-bearing southwesterly winds from the gulf of Guinea.

The ITCZ moves northwards beyond the basin at the peak of the raining season in June and July, and southward to the coast in the middle of the dry season in December and January. The change from the raining season to the dry season is rather abrupt while the onset of the rains after the dry season is gradual. Data obtained from the basin shows that February and March are the hottest months of the year. During these months, temperatures are high over the entire area. The mean daily maximum temperature for February is 31.4°C in the south and as high as 34.6°C in the north. The lowest mean minimum temperature in the north are recorded in December (17°C), that is, during the harmatan; in the southern part, the lowest mean temperature of 22.8°C was recorded in July during the raining season. In general humidity decreases northward in the basin. The lowest mean monthly humidity at 12.00 GMT is 62% in the south and 50% in the north, while the mean annual humidity varies from 75% in the south to 55% in the north. The raining season begins early in the south, which occurs in March and continues until the end of October or early November giving at least seven month of rainfall. In late July and early August, the mean wet season rainfall varies from 1020 to 1520 mm in the south

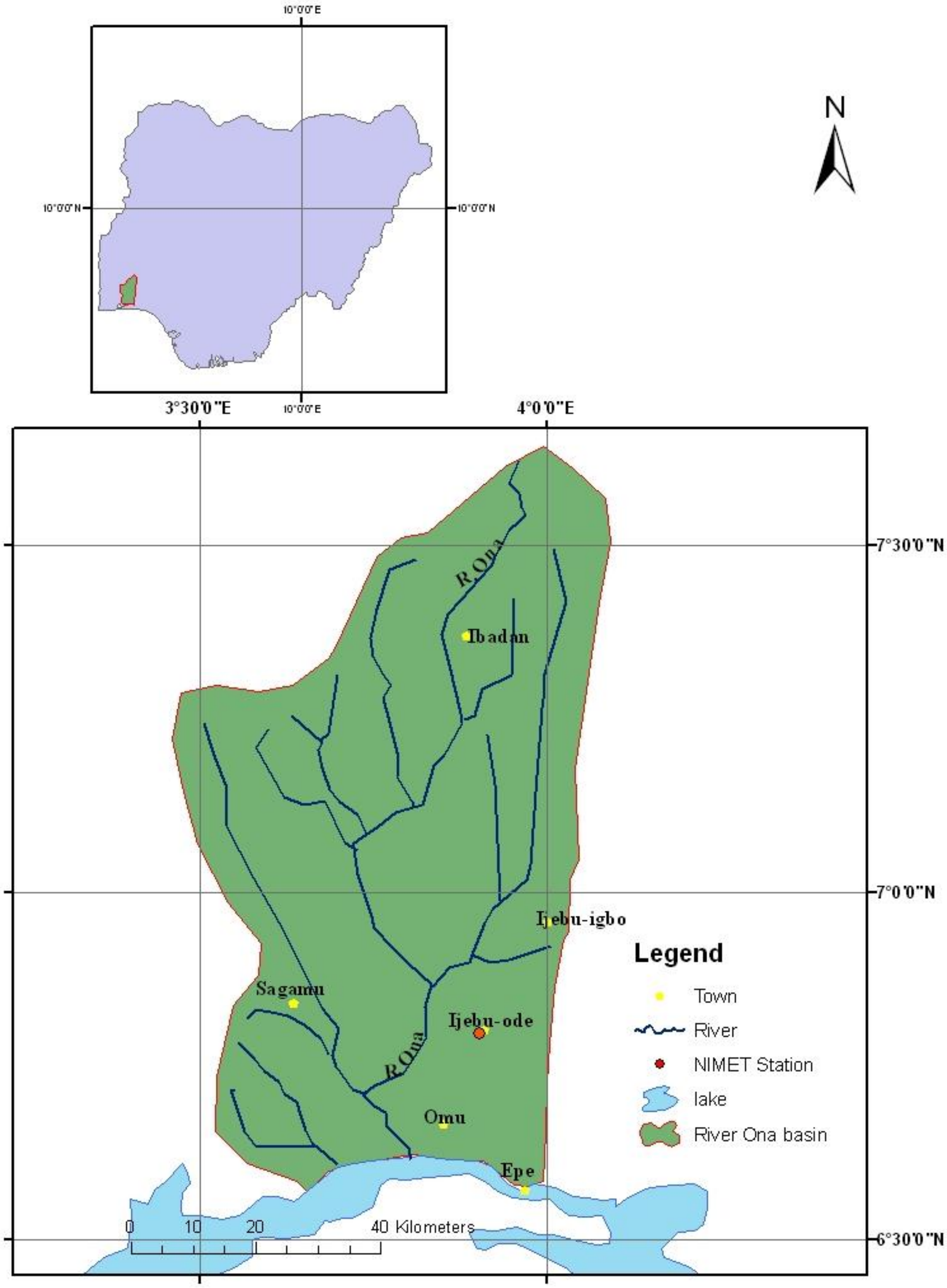

Figure 1. Map of Ona River basin.

of the basin and it is less than 1020 mm in the north. The mean dry season rainfall, on the other hand varies from 127 to 178 mm in the north and from 178 to 254 mm in the south.

Geologically, sedimentary rocks of cretaceous and latter deposit are found in the southern section of Ona River basin; the remaining section are composed of crystalline rock of the basement complex consisting folded gnesis, schist, and quartzite complexes which belong to the older intrusive series.

METHODOLOGY

The main data employed in this project are rainfall data and water

Table 1. Annual soil water budget calculation (Thornthwaite and Matter, 1957) after Backundukize et al. (2011).

	S_B = CAP	Wet season [SUR = (P-Ro) – PET > 0]		Dry season [SUR = (P-Ro) – PET < 0]
		S_B < CAP		
		(P-Ro) – PET ≤ CAP - S_B	(P-Ro) – PET > CAP - S_B	
S_B	CAP	S_B + (P-Ro) – PET	CAP	$CAP{*}e^{-APWL/CAP}$
R_N	(P-Ro) - PET	0	(P-Ro) – PET – (CAP - S_B)	0
AET	PET	PET	PET	(P-Ro) + ΔS_B
DEF	0	0	0	PET - AET

P = Precipitation (mm); Ro = runoff (mm); PET = potential evapotranspiration (mm); APWL = accumulated potential water loss (mm) [PET - (P-Ro)] accumulated for subsequent dry months; AET = actual evapotranspiration (mm); S_B = water stored in soil: $S_B = CAP{*}e^{-APWL/CAP}$; CAP = soil capacity (mm): maximum water content of soil, without gravitational water (= average rooting depth (mm) * water content at field capacity (in volume %); ΔS_B = Change in S_B; DEF = deficit (PET - AET) (mm); SUR = surplus [(P-Ro) – AET] (mm); R_N = natural groundwater recharge (SUR - ΔS_B) (mm).

levels data from wells within the river basins.

Rainfall data

Rainfall data were obtained from the Nigeria Meteorological Agency (NIMET) Ijebu-Ode, Ogun State station. The meteorological parameter obtained at this station include precipitation, maximum and minimum temperature, relative humidity, sunshine duration and cup counter anemometer. The time series of meteorological data covering 22 calendar years, that is, 1990-2012 was obtained. Time series of relative humidity, wind speed and solar radiation are only available for a period of 10 years (2000 to 2010). Missing data in time series were filled using arithmetic mean of adjacent month (Backundukize et al., 2011). Larger gaps were filled using arithmetic mean of the previous to the recent data for the period of 2000 to 2010. Time series data including solar radiation, precipitation, maximum and minimum temperature, and relative humidity are available and this enable us to compute the potential evapotranspiration using the standard Penman Monteith equation.

Water level from wells

Water level indicator was used to measure the water level daily between the hours of 4 pm for a year. The total number of wells monitored was twenty (20) scattered within the river basin.

Penman-Monteith equation

The standard Penman-Monteith method for estimating evapotranspiration can be mathematically expressed as follows (Allen et al., 1998):

$$E_0 = (\Delta/\gamma H + E_a)/\ \Delta/\gamma$$

Where Δ/γ is an empirical parameter depending on temperature. H is calculated as

$$H = (1\text{-}r)\ Rin - Ro$$

where Rin (incoming radiation) is given by:

$$(1\text{-}r)\ Rin = 0.95{*}Ra\ (0.18 + 0.55\ n/N)$$

Where Ra is the solar radiation, Ro is the outgoing radiation, r is the albedo (0.05 for water), and n/N is the ration between actual sunshine hours and possible sunshine hours. The term n/N can also be estimated using the cloudiness, e.g., a cloudiness of 60% gives an *n/N* of 40% (=100 - 60). R_0 is calculated by:

$$R_0 = \sigma\ T_a 4\ (0.56 - 0.09\sqrt{ed})(0.10+0.90\ n/N)$$

Where ed is the actual vapor pressure and σT_a^4 is the theoretical black body radiation.

Ea is calculated by:

$$Ea = 0.35(0.5 + u^2/100)\ (ea - ed)$$

Where u^2 is the wind speed in m/s and ea is the saturation vapor pressure. Remember that the relative humidity RH = ed/ea.

Soil moisture balance method

Each parameter of soil moisture balance are computed separately in an excel sheet (Table 1). In these method the concepts of water balance of the unsaturated zone (Thornwaite and Matter, 1957) is applied. It consists of keeping track of the accumulated potential water loss (APWL) and the amount of water in the soil (Sb). Calculation to determine Sb and APWL are performed for each month using monthly precipitation (p) and potential evapotranspiration (PET) (Table 3).

The monthly climatic data available were first rearranged into hydrologic years, a hydrologic year in south-west Nigeria starts with April, which is the beginning of the rainy season, and terminates at the end of March, that is, the end of the dry season.

Actual evapotranspiration (AET): (1) In wet months, when there is enough rain, that is, when P-Ro > PET, the AET is at its maximum value, which is equal to the PET (PET = AET).

(2) In dry months, when there is not enough rain, that is, when P-Ro < PET,

$$AET = PET + P\text{-}Ro$$

Soil capacity (CAP): The soil water-holding capacity of the root zone is typically expressed in mm and can be obtained by multiplying the water content at field capacity by the effective depth of the root-zone. Hence assuming a uniform water-holding capacity of 30% over the entire the root-zone and a rooting depth of 0.25 m for shallow rooted crops, the water capacity of the root zone becomes 75 mm (Table 2).

Table 2. Showing groundwater recharges estimation using soil moisture balance method.

Year	Month	P	Ro	P-Ro	PET	(P-Ro) - PET	PET - (P-Ro)	APWL	S_B	ΔS_B	AET	DEF	SUR	R_N	Annual R_N
1996	April	183.1	43.28	139.82	115.95	23.87	-23.87	0	75	-75	115.95	0.00	23.87	-51.13	
	May	87	20.57	66.43	122.02	-55.59	55.59	55.59	35.74	39.259	105.69	16.33	-39.26	0.00	
	June	360.4	85.20	275.20	127.14	148.06	-148.06	0	75	-39.26	127.14	0.00	148.06	108.80	
	July	391	92.43	298.57	125.75	172.82	-172.82	0	75	0	125.75	0.00	172.82	172.82	
	August	204.2	48.27	155.93	132.92	23.01	-23.01	0	75	0	132.92	0.00	23.01	23.01	
	September	119.5	28.25	91.25	129.4	-38.15	38.15	38.15	45.1	29.903	121.15	8.25	-29.90	0.00	
	October	338	79.90	258.10	105.44	152.66	-152.66	0	75	-29.9	105.44	0.00	152.66	122.75	
	November	1.4	0.33	1.07	86.2	-85.13	85.13	85.13	24.11	50.895	51.96	34.24	-50.89	0.00	
	December	11.6	2.74	8.86	104.5	-95.64	95.64	180.77	6.734	17.371	26.23	78.27	-17.37	0.00	
1997	January	0	0.00	0.00	131.92	-131.92	131.92	227.56	3.609	3.1254	3.13	128.79	-3.13	0.00	
	February	0	0.00	0.00	76.16	-76.16	76.16	208.08	4.679	-1.07	-1.07	77.23	1.07	0.00	
	March	272.4	64.40	208.00	109.94	98.06	-98.06	0	75	-70.32	109.94	0.00	98.06	27.74	
Total		1968.6													403.99

Table 3. Annual rainfall of the 22 years (1990 to 2012).

Year	Annual rainfall
1990/1991	1767.40
1991/1992	1601.80
1992/1993	1686.60
1993/1994	1526.30
1994/1995	1414.90
1995/1996	1908.50
1996/1997	1968.60
1997/1998	1510.08
1998/1999	1337.38
1999/2000	1756.90
2000/2001	1774.55
2001/2002	1349.90
2002/2003	1449.84
2003/2004	1616.70
2004/2005	1865.60
2005/2006	1610.90
2006/2007	1585.25
2007/2008	1572.57
2008/2009	1576.69
2009/2010	1650.50
2010/2011	1599.18
2011/2012	1586.32

Runoff (R_0): The value of runoff is precipitation multiplied by runoff coefficient (R_c), where (R_c) is equal 0.2364 (Ayoade, 1975).

$$R_0 = P * R_c$$

Change in soil moisture storage (ΔS_b): This is the difference between the current soil moisture and the previous one.

Deficit (D): The deficit is the difference between the actual evpotranspiration and potential evapotranspiration.

$$D = PET - AET$$

Surplus (S): Surplus (SUR) is computed as the difference between P-Ro and the actual evapotranspiration (AET).

Groundwater recharge (RN): Groundwater recharge occurs when there is a surplus and the soil moisture is at its field capacity. It is calculated as the remaining surplus after the soil moisture has been brought to field capacity.

$$Rn = \Delta s + SUR$$

Water-table fluctuation method

Recharge is calculated as:

$$R(tj) = Sy * \Delta H(tj)$$

Where R(tj) (cm) is recharge occurring between times t_0 and tj, Sy is specific yield (dimensionless), and ΔH(tj) is the peak water-table rise attributed to the recharge period (cm).

Key assumption and critical issues inherent in water table fluctuation that have greatly being on its successful application are: the observed well hydrograph depicts only natural water-table fluctuations caused by ground-water recharge and discharge; Sy is assumed in relation to the geologic properties of the area, and that is constant over the interval of the water-table fluctuation. For this study Sy was assumed to be 1.5%, that is for gneiss the pre-recharge water-level can be extrapolated to determine ΔH (tj) Rasmussen and Andreasen, 1959; while ΔH was computed with the graphical approach as the difference between the peak water level during a recharge even and the predicted level to which water levels would have declined to recharge event had not occurred. ΔH (tj) is estimated as the difference between the peak of a water-level rise and the value of the extrapolated antecedent recession curve at the time of the peak. This recession curve is the trace that the well hydrograph would have followed had there been any precipitation (Figure 2).

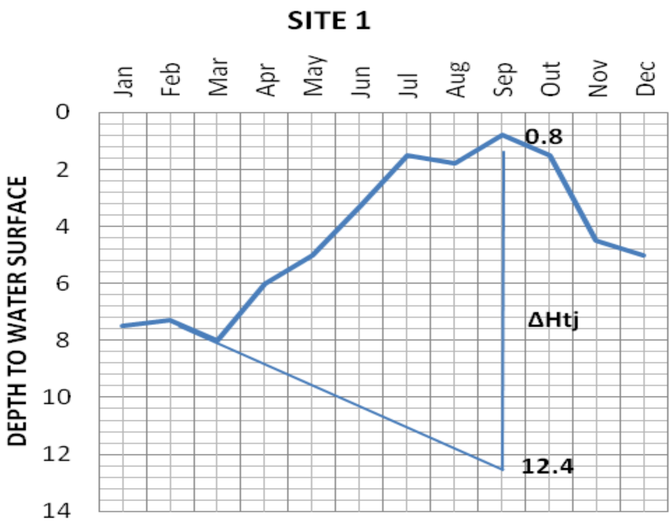

Figure 2. Depth to water surface chart.

Table 4. Descriptive statistics of the annual rainfall.

Years	Range	Minimum	Maximum	Mean	Standard deviation
22	631.22	1337.38	1968.6	1623.48	167.13

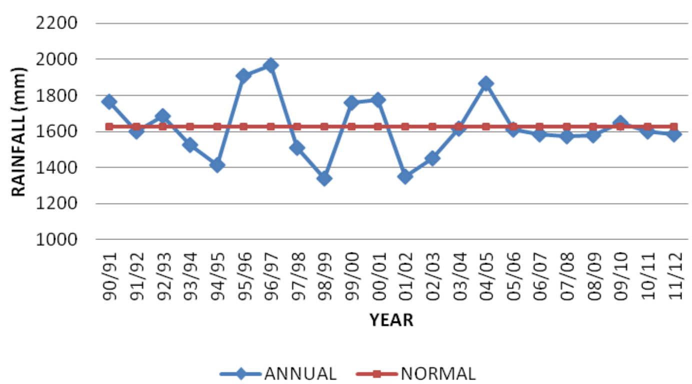

Figure 3. Trend of variation of annual rainfall for 22 years (90/91-11/12).

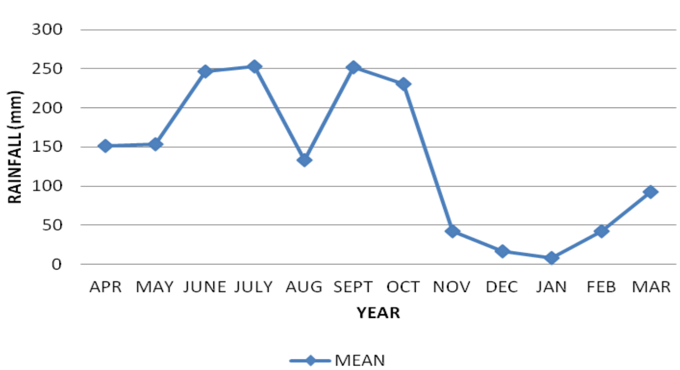

Figure 4. Trend of variation in mean monthly rainfall within the 22 years of study.

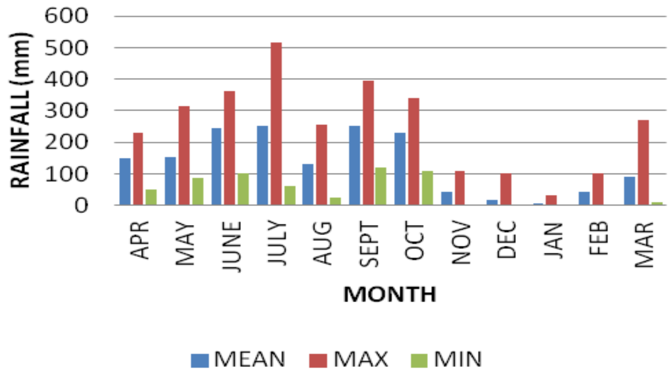

Figure 5. The mean, maximum and minimum monthly rainfall.

RESULTS AND DISCUSSION

This part encompasses the descriptive analysis of rainfall data obtained from Nigeria Meteorological Station (NIMET), the computed potential evapotranspiration and the analysis of the ground water recharge results obtained from the two methods, that is, soil moisture results balance for the duration of 22 years of the study and water table fluctuation analysis of 20 wells for the 2011.

Descriptive analysis of rainfall

Annual rainfall

The annual rainfall occurrence of the Ona River basin for the years of study (1990 to 2012) is presented in Tables 3 and 4. It can be observed that a maximum annual rainfall of 1968.6 mm was recorded for the hydrologic year 1996/1997, a minimum value of 1337.38 mm for 1998/1999. Also, a mean value of 1625.9 mm was observed for the 22 years of study according to Table 3 while a standard deviation of 167.12 mm shows that there is high variability in rainfall within the 22 years of study; this also indicate that the rainfall data deviate largely from their average value of 1625.9 mm.

The trend of variation of annual rainfall can also be observed from the line graph in Figure 3, however, there are 14 dry years (that is, years below normal rainfall of 1625.93 mm), while the remaining 8 were wet years.

Monthly rainfall

In Figure 4, the average monthly variation of rainfall was analyzed. The monthly rainfall for the Ona River basin can therefore be categorized into three seasons; which includes: two wet seasons, ranging from April to October; and a dry season from November to March; the mid break, that is, August break can also be observed.

However, it can be observed from the column chat in Figure 5 that the maximum rainfall ranges from 517.6 to

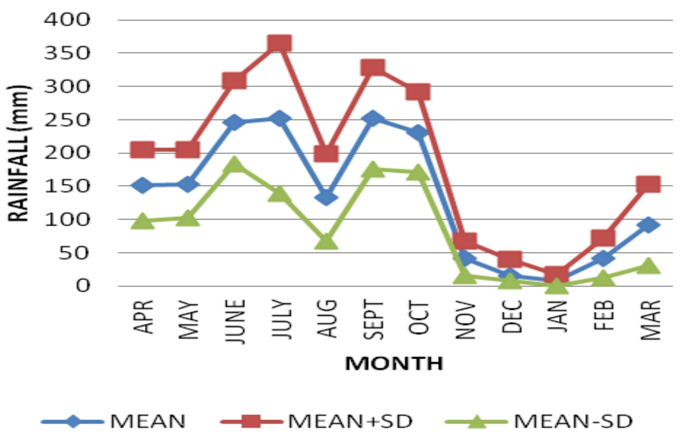

Figure 6. Variations in monthly rainfall pattern.

Table 5. Annual potential evapotranspiration computed from Penman equation.

Year	PET
1990/1991	1379.45
1991/1992	1390.44
1992/1993	1335.51
1993/1994	1353.5
1994/1995	1312.65
1995/1996	1393.01
1996/1997	1367.34
1997/1998	1376.76
1998/1999	1363.42
1999/2000	1332.19
2000/2001	1327.44
2001/2002	1334.61
2002/2003	1315.03
2003/2004	1353.09
2004/2005	1364.66
2005/2006	1434.12
2006/2007	1306.76
2007/2008	1331.8
2008/2009	1410.78
2009/2010	1415.68
2010/2011	1363.72
2011/2012	1395.04

Table 6. Descriptive statistics of annual PET.

Years	Range	Minimum	Maximum	Mean	Standard deviation
22	127.36	1306.76	1434.12	1361.68	35.31

31.8 mm, occurring in the month of July and January respectively. It can also be seen that the mean or normal monthly rainfall ranges from 252.61 mm in the month of July to 8.06 mm occurring in January. While the minimum

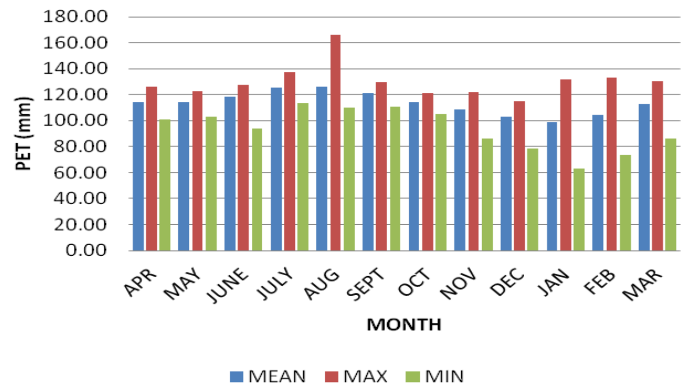

Figure 7. Monthly pattern of PET for the 22 years of study.

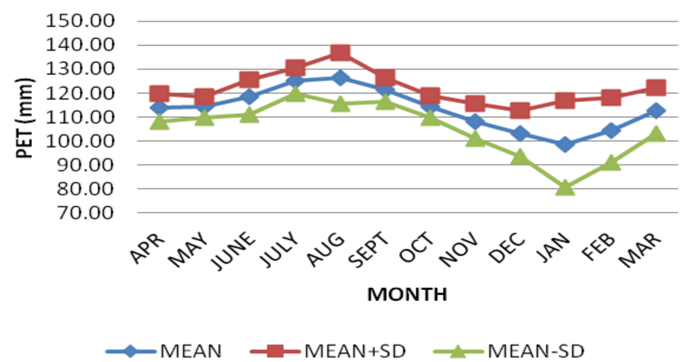

Figure 8. Seasonal PET patterns.

monthly rainfall range from 119.5 mm in September to 0 mm occurring from November to March within the 22 years of study.

It can be observed in the Figure 6 below that rainfall variation from normal occurring within each month for the 22 years of study reduces as we move into the dry season.

Potential evapotranspiration

It can be observed from Tables 5 and 6 that the maximum annual potential evapotranspiration falls in the hydrologic year 2005/2006 and with the value of 1434.12 mm, while minimum value of 1306.76 mm was observed in the hydrologic year 2006/2007; the standard deviation of 35.31 mm indicates a little deviation of annual PET from the mean value of 1361.68 mm per year. However, the mean of 1361.68 mm compared to the mean annual rainfall of 1623.48 mm shows that about 83.9% of the annual rainfall is lost to both evaporation and transpiration from plants.

It can be observed in the column chat in Figure 7 that August has the highest maximum PET with a value of 166.42 mm, while January records the lowest minimum PET with a value of 63.25 mm. In addition, it can be observed in the Figure 8 that there are high variations in

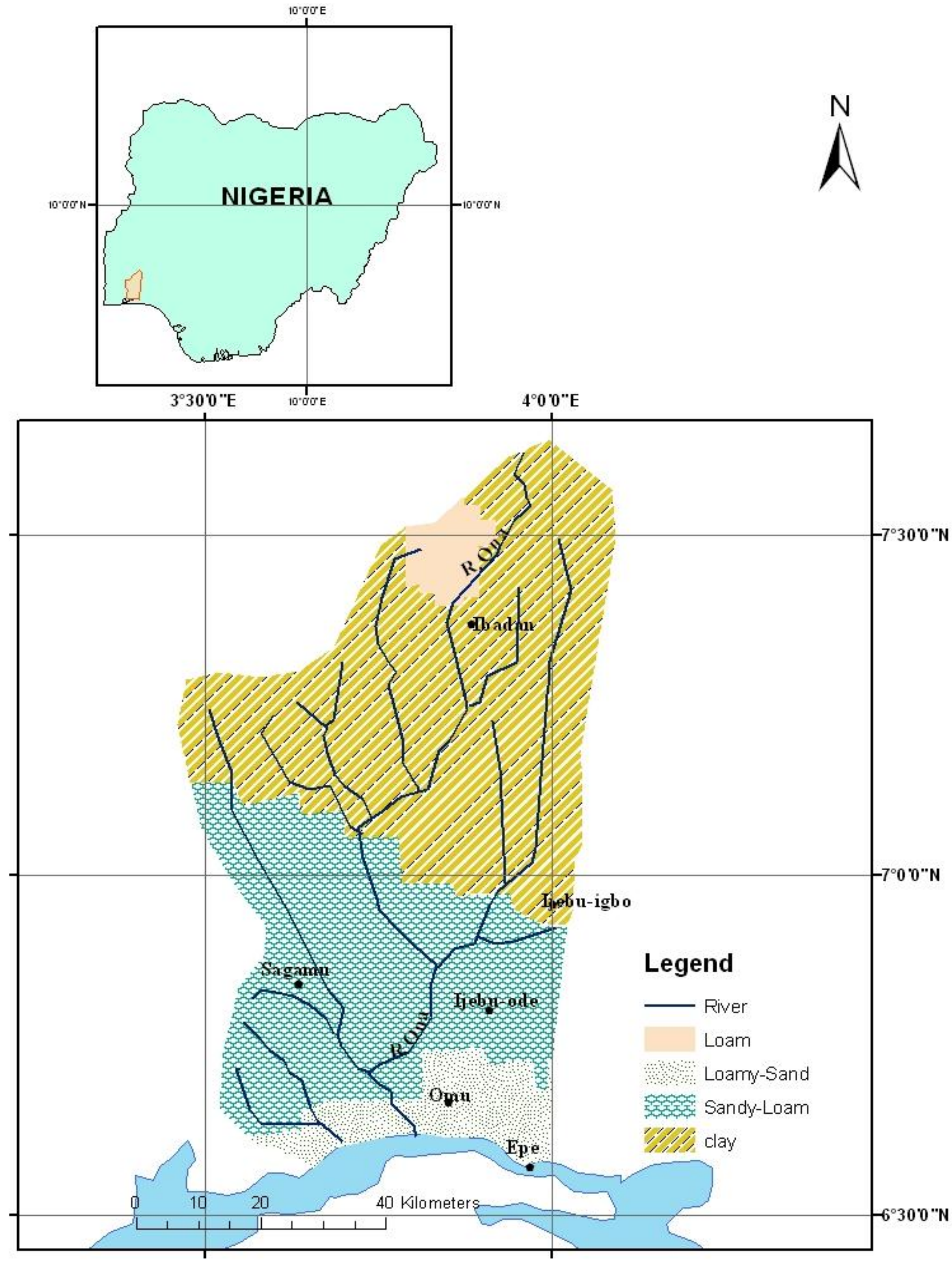

Figure 9. Soil map of the Ona River basin.

the dry months as compared to the wet months. The months with high deviation include August, along with November to March.

Analysis of groundwater recharge results obtained from soil moisture balance method

The soil dominant soil types within the Ona basin was considered for the estimation of groundwater recharge. The soils considered are clay, sandy load and fine sand (Figure 9).

From the Table 7, it can be seen that there are slight variation between recharge obtained for clay and sandy loam soils, and that obtained for fine sand.

For clay and sandy loam, the ground water recharge ranges from 509.01 to 140.82 mm, with a percentage recharge which also ranges from 24.33 to 9.20% of rainfall within the years of study.

On the other hand, the ground recharge obtained for fine sand ranges from 478.99 to 133.35 mm, with a percentage recharge, that ranges from 25.86 to 9.71% of rainfall.

From Table 8, the mean annual recharge of 273.75 mm

Table 7. Result obtained for different soils.

Year	Rainfall	Recharge			
		CAP=75		CAP=50	
		Clay and Sandy loam	%	Fine sand	%
1990/1991	1767.40	426.20	24.11	410.32	23.22
1991/1992	1601.80	229.42	14.32	229.86	14.35
1992/1993	1686.60	267.26	15.85	280.24	16.62
1993/1994	1526.30	195.22	12.79	207.70	13.61
1994/1995	1414.90	271.49	19.19	277.07	19.58
1995/1996	1908.50	338.28	17.72	341.75	17.91
1996/1997	1968.60	478.99	24.33	509.01	25.86
1997/1998	1510.08	213.53	14.14	213.53	14.14
1998/1999	1337.38	140.87	10.53	153.10	11.45
1999/2000	1756.90	422.81	24.07	426.75	24.29
2000/2001	1774.55	431.61	24.32	431.61	24.32
2001/2002	1349.90	156.84	11.62	156.84	11.62
2002/2003	1449.84	133.35	9.20	140.82	9.71
2003/2004	1616.70	266.43	16.48	280.33	17.34
2004/2005	1865.60	443.20	23.76	460.69	24.69
2005/2006	1610.90	245.13	15.22	252.06	15.65
2006/2007	1585.25	274.07	17.29	275.06	17.35
2007/2008	1572.57	213.53	13.58	213.53	13.58
2008/2009	1576.69	155.08	9.84	155.12	9.84
2009/2010	1650.50	227.83	13.80	230.48	13.96
2010/2011	1599.18	183.22	11.46	183.22	11.46
2011/2012	1586.32	243.41	15.34	245.50	15.48

CAP= (water capacity of root zone), % = (recharge/rainfall)*100.

Table 8. Descriptive statistics of the recharge results obtained.

Years	Soil type	SB	Maximum	Minimum	Mean	SD
22	Clay	75	478.99	133.35	273.75	111.78
22	Sandy loam	75	478.99	133.35	273.75	111.78
22	Fine sand	50	509.01	140.82	280.18	115.27

is computed for clay and sandy soil samples; while a mean of 280.18 mm is computed for fine sand soil sample, this shows a slight variation in results obtained (Figure 10). Consequently, the standard variation of 111.78 and 115.27 mm proves that the ground water recharge obtained for the 22 years of study deviate largely from their means.

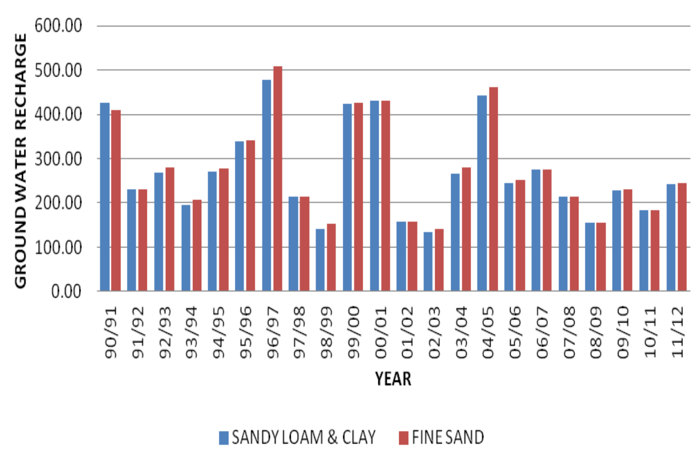

Figure 10. Column chat showing trend of variations in the computed recharge.

Rainfalls-recharge relationships

Figure 11 show that the annual ground water recharge computed follows the same trend with the corresponding rainfall. It can be observed from Table 9 that the computed ground water recharge for the three types of soil has high positive correlations of 0.848 and 0.852 with the rainfall, the value 0.00 shows that these correlations

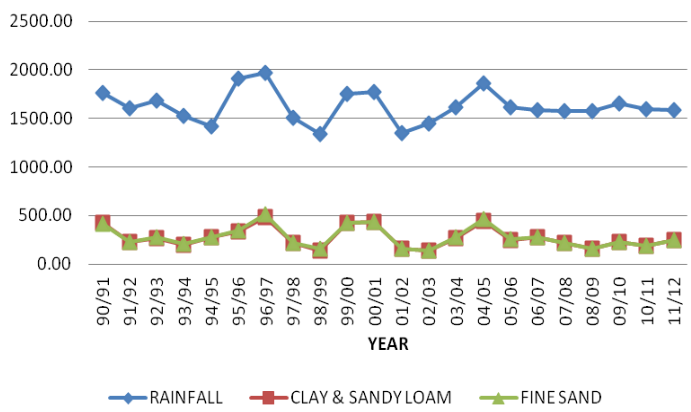

Figure 11. Trend of variation of annual rainfall and recharge.

Table 9. Correlations between recharge and rainfall.

Recharge correlation		Rainfall
Recharge clay and sandy loam	Pearson correlation	0.848**
	Sig. (2-tailed)	0.000
	N	22
Recharge fine sand	Pearson correlation	0.852**
	Sig. (2-tailed)	0.000
	N	22

**: Correlation is significant at the 0.01 level (2-tailed).

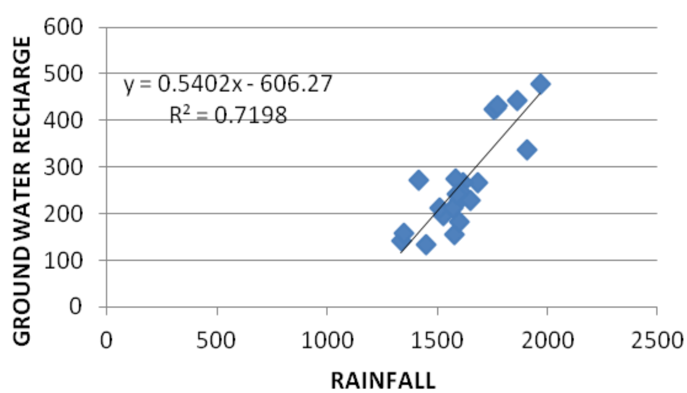

Figure 12. Regression analysis of recharge in clay and sandy loam and rainfall.

are significant at a level of p = 0.01; hence this relationship is not by chance.

The Figure 12 shows the regression analysis between ground water recharge in clay and sandy loam, and rainfall. The relationship shows a positive relationship as confirmed in the correlation analysis: y = 0.540, x – 606.2, and a coefficient of determination (r^2) value of 0.719. However, the regression analysis between recharge computed for fine sand soil and rainfall also shows a

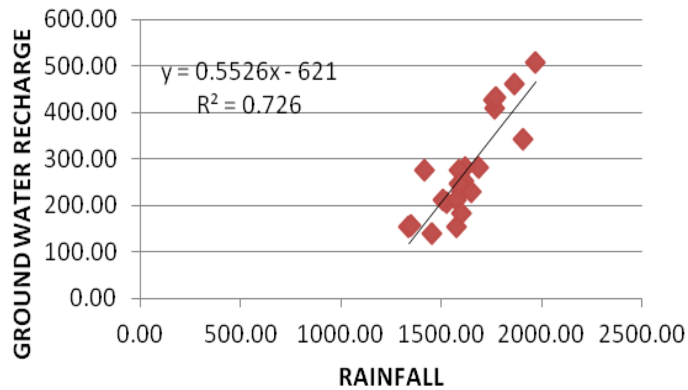

Figure 13. Regression analysis of recharge in sandy loam and rainfall.

Table 10. Ground water recharge computed.

Rainfall (mm)	SY	Range of ΔH (M)	Rn (cm)	%
1579.1	0.015	3.0	4.5	2.8
	0.015	13.5	20.25	12.8

Sy= specific yield, ΔH=peak water table rise, Rn= recharge, %= (Rn/Rainfall)*100.

positive relationship, that is, y = 0.552 x – 621, and a coefficient of determination (r^2) value of 0.726.

The r^2 values of 0.719 and 0.726 shows that there is a high relationship between observed values of rainfall and predicted values of groundwater recharge when the two equations are used (Figure 13).

Analysis of groundwater recharge result obtained from water table functuation method

It was assumed that the geologic material for the area is gneiss with specific yield (sy) of 1.5%. By multiplying the specific yield with the change in peak water rise, a recharge ranging from 4.5 to 20.25 cm (Table 10) was computed. In addition, the recharge percentage of rainfall was found to be between 2.8 and 12.8%.

Comparison of the two results

The percentage of rainfall that eventually becomes groundwater recharge in the Ona River basin ranges from 24.44 to 9.20% for the soil moisture balance method, and 19.4 to 1.9% for the water table fluctuation method. This shows that it can be concluded that the total percentage of rainfall that becomes groundwater recharge in the Ona River basin ranges from 2.8 to 24.44% (Table 11).

Table 11. Annual groundwater recharge computed from the two methods.

Method	No. of years	Range RN (mm)	Range %Rn
SMBM	22	478.99 - 133.35	24.44 - 9.20
WTFM	1	220.25 - 40.5	12.8 - 2.8

SMBM = Soil moisture balance method, WTFM =Water table fluctuation method, Rn = Recharge.

Conclusion

A quantitative evaluation of spatial and temporal distribution of groundwater recharge is a pre-requisite for the management of ground water resources system in an optimal manner. The amount of groundwater recharge depends upon the rate and duration of rainfall, as rainfall is the principal means for replenishment of moisture in the soil water system and recharge to ground water. This paper has investigated the relationship between rainfalls and groundwater recharge within Ona River basin southwest Nigeria, using two methods. The soil moisture balance and the water table fluctuation.

Analysis of rainfall trends within the Ona River basin suggests that there is considerable high annual rainfall occurrence, with a mean of 1623.48. Only eight years of the 22 years of study can be considered wet years, as the rainfall values of the eight years exceed the mean. It must be noted that the mean annual loss due to evapotranspiration of 1361.68 mm is very high when compared to the rainfall (83.9%).

The results obtained from the soil moisture balance when considering the three dominant soil types within the basin, that is, sandy loam, clay and find sand, having water capacity of root zone value of 70, 70, and 50 respectively, suggests that groundwater recharge follows a positive trend as the corresponding rainfalls. However, empirical relationships of: $y = 0.540x - 606.2$, with a coefficient of determination (r^2) value of 0.719, for sandy loam and clay; and $y = 0.552x - 621$, with a coefficient of determination (r^2) value of 0.726 for fine sand was established for the basin area. On the other hand, recharge ranging from 220.25 to 40.5 mm was computed from the water table fluctuation method.

The general conclusions drawn from this study are groundwater recharge within the Ona River basin follows a positive trend as rainfall, and that this recharge ranges from 2.8 to 24.44% of rainfall.

RECOMMENDATIONS

In other to carry out this study successfully, data from NIMET synoptic stations were obtained. As a result, the study was limited to little data recorded at this station only; therefore, it is recommended that more synoptic stations should be installed across the basin area in other to have a consistent data which would result in a more accurate study of groundwater recharge.

River basin development authorities such as the Ogun-Oshun River Basin Development Authority (OORBDA) should carry out comprehensive studies concerning the groundwater resources of the Ona River basin, as well as provision of sophisticated equipments that will aid groundwater studies. However, to improve the reliability of ground water recharge estimates, the authority must monitor aquifer behavior on a continuous or periodic basis to ensure that adequate data are available.

A 1998 international recharge estimation workshop concluded that no single comprehensive estimation technique can yet be identified from the spectrum of method available; all are reported to give suspect result. Hence, groundwater recharge estimation must be treated as an iterative process that allows progressive collection of aquifer-response data and resources evaluation. This can only be achieved by professionals in the field of ground water hydrology; therefore, the employment of professionals must be addressed.

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Full Length Research Paper

Hydro and solar-pond-chimney power scheme for Qattara Depression, Egypt

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This study summarizes previous proposals and studies concerning Qattara power projects and gives some details about a new concept, which aims to produce hydropower like all previous proposals, and also extra electric power and fresh water via a site specific solar-pond-chimney system. Sea water from the Mediterranean Sea and re-used water from the end of Rosetta branch would feed an artificial lake in the Qattara Depression, where salt gradient heating phenomena would be exploited. The proposed scheme entails two inlet water ways (for sea water and re-used water) and an outlet water way for the produced fresh water. Several experimental studies in a hydraulic lab will be required to clarify technical and economic feasibility aspects.

Key words: Desalination, hydraulics, hydro power, Qattara Depression, reused water, solar ponds.

INTRODUCTION

The utilization of Qattara Depression for the purpose of hydropower generation was first investigated (Ball, 1933) by Professor Penk in 1912, and later by Dr Ball in 1927. The depression is located in the north-western part of Egypt and is the world's fifth deepest natural depression (Figure 1). The depression has, at sea level, a length of about 300 km, a maximum width of 145 km, and an area of 19,500 km^2. The northern edge of the embankment is bounded by a hilly ridge with an elevation of about 200 m above sea level, with the shortest distance from the Mediterranean Sea of about 56 km. Among the development schemes studied by scientists and engineers, the following ones are singled out: Ball (1933), Bassler (De Martino, 1973), Gohar (De Martino, 1973), and lately in 2010 MIK Technology (http://miktechnology.com/powerfromseawater.html, 1973; Kelada, 2010). All these proposed schemes and studies focused on hydropower production, but the scheme proposed by Kelada (2010) exploits the physical phenomenon of osmosis and allows production of both hydropower and desalinated water.

The current study reviews previous schemes and proposes a new concept which entails storing both sea water and drainage water to produce hydropower, and exploiting salt gradient heating phenomena in solar ponds (http://www.teriin.org/; http://www.teriin.org/) to produce both fresh water and extra electric power.

REVIEW OF PREVIOUS SCHEMES AND STUDIES

Qattara Depression project

As indicated by many scientists (De Martino, 1973; Kelada, 2010), the Qattara hydropower project has a primary objective to generate a sustainable source of energy corresponding to 315 MW and a secondary goal to provide an elevated storage of 45 million cubic meters to manage peak power demands.

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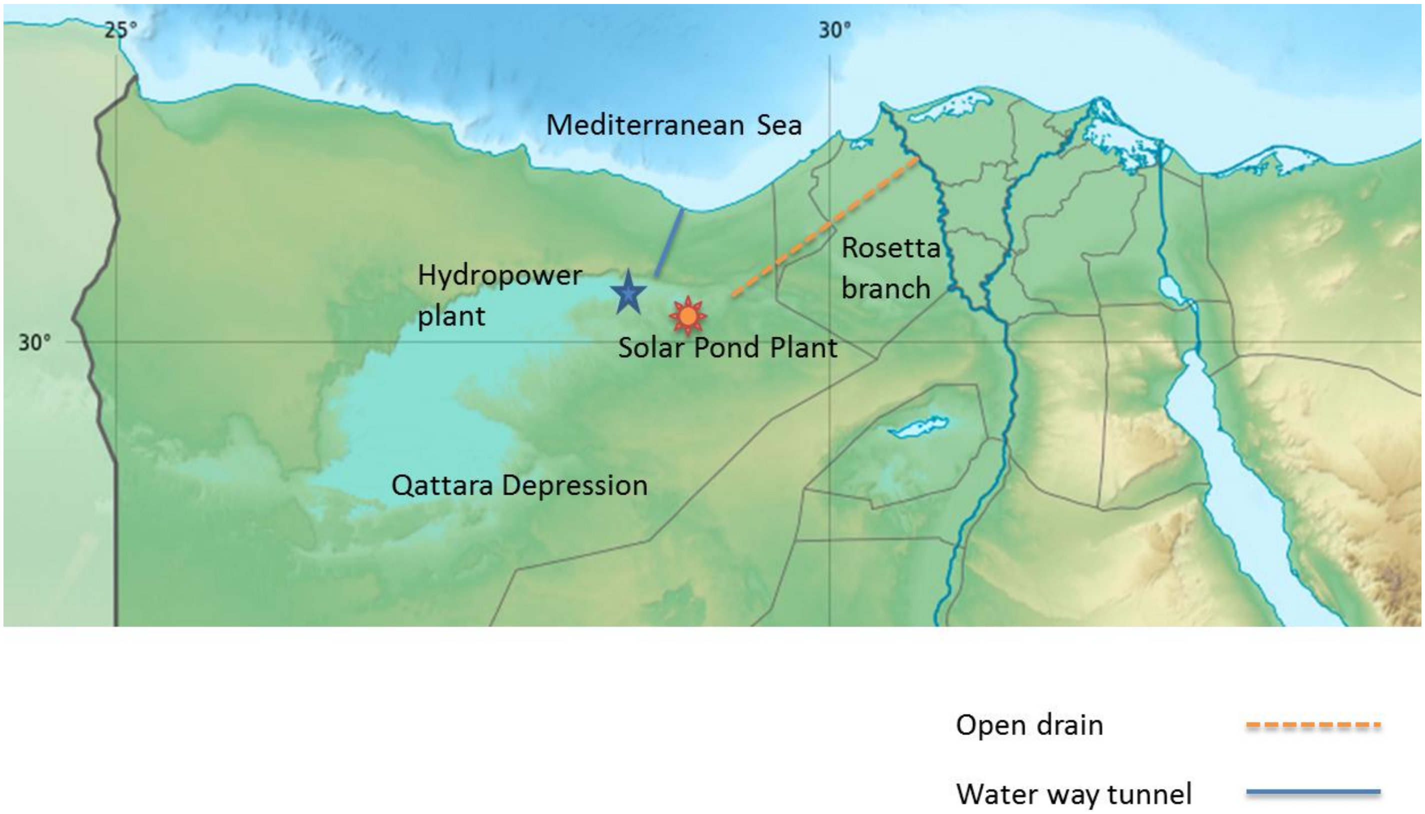

Figure 5. Aerial view for the settings of the hydro and solar-pond power plants, and the proposed water ways.

Ball's researches

Based on geological investigations, Dr. Ball (1933) studied the possibility of utilizing the Qattara Depression for hydropower generation through the formation of artificial lakes at final levels of 50, 60, or 70 m below sea level. The corresponding surface areas for the three alternatives were 13500, 12100 and 8600 km^2. Moreover, he indicated the most convenient water flow route related to each alternative. Ball considered variables such as rainfall, evaporation and seepage inflow. With respect to the rainfall, and taking into consideration the rainfall that would not precipitate directly into the lake but would find its way into the depression, Ball assumed a daily average rainfall depth of 0.15, 0.16, and 0.18 mm for the three lakes' water levels alternatives of 50, 60 or 70 m below sea level. Regarding the evaporation, and based on similar research studies at other nearby locations, he concluded that the average evaporation rates from the surfaces would be 4.6, 4.3 and 4.0 mm/day, for the same alternatives respectively. Regarding the volume of seepage inflow to the lake, Ball estimated that the daily volume would be equivalent to depths of 0.21, 0.24 and 0.33 mm, for the three alternatives, respectively. Balancing the difference between the evaporation volume and the sum of both rainfall and seepage inflow volumes, he estimated the daily volumes of feed sea water to keep the lakes' surfaces balanced at the specified levels. He could thus conclude that the daily volumes of sea water entering the depression should correspond to flow rates of 656, 546 and 348 m^3/s, respectively (Kelada, 2010).

Ball also studied the progressive increase of salinity in the artificial lakes and calculated that the maximum concentration would be reached after 160, 120, and 100 years for the three alternatives respectively (Ball, 1933). Finally, he showed that the most convenient solutions were those related to lakes' surfaces at 50 and 60 m below sea level. He suggested construction of an open channel for the first 20 km, and three tunnels of 11 m diameter to supply the required sea water. The resulting power potential would be about 175 MW for a lake surface level of -50 m. Moreover, he anticipated the possibility of using a power surplus during periods of low demands to pump part of the inflow water into a high-level reservoir and thus obtain a total head of 200 m for hydropower generation to meet peak-load requirements.

Bassler's scheme

The question of developing Qattara project was raised again at the end of the 1950s. Then Siemens proposed a scheme involving the creation of an artificial balancing

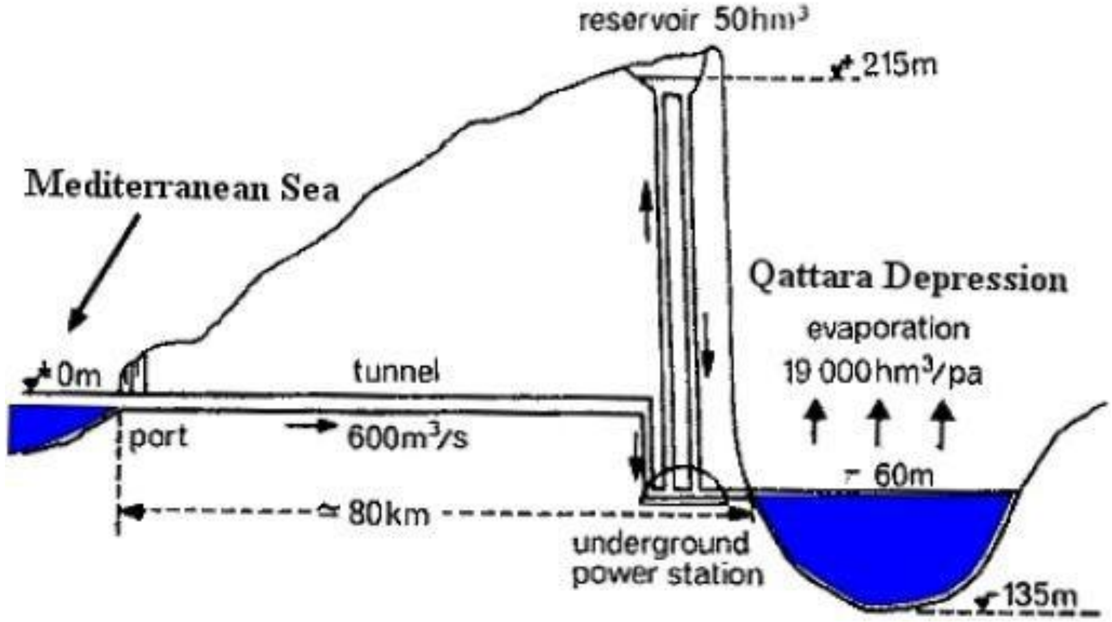

Figure 2. Cross section showing the outline of the hydropower scheme proposed by Professor Bassler.

reservoir on the edge of the depression, continuously fed by two conduits from the Mediterranean. The estimated power potential was about 100 MW, and the turbines were to function only for 6 h (De Martino, 1973). In 1964, Professor Bassler was appointed by the West German Ministry of Economics to study in greater details possible development schemes. Following geological and engineering researches, Bassler presented the scheme shown in Figure 2. The research, which was carried out in 1964 to 1965, aimed at investigating the technical and economic feasibility of a power plant in the Qattara Depression. According to Bassler (De Martino, 1973), it was also anticipated that the Qattara artificial lake would have to be fed by a sea water flow of 600 m^3/s to compensate for the evaporation volume. Similar to Ball's scheme, the construction of three tunnels having a length of 80 km would be required to feed a hydropower plant as shown in Figure 2. During the hours of low demands, the energy produced could be used to pump water into a high-level natural reservoir having a capacity of about 50 million cubic meters. Such a basin is located at the edge of the depression at an elevation of 215 m above sea level.

To summarize, this scheme combines a low head with a high head system, can produce peak power up to 450 MW, and is adaptable to a varying demand pattern.

Gohar's scheme

Gohar suggested an alternative scheme in which sea water is supplied from the Mediterranean Sea via one specific channel (route) located to the east of the routes suggested by Dr. Ball (De Martino, 1973). His point of view is that this route has more advantages than the routes suggested by Ball. He also indicated that the highest point of land between the sea and the depression was located only 11 km from the Mediterranean coast, and he suggested that sea water could be pumped up to a convenient location and then made to flow in an elevated open channel. According to Gohar (De Martino, 1973), his design could result in a simpler and more economic scheme than Ball's and Bassler's schemes which have three tunnels. At the end of the channel, the water could be carried out to supply an underground power station at a suitable location midway from the depression. However, water would need to flow in a tunnel to reach the depression. He suggested that the best scheme among various possibilities was the formation of the lake at a level of -75 m, along with a channel at a level of +80 m discharging 266 m^3/s.

The continuous net power production for his scheme would be about 100 MW, while the maximum power capacity would be 345 MW.

MIK technology scheme

The MIK Technology (http://miktechnology.com/power fromseawater.html) concept for power generation is based on the osmosis phenomenon, targeting world saline dry natural basins and salt lakes such as the Qattara Depression-Egypt, and Great Salt Lake-U.S.A. Simply, osmotic power can be generated by running salt water solutions of differing concentrations along the two sides of a suitable semi-permeable membrane (Kelada, 2010). Water tends to permeate spontaneously into the more concentrated solution and this water flow can be used to drive a power generation turbine. MIK Technology alternative scheme (Kelada, 2010) is an osmotic power generation facility that provides a source of sustainable energy at a comparable power potential, and at a considerably reduced sea water intake requirement than previously mentioned schemes. The proposed osmotic power system requires only 60 m^3/s of sea water to generate 360 MW of power. Since osmotic power requires high salinity brine, then seawater has to be concentrated by solar evaporation to reach the required salinity. Therefore, an area of low land approximately 630 km^2 will be required as proposed by Kelada (2010) to generate the brine for this process as shown in Figure 3.

HYDRO AND SOLAR-POND-CHIMNEY POWER SCHEME

Here a new concept for the Qattara Depression, conceived as a two-stage power system is introduced. The first stage concerns a conventional hydropower scheme fed by sea water and somewhat similar to previously proposed ones. The second stage concerns a hydropower scheme fed by re-used water and a site-specific solar-pond-chimney power system. The first-stage power plant would produce hydropower of about 190 MW, while the second-stage power plants would raise the total production to reach about 410 MW.

Solar-pond-chimney power system

The 'solar pond' exploits a heat storage phenomenon in a large salt water body such as a lake, which operates as a natural collector of solar radiation (http://www.greenidealive.org/; http://www.solar-chimney.biz/). For various applications, the temperature of the water should be as hot as possible but lower than 100°C to avoid boiling at the bottom of the lake. Relatively high temperatures (60 to 80°C) may be obtained, by exploiting the higher density of the more concentrated salty water of the lake, in a so called salt gradient solar pond. So below a thick insulating gradient layer, a hot bottom layer heated by the sun can store heat for several days (http://www.teriin.org/). The mean temperature of the bottom layer of the pond will be around 60 to 80°C and that of the cooler upper layer 30°C. Similar to other researches, the Solar Pond is coupled to a suitable vertical chimney to generate power by the solar chimney effect (Dhahri and Omri, 2013; Akbarzadeh et al., 2009). To this end, saturated air at the lake surface is heated by extraction of heat from the hot water bottom layer of the solar pond and fed into the Chimney at its base. After rising by the chimney effect, air gets back saturated and cooler at the lake surface.

Here, it may be diverted to chillers to catch desalinated water, and then fed back again into the chimney to repeat the cycle.

Project description

The Qattara project proposed in the present study envisages two construction stages. Stage 1 concerns the construction of a conventional hydropower plant fed by sea water, and stage 2 concerns the construction of a conventional hydropower plant fed by re-used water and a Solar-Pond-Chimney Power Plant (SPP). Figure 4 shows the cross section of the combined power system with indication of the artificial lake, the two hydropower plants and the chimney. Figure 5 shows an aerial view for the settings of the project components. The first stage hydropower plant at the left side would have a potential head of up to 70 m for the lowest lake surface level, and a sea water flow rate Q_s = 460 m^3/s. The available head would drop to 50 to 60 m at the construction end of the second stage with re-used water delivered at the top of the lake surface. The expected generated hydropower for the first stage would be around 190 MW for the lowest lake surface level of -70 m and for 60% turbine efficiency. The SPP, at the right side of the figure, should be fully operational with the completion of the second stage of the project. An additional re-used water flow rate Q_r of about 200 m^3/s would be needed to keep the lake top water level balanced at –50 m. This flow rate would be diverted from the surface drainage water of the Delta at an average salinity of 0.1% and would produce about 60 MW of hydropower with 60% turbine efficiency.

The SPP has a tall vertical chimney suitably sited above the lower lake surface. The air over this surface, and in the neighborhood of the chimney base, is first heated by hydrophobic heat wheels that convey heat from the hot water bottom layer of the lake and then enters the chimney base. The air flowing over the lake surface would be saturated by water vapor at a temperature of 30°C and, after being heated; it would have a temperature of 80°C and a density of 1 kg/m^3. With a density of the saturated air around the chimney of 1.2 kg/m^3, a pressure difference of (1.2 - 1) × 9.81 × 1000 = 1.962 kPa would be available for a chimney height of 1000 m. The chimney wind turbines may exploit this pressure difference to generate useful electrical power. For a chimney with a throat area of 1400 m^2, the electric power produced only by the SPP system would be around 200 MW (http://www.greenidealive.org/; http://www.solar-chimney.biz/). With the functioning of the SPP system and the hydropower plant fed by 200 m^3/s of re-used water, the available head would drop to about 55 m, and the additional hydropower produced by the re-used water plant would be around 66 MW at 60% turbine efficiency. The overall electric power produced by the

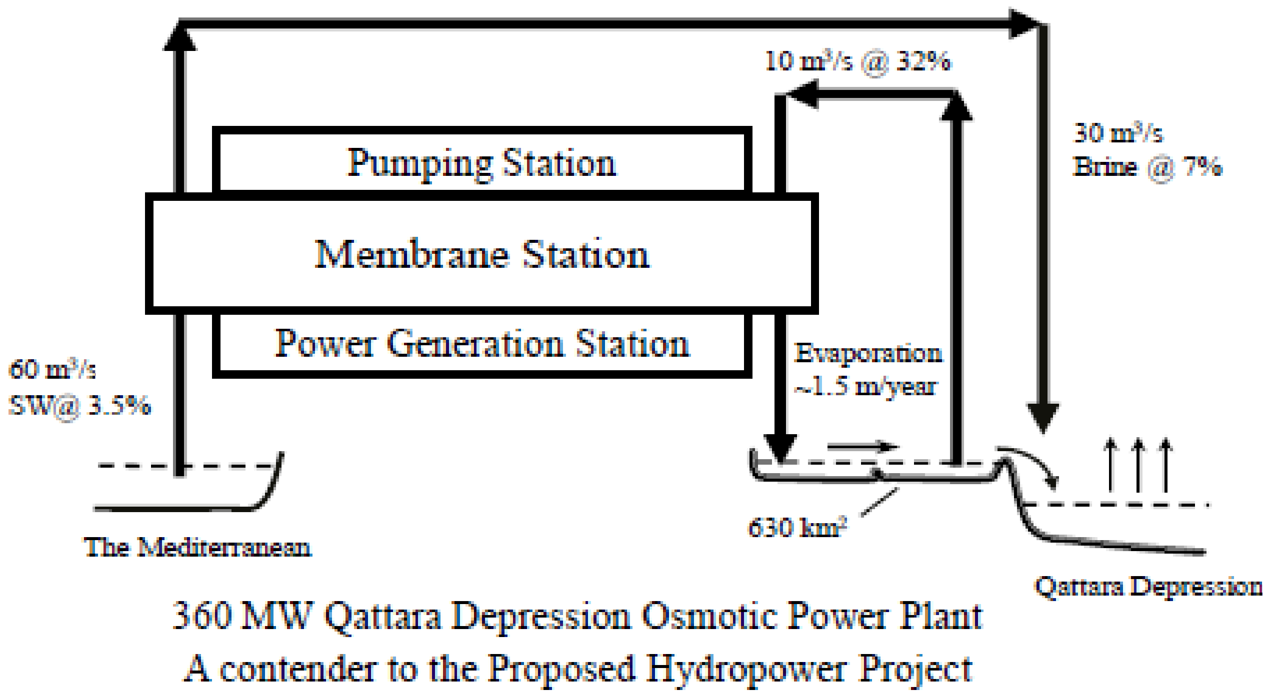

Figure 3. An alternative energy scheme for a hydro-solar system proposed by Kelada (2010).

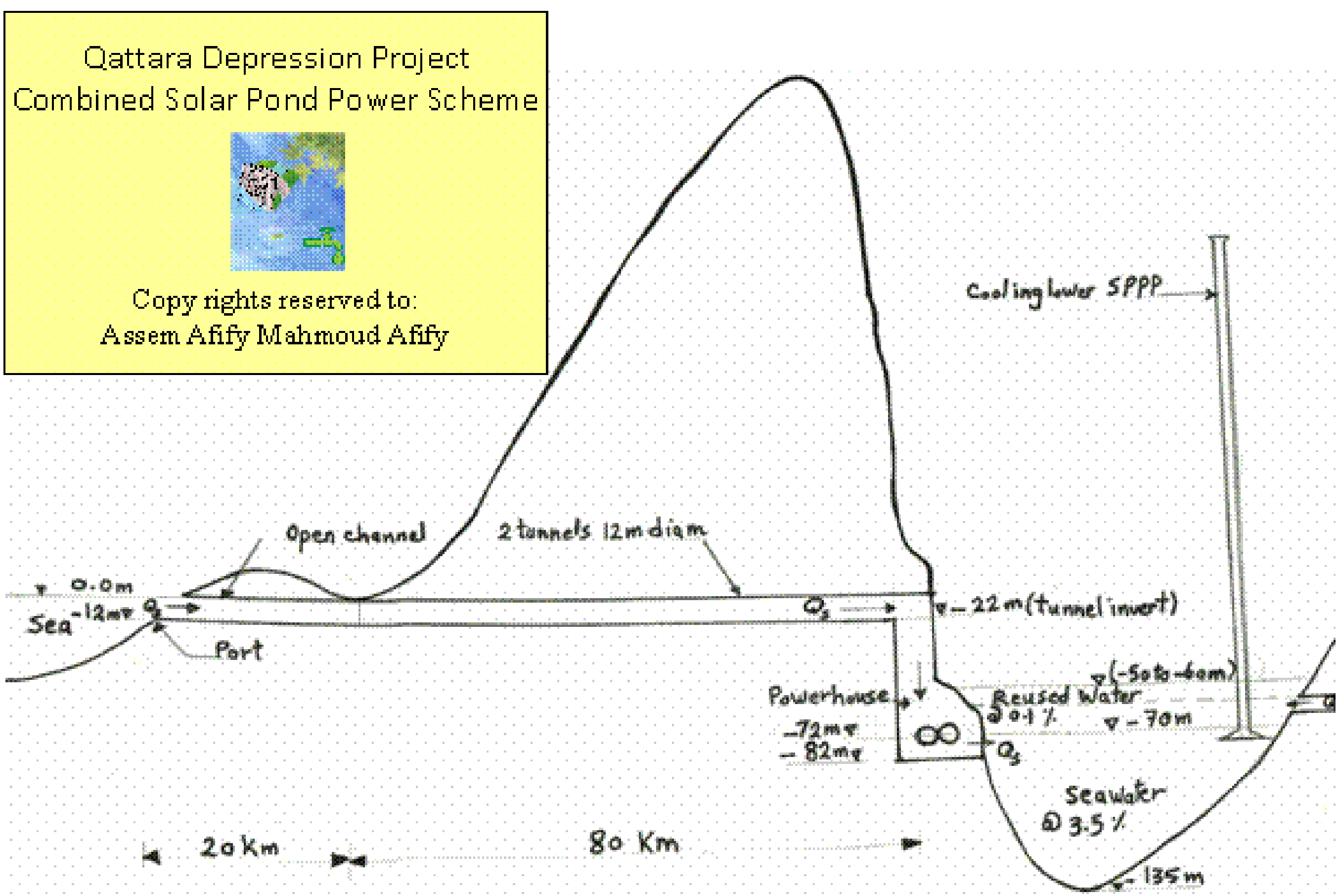

Figure 4. Cross section showing the configurations of two hydropower plants and a Solar-Pond-Chimney power plant.

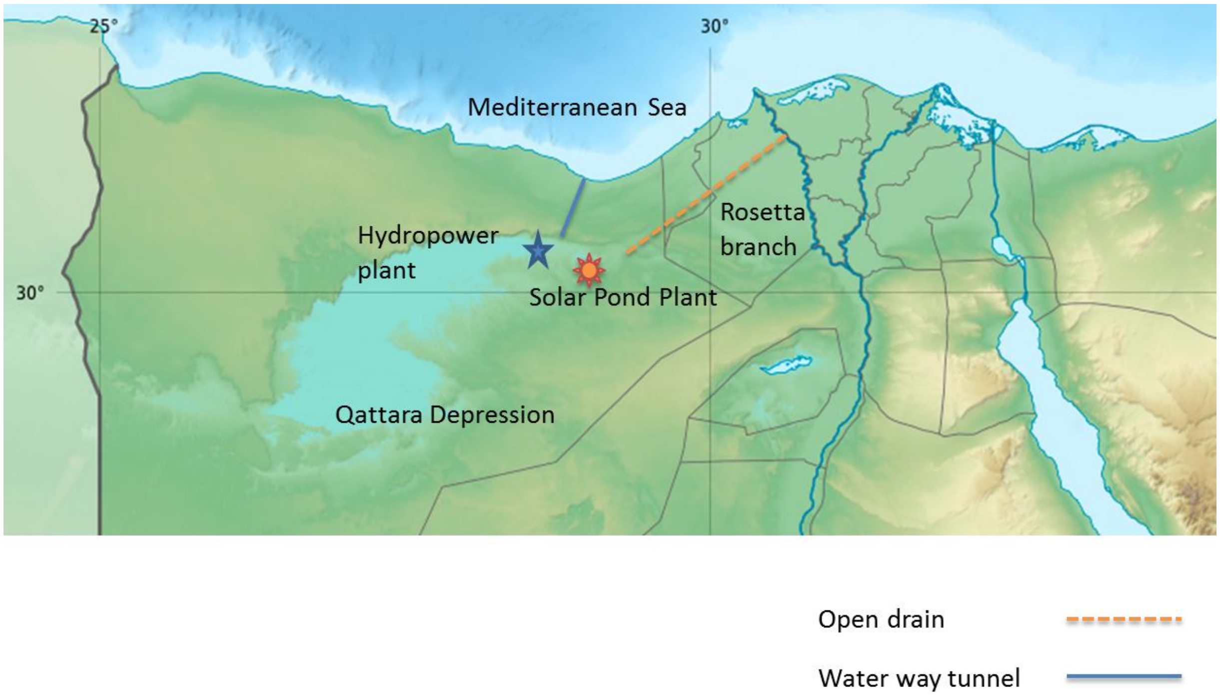

Figure 5. Aerial view for the settings of the hydro and solar-pond power plants, and the proposed water ways.

three power plants (in the first and second stages) might reach 480 MW with more efficient turbines.

Summary and comparison of schemes

Design parameters of the different schemes are summarized as listed in Table 1 for the purpose of comparison among them. The last column shows findings for the scheme proposed by the present study. The most important parameter is the artificial lake water level, which will finally govern all the remaining parameters. The lower the water level, the smaller the evaporation volume would be, and hence the needed flow rate of sea water would be less to keep the lake balanced. A clear example of this is Gohar's scheme, which proposes a water way (open channel) of reduced carrying capacity and dimensions compared to other similar schemes, such as the three tunnels proposed by Ball and Bassler. The present hydropower and Solar-Pond-Chimney scheme requires only two tunnels. However, additional water flow rates would be needed to balance the artificial lake if a partial flow rate of re-used water were diverted for the production of desalinated water. MIK Technology scheme is an exceptional case. It would require the least sea water flow rate of 60 m^3/s to produce 360 MW of hydropower, which is somewhat comparable to the peak powers expected in other schemes. However, if the sea water flow rate is relatively small with respect to the huge amount of evaporation loss, problems related with salt accumulation and unbalanced lake water surface have to be taken into account.

Project benefits and obstacles

When completed, the project would provide a yearly averaged power production of about 400 MW. In addition, it would create job opportunities in the area as well as benefit industrial and tourism developments. Excess power during periods of low demands might be used to produce desalinated water and thus help development activities. In particular, production of desalinated water may be obtained by coupling solar pond technology (Huanmin et al., 2002) with a thermal desalination plant.

Many obstacles face the Qattara project, and among them is the presence of dangerous explosives from the Second World War. As for site investigations, remote sensing can offer a solution to this problem. The problem of groundwater losses in the area has already been investigated through a hydro-geological study (Bastiaanssen and Menenti, 1990) using satellite data. Another critical issue for the project concerns the national strategic defense from the western side borders. The claims that the sea water channel would be a water barrier can be resolved, since a major part of this water way would be tunneled.

Groundwater salinity is also a big concern and has to be further studied with the help of hydraulic models so as to come up with the most suitable water level for the salty lake and thus prevent outward seepage flow.

Table 1. Design parameters in some schemes proposed for the Qattara project.

<table>
<tr><th rowspan="2">Design parameters</th><th colspan="5">Schemes</th></tr>
<tr><th>Ball</th><th>Bassler</th><th>Gohar</th><th>MIK Technology</th><th>Present hydro SPP</th></tr>
<tr><td rowspan="2">Flow rate (m³/s)</td><td rowspan="2">656</td><td rowspan="2">600</td><td rowspan="2">266</td><td rowspan="2">60</td><td>Q_s = 460</td></tr>
<tr><td>Q_r = 200</td></tr>
<tr><td rowspan="2">Lake water level (m)</td><td rowspan="2">-50</td><td rowspan="2">-60</td><td rowspan="2">-75</td><td rowspan="2">-40</td><td>Top = -55</td></tr>
<tr><td>Saline = -70</td></tr>
<tr><td rowspan="2">Mean power (MW)</td><td rowspan="2">175</td><td rowspan="2">190</td><td rowspan="2">100</td><td rowspan="2">360</td><td>190 (1st stage)</td></tr>
<tr><td>410 (from both 1st and 2nd stage)</td></tr>
<tr><td>Peak power (MW)</td><td>175</td><td>450</td><td>345</td><td>360</td><td>480</td></tr>
<tr><td rowspan="2">Project main features</td><td colspan="2">Open channel for the first 20 km, followed by 3 tunnels with 11 m diameter.</td><td rowspan="2">Elevated open channel at a level of 80 m and reservoir capacity not mentioned</td><td rowspan="2">Brine lake to be formed with an area around 630 km², another lake "Qattara sea" at a level of -20 m</td><td>Lake is connected to the sea via two tunnels of 12 m diameter, and to the Delta via an open drain.</td></tr>
<tr><td>Reservoir capacity not mentioned.</td><td>Elevated reservoir capacity of 50 million m³ at a level of +215 m.</td><td>Solar-pond-chimney plant and two conventional hydropower plants.</td></tr>
</table>

CONCLUSIONS AND RECOMMENDATIONS

The proposed scheme promises some advantages with respect to previous schemes. In particular, for the hydropower plant fed by sea water (first stage), only two tunnels are needed rather than three as suggested by Bassler. Also, no elevated reservoir is needed since the produced power during low demand periods can be utilized in the desalination process of re-used water (drainage). Feeding a hydropower plant with re-used water (2nd stage) allows storing re-used water on top of sea water in the artificial lake and thus minimizes risks of increasing groundwater salinity. Funds for the construction of the SPP power plant (2nd stage), with suitable chimney dimensions, will be available by selling extra electric power generated and produced desalinated water for the development of tourism and industry. An overall feasibility study encompassing all aspects of project components is strongly recommended. Groundwater modeling should be specially investigated to find out the most suitable level of the artificial lake. A physical model may also be needed to find proper locations for the chimney and for the drain inlet of the re-used water so as to avoid hydraulic mixing with the insulating salty layer of the lake.

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Full Length Research Paper

Groundwater conditions and hydrogeochemistry of the shallow Benin Formation aquifer in the vicinity of Abraka, Nigeria

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Shallow borehole and dug well data are used in describing groundwater conditions in the vicinity of Abraka in the Nigerian coastal plain. Drill cuttings from ten boreholes show that the Abraka area is underlain by reddish brown unconsolidated sands, followed by a succession of grey- off-white medium grained sands of the Benin Formation. Hydraulic conductivity estimated from grain size analysis of cuttings obtained from typical borehole screened horizons range from 0.12 to 0.19 msec^{-1}. Regional groundwater flow is from north east to southwest with local distortions on this regional trend resulting from ground water abstraction in densely populated areas. Maximum TDS in ground water was recorded at 28 and 85 mg/l from dug wells. The trilinear plots of major ions in water indicate a mixing of mainly sodium chloride and calcium chloride water types. The stiff diagrams are also suggestive of possible stratification of water chemistry with depth. Borehole water quality is well within WHO and Nigerian drinking water quality standards while that from dug wells contains minimal levels of fecal coliform. Ground water and surface water are determined to be suitable for irrigation. It is also shown that the quality of water in the River Ethiope, TDS 6.6 to 8.09 mg/l, *Escherichia coli* occurrence at less than an average of 50 cfu/100 ml from selected recreation sites meets WHO standards for body contact recreation.

Key words: Benin Formation, River Ethiope, Abraka, Niger Delta, groundwater, water quality.

INTRODUCTION

The Abraka area is located in the western Niger Delta and underlain by the Benin Formation that bestrides the River Niger and stretches from west of the Lagos area to the Calabar Flank in eastern Nigeria. The formation which contains prolific aquifer horizons is heterogeneous and has been studied in some detail in the Port Harcourt area by Amajor (1991) who characterized the water bearing sandy layers of its upper (300 m) horizon and described rapid horizontal and vertical variations in lithology and hydraulic characteristics. Ibe and Njemanze (1998) also identify at least three aquifer horizons that 200 m of the formation in the vicinity of Owerri, also in the are separated from each other by clay layers in the upper eastern sector. West of the River Niger, Oteze (2011) and Akujieze and Oteze (2006) have described the water bearing upper horizons of the formation and identify lateral variations in hydraulic properties in the vicinity of Benin City. Longe (2010) also reports the presence of three aquifer horizons that are separated by thin clay layers in the upper 100 m of the formation in the Shomolu area of Lagos State. There is a dearth of similar studies in the Abraka area and existing ground water conditions in the underlying Benin Formation are not well understood. *Laissez faire* exploitation of ground water

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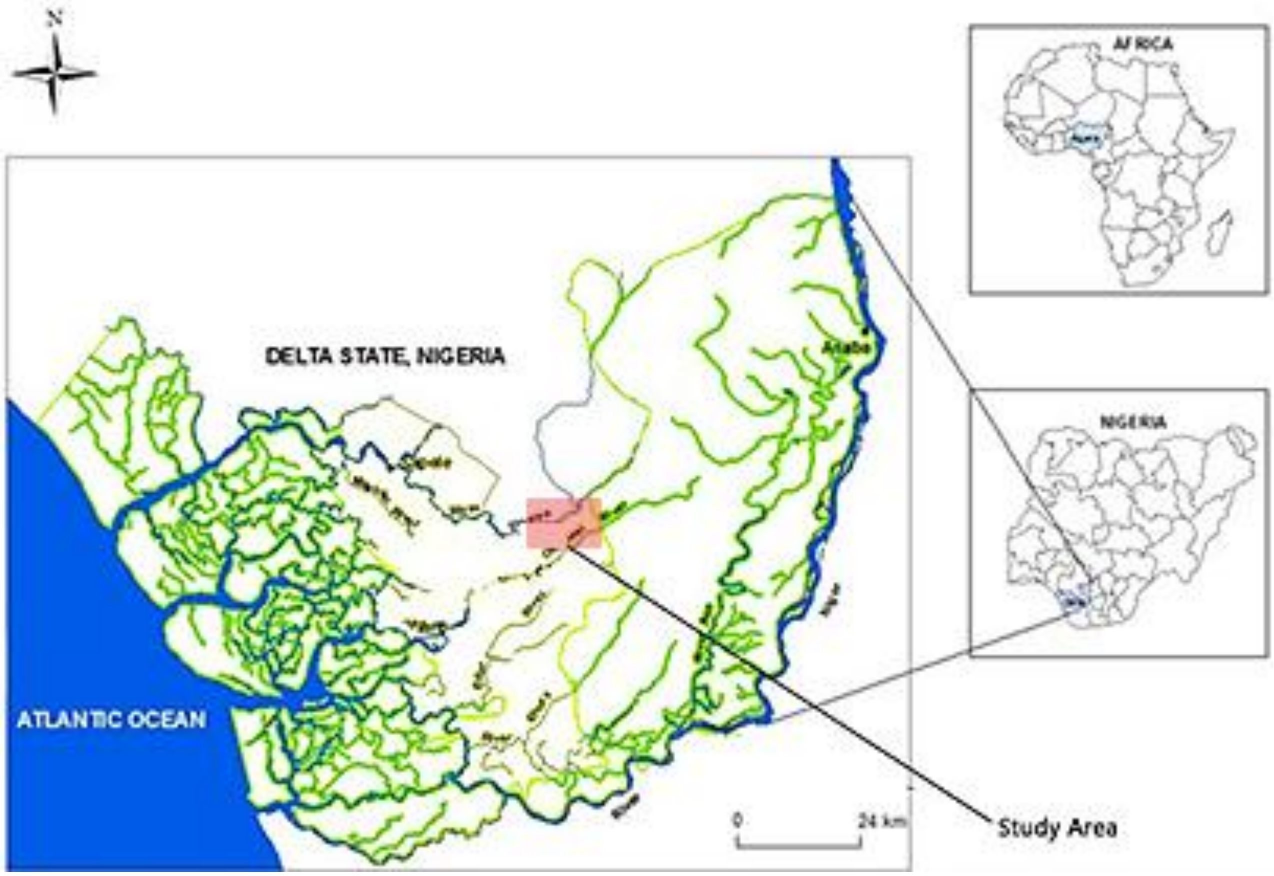

Figure 1. Map of Delta State Nigeria showing location of study area.

especially in this rapidly expanding university community that is witnessing rapid growth could potentially create problems for the ground water system in the long term. This is because in the absence of public water supply facilities to serve an estimated population of 90,000 (Oje and Origbo, 2012), all water supplies for domestic, commercial and industrial uses are obtained from privately owned boreholes that tap the shallow Benin Formation.

An appreciation of existing ground water conditions is not only desirable but a requirement for urban expansion and regional planning. The objective of this investigation is thus to gain an understanding of ground water conditions in the area, associated hydrogeochemistry, as well as determine the suitability of surface water and ground water for domestic use, irrigation, water contact recreation and industry. Furthermore, the results will add to and contribute to the expansion of current regional knowledge and understanding of this prolific, extensive and important aquifer.

STUDY AREA

The Abraka area, situated between latitude 5° 45' and 5° 50' N and longitude 6° and 6° 15' E is located on the south bank of the River Ethiope and is an agglomeration of several communities that are aligned linearly along the New and Old Sapele– Agbor highway (Figures 1 and 3). These communities include from the west, Oria, Ajalomi, Abraka PO, Ekrejeta, Urhuoka and Umeghe. Ajalomi, Abraka PO, Ekrejata and Urhuoka have grown in size and are now conjoined to form what is loosely referred to as Abraka Urban, the seat of all three sites of the Abraka Campus of the Delta State University. Southwards, the rural communities of Ugono, Aragba, Abraka Inland and Ughere - Uragbesa are as well, bona fide Abraka communities (Figure 3).

Physiography and climate

The Abraka area is a typical coastal plain terrain, monotonously lowland and flat with a gentle slope towards the Ethiope River. The climate is equatorial, hot (23 to 37°C) and humid (relative humidity, 50 to 70%). There is a dry season from about November to February, and a wet season that begins in March, peaks in July and October. Six -years (2000 to 2005) annual mean rainfall measured at the Delta State University weather station is

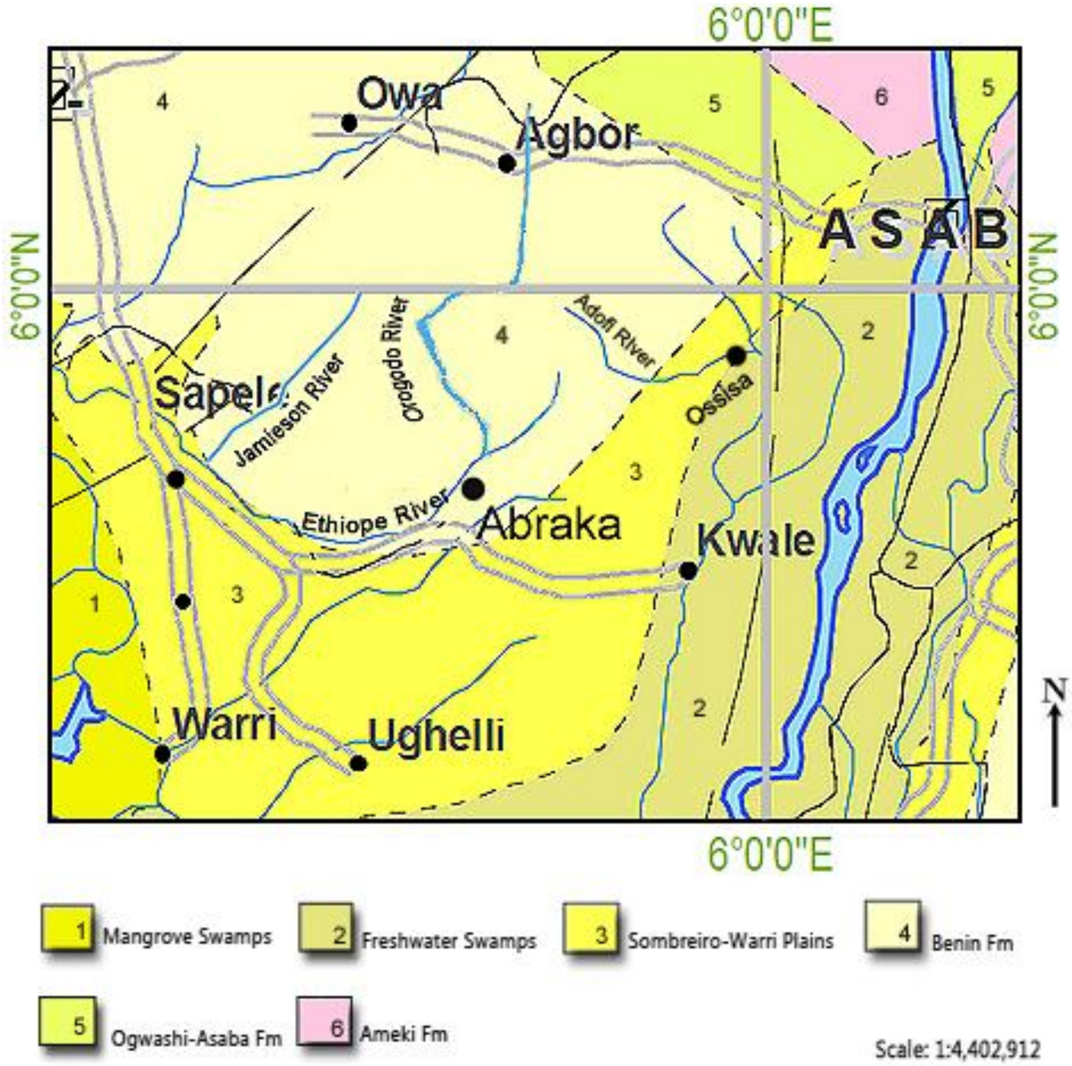

Figure 2. Regional geology of part of the Western Niger Delta showing the Abraka area (NGSA, 2006).

3317.8 mm. Vegetation is rainforest, most of which has been decimated and replaced with farmlands and secondary forest. However, lush, dense and swamp primary forest flanks the river banks.

Geology

The area is located in the Niger Delta Basin, a much studied and important petroleum province. Briefly, there is general agreement that the basin was formed as a result of an aulacogen type development that was triggered by the separation of the African and South American plates in the Jurassic. The resulting trough has been filled by a series of marine transgressions, regressions and deltas, the present Niger delta being the most recent. The basin fill has been described by Short and Stauble (1967), Reijers et al. (1996), Nwajide (2006), among many others and consists of three formations, namely, from the oldest to the youngest, the Akata Formation, Agbada Formation both of Eocene to Recent and the Miocene to Recent Benin Formation. However, west and just south of Abraka the Benin Formation is masked by the younger Holocene deposits of the Sombreiro-Warri Deltaic Plain, the Mangrove Swamp and Freshwater Swamp wetlands. These deposits which have not been assigned formal geological names because they are universally considered to be recent expressions of and a continuation of the Benin Formation are only identified by the physiographic terrains in which they occur. The aerial distribution of these delta top deposits coincides somewhat with the associated physiographic subdivisions shown in Figure 2. The inferred boundary between the Sombreiro–Warri Deltaic Plain and the Benin Formation outcrop as can be seen from Figure 2 passes through the Abraka area such that the southern

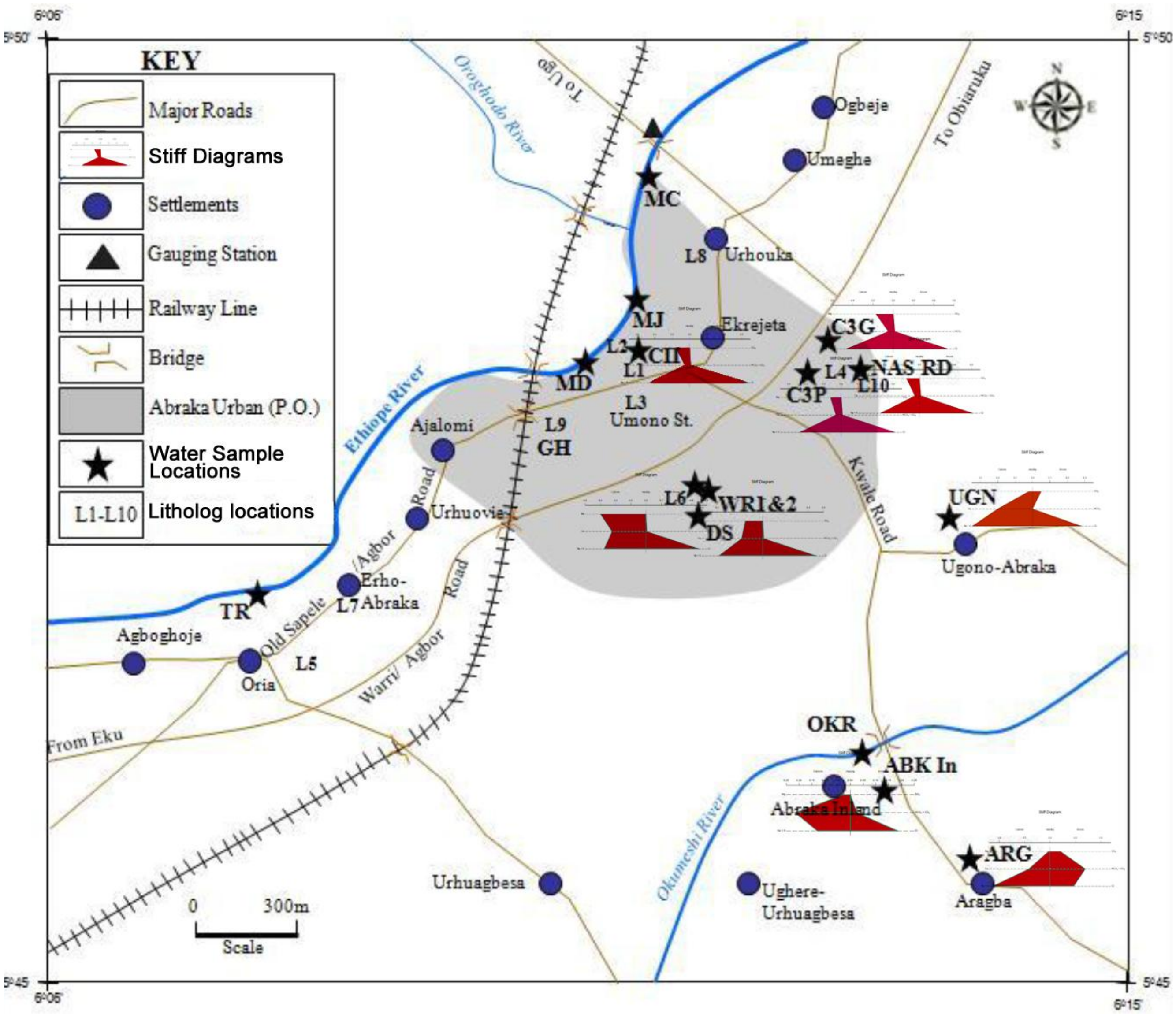

Figure 3. Borehole drill - cutting sample locations, water sample locations and associated stiff diagrams. L1(CII), Geology Lab; L2, Abraka Hall; L3, Omono Street; L4, Campus 3 New Administrative Block; L5, Oria; L7, Erho; L8, Urhuoka; L9, General Hospital; L10 (Nas Rd), Nassarawa Road; ARG, Aragba; ABK In, Abraka Inland; UGN, Ugono; CII, Geology Lab; C3G, Campus 3 Gate; C3P, Campus 3 Pool site; WR1, Winner's Road 1; WR2, Winner's Road 2; DS, Dump site; MC, McCarthy Beach; MJ, Majoroh Beach; MD, Mudi Beach; TR, The Turf; okr, Okemesi River; L6, Winner's Road (not WR1or WR2).

part of the area is underlain by Sombreiro-Warri Deltaic Plain deposits while the north rests on Benin Formation outcrop.

The Ethiope River, the most important physiographic feature in the area flows almost exclusively on the outcrop of the Benin Formation. The Benin Formation in the Abraka area is overlain everywhere by reddish brown colored ferruginized regolith that is usually no less than 2 m thick. This can be observed clearly at two locations on the Abraka – Ugo road (Figure 3). The first site is a large borrow pit located just before the bridge on the River Ethiope and from where material is being excavated for building and road construction and the second at the rail road crossing near the overpass on the Abraka – Ugo Road. At both locations, the formation is massive and deeply weathered.

METHODOLOGY

Drill cuttings were collected and described from ten sites (Figure 3) where shallow water supply boreholes were drilled for private home owners. Sieve analysis of drill cutting samples obtained from the screened and usually the lowermost horizon penetrated was undertaken at the laboratories of the Department of Geology, Delta

State University. The sampling procedure for groundwater involved the collection of replicates from six randomly located boreholes that could be accessed and three dug wells. Borehole water samples were collected after boreholes were pumped continuously for about 1 h. Surface water samples were also collected from selected recreational points along the River Ethiope, from the Okemeshi River as well as from a water filled quarry that is being used as a dump site. Sampling sites are shown in Figure 3. The set of samples designated for heavy metal analysis were stabilized *in situ* with nitric acid. Electrical conductivity and total dissolved solids were also measured *in situ* using the HACH conductivity/TDS meters, respectively. The pH was determined by means of a Schott Gerate model pH meter and temperature was determined using mercury–in-glass thermometer calibrated in 0.2°C units from 0 to 100°C. The Pye Unicam Atomic Absorption Spectrophotometer SP 2900 was employed in the determination of the heavy metals while the HACH Spectrophotometer was employed in determining the NO_3 ion using the cadmium reduction method. Na and K ion concentrations were obtained with a Jenway Clinical flame photometer. Sulphate content was determined by turbidimetry and Ca, Mg, HCO_3 and Cl with appropriate titrimetric methods (APHA, 1992). In order to determine the presence of total and fecal coliform, 100 ml of each water sample were passed through a membrane filter consisting of uniform pore diameter of 0.45 nm following which the membrane filter was placed in a petri-dish containing Mac-Conkey Agar and Eosin-Methylene blue Agar, in duplicate with the grid side up and incubated at 35 and 45°C for 18 to 24 h, respectively. Bacteria colonies if present were counted and expressed as numbers of coliform per 100 ml of water.

Four dug wells and six boreholes (Table 1) were selected on the basis of spread for depth to water level measurements. Depth to water level in each of the boreholes and dug wells was measured with an electronic well sounder. An Ertec model GPS instrument was used to determine wellhead coordinates. Because existing maps of the area are devoid of contours, averaged elevation readings from three GPS instruments at each site were used with the sparsely distributed benchmarks to approximate the elevation of each well location. Surfer 8 (Golden Software Inc., 2002) was employed in generating water table contour lines of equal head.

RESULTS AND DISCUSSION

Lithology

Cuttings recovered from boreholes show a succession of fine grained reddish brown sands underlain by typically clean, grey - off white and fine - medium - coarse grained, angular to sub- rounded well sorted quartz sands. In addition to remarkable lithological similarity, a layering and cyclical fining upward sequence is apparent at some locations (Figure 4). The consistent absence of clays gives an indication of the potential high vulnerability of the shallow aquifer to contamination from surface sources.

Groundwater conditions

Water table conditions prevail in the Abraka area. Depth to water varies from about 4 m at Abraka Inland to 26 m at Oria. Water table head above mean sea level determined at each location is shown in Table 1 and associated water table contour lines of equal head in meters above sea level are plotted in Figure 5. Sustained groundwater abstraction in the more densely populated Abraka Urban has resulted in a depression of the water table in the town centre that stretches from Oria through Winner's Road to Ugono and towards which groundwater is flowing from virtually all directions. This has thus caused a local distortion on regional south westward groundwater flow (Akpoborie, 2011; Aweto and Akpoborie, 2011) that mirrors the seaward slope of the coastal plain. There also appears to be a mound at the Abraka Inland community that extends to Umuebu from which water is moving in all directions.

Hydraulic characteristics

Sieve analysis curves for cuttings retrieved from boreholes at Geology Laboratory, Oria, Erho, behind the General Hospital and Nassarawa Road, locations L1, L5, L7, L9 and L10 respectively in Figure 3, were plotted as shown in Figure 6. Cuttings from all ten boreholes sampled in this investigation were all remarkably similar upon visual examination in terms of textural attributes and which similarity is reflected in the curves for the five representative samples shown in Figure 6. Following Odong (2007) and Fetter (2004), hydraulic conductivity was estimated with the Hazen (1892) approximation:

$$K = C\ (D_{10})^2$$

Where K is hydraulic conductivity in cm/s, D_{10} is the effective grain size in cm, C is a coefficient that is based on the aquifer matrix.

Estimated values of K obtained with C = 6 (Uma et al., 1989) range from 0.12 to 0.17 cm/s with uniformity coefficient ranging from 1 to 1.4. It should be stressed that all sampled boreholes are located on the outcrop of the Benin Formation and that maximum depth penetrated and sampled is a shallow 18 m which makes the results of limited application especially with respect to the reputed average 2000 m thickness of the Benin Formation. However, they are interesting to the extent that in the absence of formal aquifer tests, this is the first indication of hydraulic properties of this horizon of the Benin Formation in this area.

Water chemistry

Characteristics of surface and ground water

The physical and chemical characteristics of surface water from different recreational sites located on the south bank of the Ethiope River are shown in Table 2. One sample collected from the bridge crossing on the Okumesi (Warri) River, near Abraka Inland, and another

Table 1. Depth to water level measurements.

Eastings	Northings	Location	Well type	DWL	Head
6.1369	5.731333	Aragba	Dug Well	5.1	9.01
6.125633	5.746067	Abraka Inl	Dug Well	3.9	13.22
6.137133	5.782383	Ugono	Dug Well	4.5	5.7
6.097833	5.792	Geology Lab.	Borehole	3.69	16.3
6.103472	5.778833	Winners Rd	Borehole	14.63	4.27
6.117789	5.789828	Delsu, Site 3 Pool	Borehole	16.82	12.77
6.063889	5.75825	Oria	Borehole	15.03	3.87
6.148333	5.783875	General Hospital	Borehole	13.41	10.36
6.159883	5.752183	Umuebu	Dug well	4.2	11.42
6.148333	5.846183	Morka Primary School, Obiaruku	Borehole	31.2	3.10

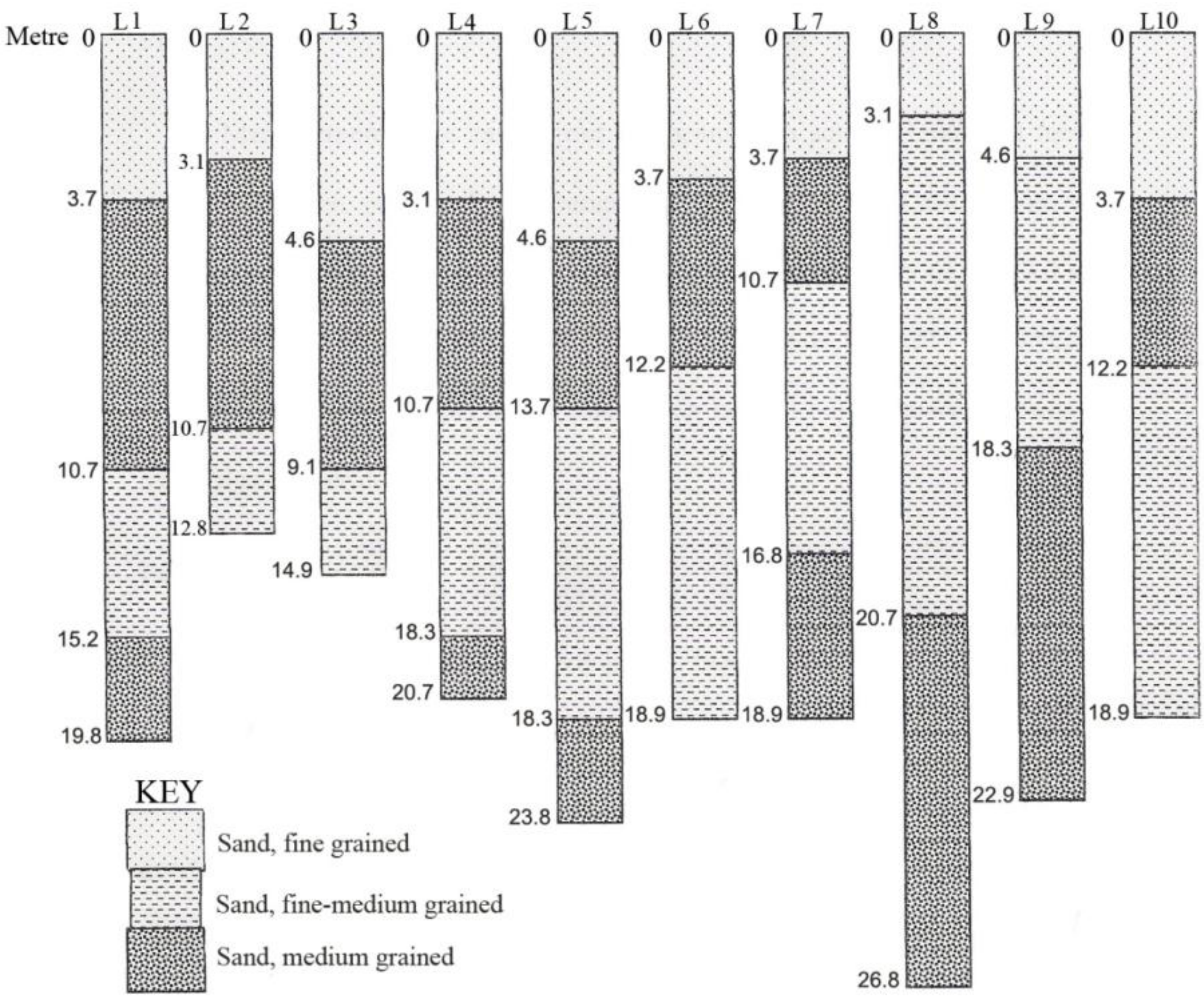

Figure 4. Lithologs from water supply wells in Abraka. L1, Geology Lab; L2, Abraka Hall; L3, Omono Street; L4, Campus 3 New Administrative Block; L5, Oria; L6, Winner's Road; L7, Erho; L8, Urhuoka; L9, General Hospital; L10, Nasarrawa Road.

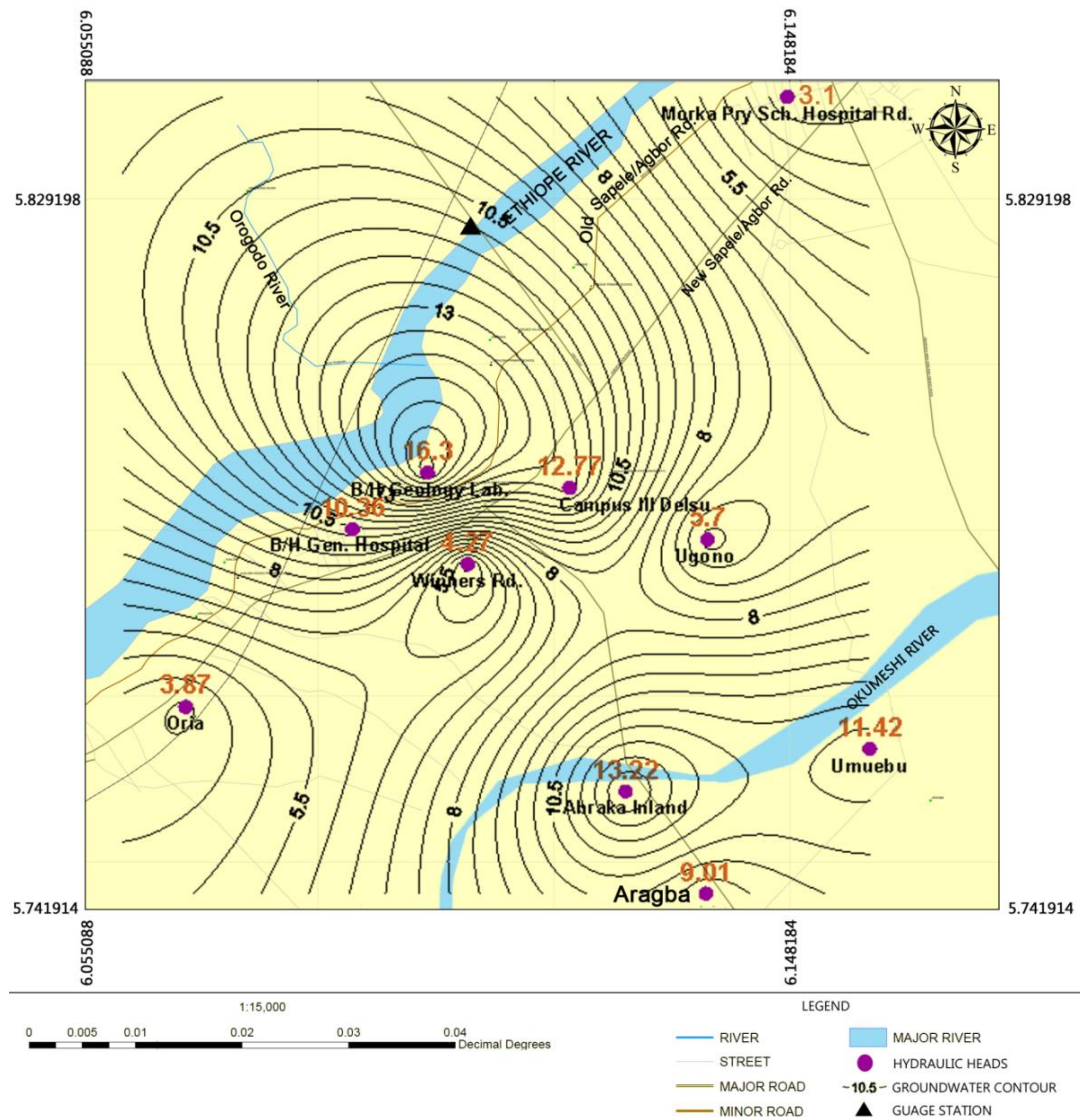

Figure 5. Water table contour lines of equal head in meters above sea level in the vicinity of Abraka.

from the Jamieson River are also included for comparison. Sampling sites except for the Jamieson River are shown in Figure 3. TDS at all sites is very low and all ions show very low levels of occurrence. However, TDS from Ethiope River is much lower at mean 7.18 mg/l than Okumeshi River water which returned a TDS value of 16.5 mg/l. Indeed, Kaizer and Osakwe (2010) in a regional comparative study of water quality from five rivers in Delta State show that the Ethiope River contains the lowest total dissolved solids. Water in both the Ethiope and Okumeshi Rivers is also slightly acidic, which as reported from previous studies (Efe, 2005; Olobaniyi and Efe, 2007; Kaizer and Osakwe, 2010) is reflective of associated gas flaring in the Niger Delta petroleum province. The physical and chemical characteristics of ground water collected from boreholes and dug wells in the Abraka area are shown in Table 3. TDS is low at mean 26.67 mg/l (standard deviation 21.3) and as expected, higher than TDS in surface water. The highest TDS at 85 mg/l was recorded from the dug well at Aragba, but water from this dug well is not represenative as it is uncovered and in the wet season regularly receives runoff from surrounding areas. Ground water is also weakly acidic at an average pH of 6.64. The acidity

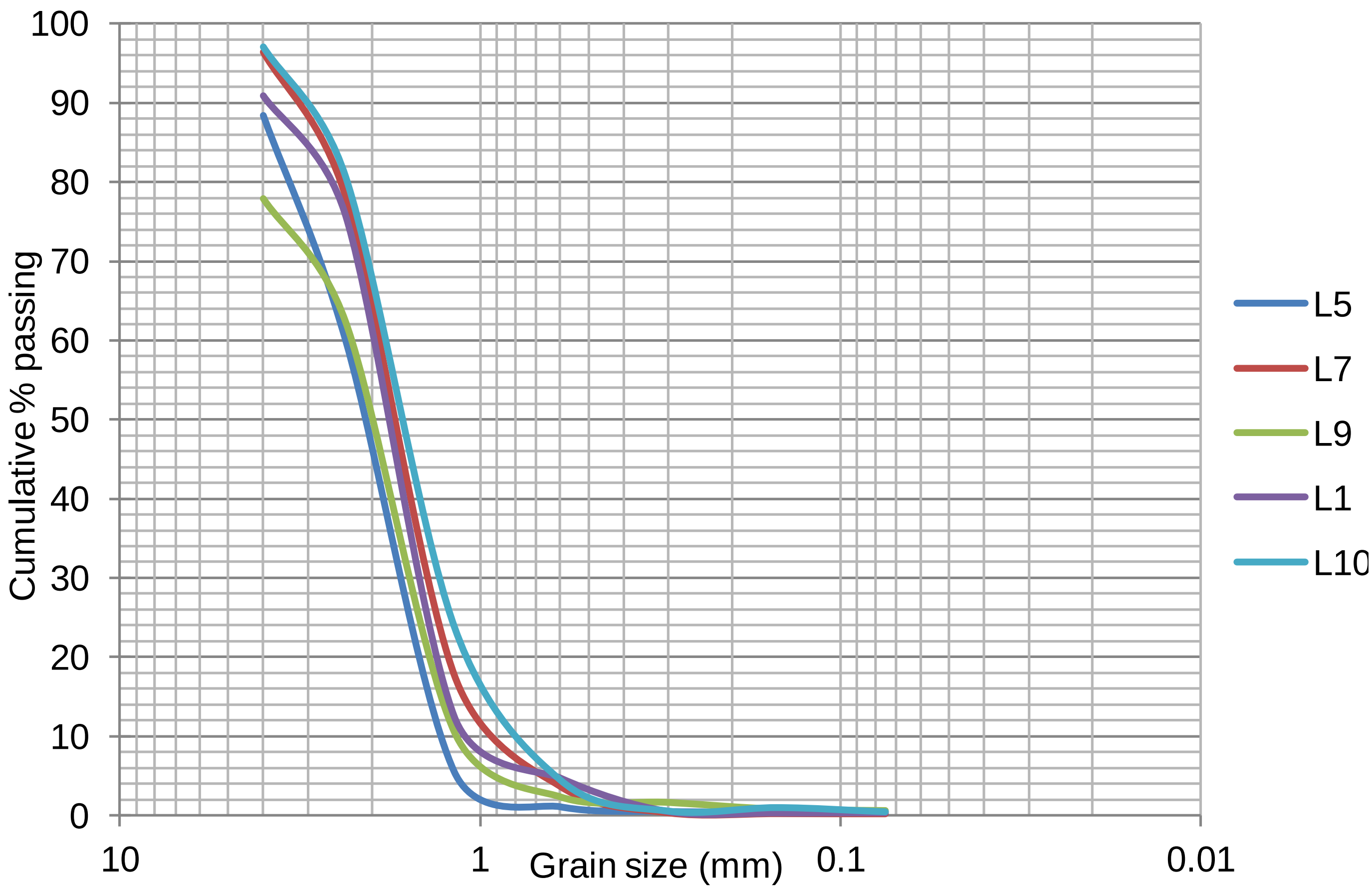

Figure 6. Typical grain size curves from screened horizons in selected boreholes in Abraka.

Table 2. Physical, chemical and microbiological characteristics of surface water from the Ethiope River and the Okumeshi River (mg/l, except where indicated), bacteria counts in (cfu/100 ml).

Parameters	Sampling points					
	MC	**MJ**	**MD**	**TR**	**OKR**	**JMR**
Temperature (°C)	27.8	28.2	27.5	27.5	28.1	-
TDS	6.62	8.09	7.21	6.83	16.5	8.91
EC (µ/cm)	12.74	15.51	13.87	13.14	33	17.85
pH	5.27	5.14	5.18	4.92	6.33	8.0
Ca	0.96	3.45	1.84	1.23	3.99	0.41
Mg	0.32	2.72	4.67	2.72	0.20	0.88
Na	1.91	2.33	2.08	1.97	0.86	0.42
K	0.51	0.62	0.55	0.53	1.46	0.10
HCO_3	1.01	3.05	0.61	0.16	2.20	0.65
SO_4	1.24	0.25	0.12	0.12	6.60	1.01
Cl	4.1	4.02	4.3	4.07	3.33	2.26
NO_3	0.00	0.65	0.26	0.18	0.20	1.25
Total bacteria	3.3×10^2	1.7×10^3	4.2×10^3	3.0×10^3	Nd	
Total coliform	11	35	45	80	Nd	0.0
Total *E. coli*	4.0×10	1.5×10	2.8×10	4.0×10	Nd	0.0
Total Salmonella	0	0	0	0	Nd	

MC = McCarthy Beach, MJ = Majoroh Beach, MD = Mudi Beach, OKR = Okumeshi River, TR = The Turf, JMR = Jamieson River, Nd = Not determined.

Table 3. Physical and chemical characteristics of groundwater (mg/l except where indicated).

Parameters	Sampling locations										
	CII	C3G	C3P	NAS Rd	WR2	WR1	UGN	ABK In	ARG	DS	SON
Temperature (°C)	28	27	28	27	28	27	27	27	28	28	
H	7.1	7.4	6.9	7.13	5.7	5.6	6.25	6.39	7.29	8.9	6.5-8.5
TDS	28	25	27	26.67	41.2	20.9	20	13	85	424	500
EC (µ/cm)	58.2	52.5	47.8	52.83	82.8	41.08	40	26	170	849	
Turbidity (NTU)	0	0.4	0.1	0.17	0.32	0.00	0.25	0.19	0.20	6.95	5
Ca	1.0	1.01	1.2	1.07	9.0	2.8	4.05	4.32	8.46	65.3	
Mg	1.8	2.1	1.5	1.8	7.3	1.4	0.26	0.30	0.41	54.6	0.2
K	3.5	3.6	2.0	3.03	4.32	2.43	4.09	0.84	9.95	74.4	
Na	7.2	8.5	9.8	8.5	10.11	5.21	5.58	2.49	20.34	109.1	
Cl	24.0	19.0	22.0	21.67	24.84	12.54	9.99	6.67	16.66	254.7	
HCO_3	1.3	1.0	1.4	1.23	5.01	3.22	<1.0	3.17	47.82	87.09	
SO_4	0	0	0.1	0.03	0.04	0.00	2.39	<1.0	10.07	9.7	200
NO_3	0	0	0	0	0.29	0.15	0.26	0.19	0.29	5.12	10
Pb	0	0.01	0	0	0	0	ND	ND	ND	0.04	0.01
Zn	0.1	0.2	0.1	0.13	0.1	0.13	ND	ND	ND	ND	3
Cd	0.01	0	0.02	0.01	0.001	0.00	ND	ND	ND	0.006	0.003
Fe	0.04	0.06	0.03	0.043	0.18	0.09	ND	ND	ND	7.65	0.3
Cr^{6+}	0	0	0	0	0.00	0.00	ND	ND	ND	0.008	0.05
Total coliform (cfu/100 ml)	0	0	0	0	6	0	8	8	8	54	
Faecal coliform (cfu/100 ml)	0	0	0	0	4	0	4	6	4	42	0

ARG, Aragba; ABK In, Abraka Inland; UGN, Ugono; CII, Geology Lab; C3G, Campus III Gate; C3P, Campus 3 Pool site; Nas Rd, Nassarawa Rd; WR1, Winner's Road 1; WR2, Winner's Road 2; DS, Dump Site; SON, Nigerian Drinking Water Standards.

is retained from that of recharging rainfall which as explained has been attributed to gas flares.

The unusually low TDS in the Ethiope River water could possibly be explained by the fact that its catchment is exclusively situated on the outcrop of the Benin Formation which is directly recharged perenially by rainfall. The Jamieson River its only tributary (Figure 2) was also sampled at its headwaters near Ugo, Edo State as part of this investigation and returned similar low TDS of 8.91 mg/l (Table 2). Reported regional variation in groundwater TDS (Olobaniyi and Owoyemi, 2004; Emeshili, 2008; Sarner PFM, 2011; SPDC, 2004, 2008) indicate that shallow groundwater from Benin Formation outcrop areas appears to be relatively lower in mineral content than that from areas where the formation is masked by younger layers.Thus, following from Domenico (1972), it does appear that while recharging, rainwater may have over time leached the upper layers of the Benin Formation of all soluble mineral matter with the resulting low total dissolved solids in shallow groundwater, it continues to dissolve mineral matter from overlying younger deposits where they occur. Because regional groundwater flow is from northeast to southwest, that is from Benin Formation outcrop areas southwestwards and contributes more than 80% to total flow of the River Ethiope (Akpoborie, 2011), it follows that river water would also be low in dissolved solids. Furthermore, this high contribution of low TDS ground water to stream flow could be partly responsible for the remarkable and unique clarity of water in the Ethiope River as well as the Jamieson River.

With respect to the microbial content, water from the boreholes in both campuses of the university at Abraka CII, C3G, C3P and Nas Rd is free of coliform bacteria. However, one borehole at Winners Road, WR2 is possibly receiving water from the heavily contaminated water in the abandoned quarry (DS, Table 3) as indicated by the relatively higher coliform count. That this contamination is limited for the time being to the immediate vicinity of the quarry is borne out by the fact that borehole WR1 which is also near the quarry but further away from it than WR2 is coliform free. Also, water in all the dug wells in rural Abraka at Ugono, Abraka Inland and Aragba contains faecal coliform which may be explained by the fact that the wells are shallow, uncovered and are often left in an unsanitary state.

Major ion geochemistry

Major ion content is used in interpretive diagrams (Hem, 1991; Piper, 1944; Keheew, 2001) to describe, classify and determine geochemical trends in ground water and has subsequently been used in several ground water

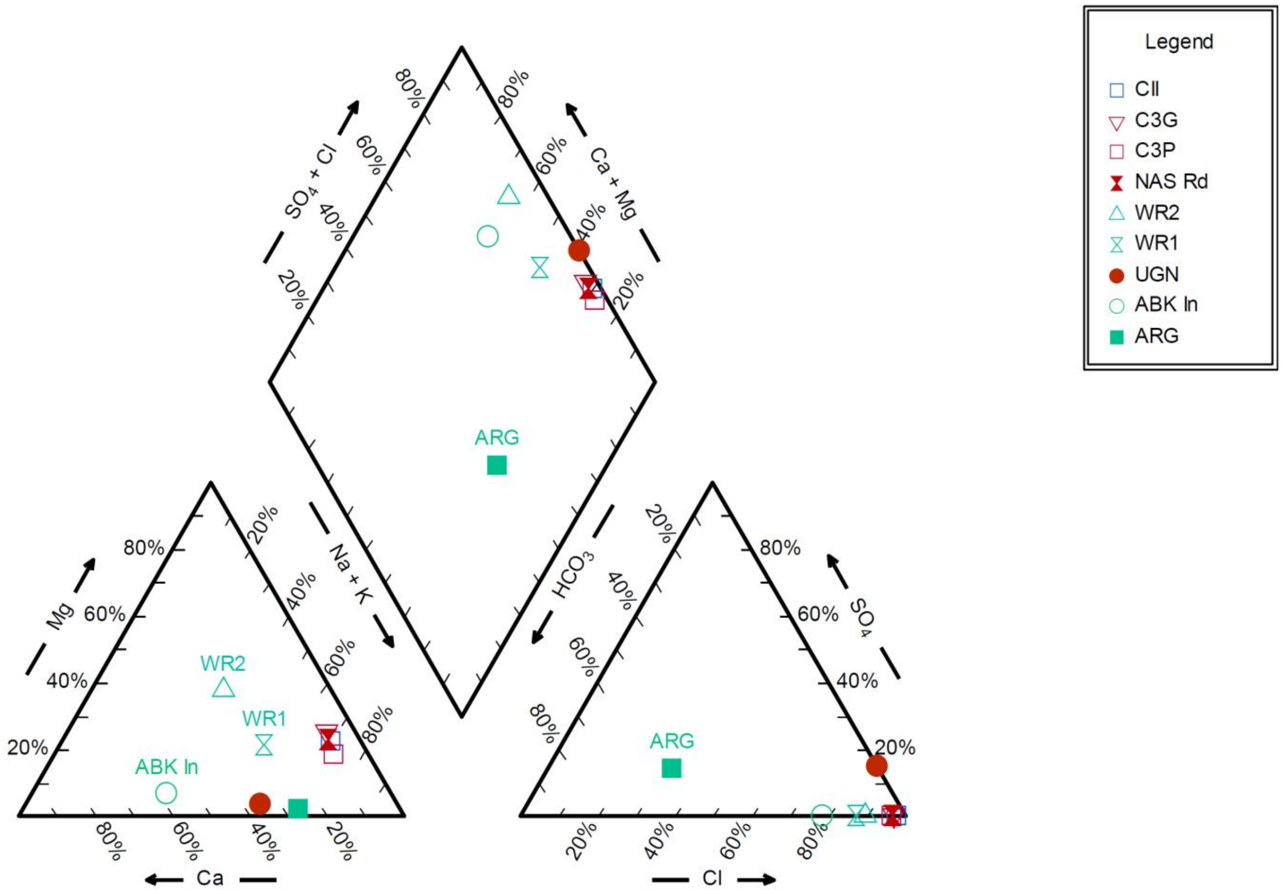

Figure 7. Piper diagram of groundwater analyses from Abraka area. ARG, Aragba; ABK In, Abraka Inland; UGN, Ugono; CII, Geology Lab; C3G, Campus 3 Gate; C3P, Campus 3 Pool site; WR1, Winner's Road 1; WR2, Winner's Road 2; Nas Rd,

studies (Arabi et al., 2010; Naseem et al., 2010; Smith and Wahl, 2003; Rafael et al., 1998). The Piper diagram plots of the chemical constituents in ground water presented in Table 3 are shown in Figure 7. All samples except Aragba (ARG) plot in the right hand quadrant of the diamond that stretches from about 20 to 60% calcium + magnesium, while sulphate + chloride are between 70 to 80% indicating a mixing trend as well as direct recharge by rainfall (Petalas and Diamantis, 1999). Ground water from both campuses of the University overlap at the 25% point on the Ca + Mg axis while Ugono plots slightly higher at 40%. Keheew (2001) classifies hydrochemical facies using the Piper plot and on the basis of which ground water from the boreholes at the university and at Ugono, UGN, may be described as the sodium chloride type while at Abraka Inland (ABK In), ground water is the calcium chloride facie. At Aragba, the water is dominated by sodium and potasium which constitute about 70% of the cations while the bicarbonate and chloride ions occur respectively at 60 and 35%; hence, the water is uniquely for this area, the sodium bicarbonate type. As has been noted however, this sample is from an unringed dug well that is always left uncovered and may not be considered representative of groundwater in the area.

The Stiff diagrams (Hem, 1989; Kehew, 2001) plotted for each sampling location and superimposed on Figure 3 confirm these facie classifications as well as further highlight the differences in shallow dug well water and water obtained from deeper in the aquifer from drilled wells. Ground water from boreholes located at the university for example presents a distinctive inverted funnel shape that may be considered representative of native ground water in Benin Formation outcrop area. At WR1, the funnel shape is mildly distorted due to relative enrichment in calcium occasioned by recharge from the nearby waste dump. At WR2, the borehole location closest to the dumpsite, ground water is already an admixture of native ground water and dumpsite water, and the funnel shape is completely distorted. In comparison to groundwater obtained from deeper in the aquifer, dug well water from shallower horizon and outside Benin Formation outcrop area at Aragba and Ugono present distintively different shapes than the university campus wells which is suggestive of possible hydrogeochemical stratification.

Suitability for domestic water supply

The depth at which water would be encountered in a well has always traditionally influenced the choice of domestic water supply source in the Niger Delta. The shallow water table at Umuebu, Aragba and Abraka Inland (Table 1), explains the preponderance of manually dug wells in these areas. Boreholes predominate at Abraka Urban and other areas located on the outcrop of the Benin Formation where the water table is deeper. The chemical parameters for both water supply sources in Table 3 are below the Nigerian guidelines for drinking water (SON, 2007). However, the presence of cadmium detected at three locations CII, C3P and NAS Rd where it occurs above the guideline value of 0.003 mg/l is worrisome and needs to be monitored because of its toxicity (Ifeagu and Ayankora, 2012). The source of cadmium enrichment in the area is unknown but its presence in stream sediments at elevated levels has been reported from nearby Ndokwa area by Emeshili (2008). Akpoborie (2011) and Aweto and Akpoborie (2011) have drawn attention to the potential problems that could be associated with continous ingestion of low TDS water in the long term especially when combined with very low levels of calcium and magnesium in drinking water supplies as reflected in the values for both ions in Tables 2 and 3.

Calcium and magnesium are essential micronutrients and their deficiency in drinking water supplies especially when dietary habits exclude foods rich in calcium and magnesium has been associated with increased risks of osteoporosis, nephrolithiasis (kidney stones), colorectal cancer, hypertension and stroke, among others (Ong, 2006; Kozisek, 2006). Enrichment of these micronutrients is therefore recommended if the water in this area is to be used as a source of raw water for public water supply schemes. Finally, gradual impairment of ground water with coliform bacteria (WR2, Table 3) by water from the abandoned quarry at Winner's Road confirms the potentially high vulnerability of the shallow and upper layers of the Benin Formation in this area to contamination as suggested by the predominantly sandy lithology.

Suitability for water contact recreation

The River Ethiope is the most prominent natural feature in Abraka area. The waters of the river are crystal clear, and the white river sands are of clean quartz grains with the result that the river is like a giant natural aquarium where fish and other organisms may be observed. This natural beauty is the main attraction for the rapid development of the hospitality industry along the river's south bank. Indeed, the river is an international tourist destination site and a gallery of spectacular pictures from some of the recreational beaches has been posted on the World Wide Web by Emiel Jegen (Jegen, 2004). In order to establish the suitability of river water for full body contact recreation, water samples from the more popular sites (Figure 3) were screened for the presence of coliform bacteria over a 30 day period in March 2011 in the middle of the dry season when the sites enjoy maximum patronage. The results which are shown in Table 2 indicate that occurrence of *Escherichia coli* is less than 50 cfu/100 ml at all sites. This level of occurrence is well below the guideline value of 126 cfu/100 ml for *E. coli* specified by the U.S. Environmental Protection Agency (USEPA, 2003) and affirmed by Wade et al. (2003) who reviewed the issue of using *E. coli* as the choice indicator of fecal contamination of bathing waters. Omo - Irabor and Olobaniyi (2007) report a mean *E. coli* occurrence of 145 MPN/100 ml in River Ethiope water with a range of 39 to 502 MPN/100 ml but do not provide results from individual sample sites thus precluding direct comparison with results shown in Table 2.

With respect to chemical quality, the World Health Organization (WHO, 2003) and the Australian National Health and Medical Research Council (NHMRC, 2008) are in agreement that health risks associated with chemical contamination during swimming are usually insignificant. The results in Table 2 indicate that the quality of water in the River Ethiope is suitable in this regard for swimming purposes.

Suitability for irrigation

The standard indices that are universally utilized to determine suitability for irrigation purposes have been determined for all samples and the results shown in Table 4 are summarized as follows:

Salinity hazard: High TDS in irrigation water affects soil efficiency, plant growth and yields. Following from Wilcox (1955) water with TDS that is less than 200 mg/l is excellent for irrigation and all water sampled in this study falls in this category.

The sodium adsorption ratio (SAR), the tendency of water to replace adsorbed calcium and magnesium with sodium was calculated as follows (Hem, 1991):

$$SAR = Na^{+} / \{[Ca^{2+} + Mg^{2+}] /2\}^{0.5}$$

Where the concentrations are expressed as milliequivalents per liter. All water sampled in this study falls within the low (< 10) SAR category (Richards,1954) and is thus suitable for irrigation.

Magnesium hazard was estimated with the Szabols and Darab (1964) relationship:

$$MH = (Mg^{2+} \times 100)/ (Ca^{2+} + Mg^{2+})$$

Table 4. Parameters for determining suitability for irrigation.

Sample site[a]	Parameter[b]				
	Facie	SH	SAR	MH	RSC
ARG	Na-HCO_3	Low	1.85	7.4	0.24
ABK INL	Ca-Cl	Low	0.312	10.3	0.0
UGN	Na-Cl	Low	0.725	9.57	N/A
CII	Na-Cl	Low	0.994	74.8	0.0
C3G	Na-Cl	Low	1.11	77.4	0.0
C3P	Na-Cl	Low	1.41	67.3	0.0
NAS Rd	Na-Cl	Low	1.16	73.5	0.0
WR1	Mg-Cl	Low	0.606	57.2	0.0
MC	Na-Cl	Low	0.476	35.5	0.0
MJ	Mg-Cl	Low	0.186	56.5	0.0
MD	Mg-Cl	Low	0.207	80.7	0.0
TR	Mg-Cl	Low	0.239	78.5	0.0
OKR	Ca-SO_4	Low	0.114	7.63	0.0

[a] ARG, Aragba; ABK In, Abraka Inland; UGN, Ugono; CII, Geology Lab; C3G, Campus 3 Gate; C3P, Campus 3 Pool site; WR1, Winner's Road 1; WR2, Winner's Road 2; DS, Dump site; MC, McCarthy Beach; MJ, Majoroh Beach; MD, Mudi Beach; TR, The Turf; okr, Okemesi River; Nas Rd, Nassarawa Rd. [b] SH, Salinity Hazard; SAR, sodium absorption ratio; MH, magnesium hazard; RSC, residual sodium carbonate.

Waters that have MH ratios > 50 are considered harmful to soils and may not be used for irrigation without appropriate treatment. The results in Table 4 indicate that water in the Abraka area has a high magnesium hazard and needs to be carefully evaluated in this regard before being utilized for irrigation.

Residual sodium carbonate (RSC) was obtained from the folowing relationship:

$$RSC = (CO_3^{+} + HCO_3^{2-}) - (Ca^{2+} + Mg^{2+})$$

Where all ionic concentrations are expressed in epm. Following the Eaton (1950) classification, RSC values from Abraka are all less than the + 1.25 threshold and may thus be safely used for irrigation.

Conclusions

This study has described for the first time aspects of the hydrogeology of the upper 20 m horizon of the Benin Formation aquifer in this part of the coastal plain and the Niger Delta. This horizon consists of a succession of fine grained reddish brown sands underlain by typically clean, grey – off white and fine – medium - coarse grained, angular to sub- rounded well sorted quartz sands. Depth to water level in the water table ranges from about 4 to 16 m. Sustained groundwater abstractions around the more densely populated Abraka Urban have resulted in a depression of the water table in the area towards which groundwater is flowing from virtually all directions in a distortion superimposed on regional southwestward groundwater flow. Hydraulic conductivity of the medium grained sands that are usually screened at an average 20 m depth in production wells is estimated from grain size analysis to range from 0.12 to 0.19 $msec^{-1}$. The major ion geochemistry indicates that groundwater is an admixture of NaCl, CaCl and $NaHCO_3$ facies and there is evidence of possible hydrogeochemical stratification. All water has very low TDS and this suggest that the perennial leaching of soluble minerals by recharging rainfall from the near surface horizon of the Benin Formation is probably responsible for the presence of minimal amounts of mineral content in water. It has also been determined that surface water and ground water are suitable for domestic use, irrigation and industrial purposes without prior treatment and that the water in this stretch of the Ethiope River is suitable for full body contact recreation.

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Full Length Research Paper

Strategies and techniques of providing adequate and affordable potable water in rural areas of Nigeria

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Water is next to air in importance. The World Bank declared water as an economic good while endorsing the international demand for water supply. Human health depends on having access to safe, adequate and reliable water supply. In Africa, and of course in Nigeria, one half of the entire continent's people (particularly in rural areas/communities), suffer from one or more of the six main diseases associated with poor or polluted water. Statistics show that Africa has the highest occurrence of cholera and typhoid epidemics as well as child diarrhea. Of the 46 countries in which schistosomiasis are endemic, 40 are in Africa, of the 19 countries reporting guinea worm, 16 are in Africa. In September 2000, 147 heads of state and governments, and 189 nations in total, committed themselves to the Millennium Development Goals (MDGs). One of the targets defined for achieving the MDGs is to "halve by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation". This paper constitutes a source of information for water and sanitation coverage estimates in southwest geo-political zone of Nigeria. It provides information of the current status of water supply and sanitation in the zone. The paper attempts to look into the appropriateness of the use of the technology of integrated mini water scheme and infiltration gallery as a means of providing safe and adequate domestic water to rural community people to serve as the best preventive medicine against the prevalent water diseases.

Key words: Strategies, affordable, adequate, potable, water.

INTRODUCTION

Water is a ubiquitous chemical substance that is composed of hydrogen and oxygen and is vital for all known forms of life. In typical usage, water refers only to its liquid form or state, but the substance also has a solid state, ice, and a gaseous state, water vapor or steam. About 71% of the Earth's surface is covered by water. On Earth, it is found mostly in oceans and other large water bodies, with 1.6% of water below ground in aquifers and 0.001% in the air as vapor, clouds (formed of solid and liquid water particles suspended in air), and precipitation. Oceans hold 97% of surface water, glaciers and polar ice caps 2.4%, and other land surface water such as rivers, lakes and ponds 0.6%. A very small amount of the Earth's water is contained within biological bodies and manufactured products.

The impact of water use on our ecosystems should be an intricate issue of special concern in every area of the world as water is the one resource we cannot live without. Water is our most precious resource. Yet it is currently under attack by our waste, pollution, privatization, and the exacerbation of climate change. We must be aware of this and work to preserve and conserve water for future generations. This will be our legacy to our children (Harlander and Labuza, 2006).

It is good to finally see life cycle assessments being done for water use. More water is wasted (and polluted) in industry, yet they are not accountable for the water they use. And even though these assessments are not

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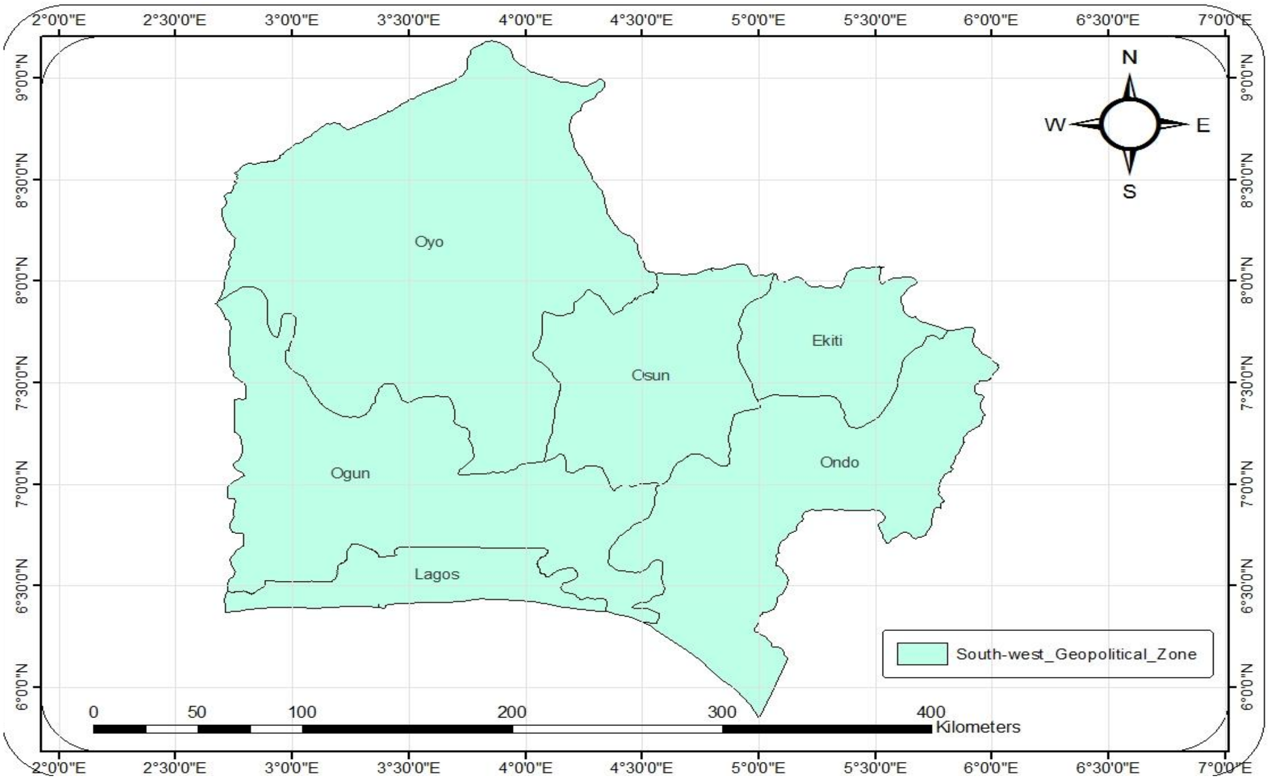

Figure 1. South-Western Nigeria.

based on changing factors over time, they at least give a good idea of what is being used, wasted, and how best to conserve water in different regions of the world experiencing different effects regarding that usage due to population, population growth, deforestation, agriculture, and now chiefly, climate change which is precipitating drought and melting glaciers more rapidly which absolutely effects the life cycle of water and all that depend on it (Osho and Dashell, 1997).

Africa is endowed with abundant water resources although its distribution and availability for use varies widely, with quite a number of countries facing water shortage and water stress. Regional and national water figures often conceal the dramatic effects of local water scarcity, limited or polluted supplies and inadequate distribution systems. Access to fresh water has been identified repeatedly as a key condition for development. National water policies and conservation efforts often tend to focus on the supply-side for domestic and agricultural use, and less commonly on industrial needs. Under these circumstances the uncontrolled use of a limited resource by water intensive industries takes on a special significance (UNEP, 2006). Potable water supply in our rural is achievable when we take all the necessary steps to achieving this, Adesogan (2008) stated that our world can be a world of plenty if we wish to make it so. In the past, many attempts have been made to solve the problem of water supply. These include the use of stream waters; construction of reservoirs and digging of shallow wells. These methods are not full proof as there are still records of potable water shortages even with these in place. The construction of reservoirs makes water to be susceptible to odour because the water in the reservoir may not be adequately aerated. Shallow wells, if too close to the septic tank can be polluted. These problems arising from poor water supply are crucial in the development of any community and efforts must be made to minimize or where possible eliminate them. An understanding of the strategies and techniques of providing potable water in our rural areas is necessary to be able to achieve this and therefore, there is need for this research. There is therefore the need to look into the appropriateness of the use of the technology of integrated mini water scheme and infiltration gallery as a means of providing safe and adequate domestic water to rural community people to serve as the best preventive medicine against the prevalent water diseases.

Study area

This study was carried out in Southwestern Nigeria comprising Oyo, Ogun, Lagos, Ekiti, Ondo and Osun states. The region has a bi-modal wind pattern with peaks occurring in April and August associated with rainstorm causing pollutions to water sources (Figure 1).

Table 1. Summary of water supply situation in Southwest Nigeria.

State	% Access to improved water supply			% Water supply coverage		
	Urban	Small towns	Rural	Urban	Small towns	Rural
Ekiti	56	68	57	29	33	27
Lagos	87	83	73	24	21	21
Ogun	84	66	55	49	36	27
Ondo	67	60	60	18	16	16
Osun	71	62	44	23	25	17
Oyo	72	59	54	27	22	21

Source: Survey (2009).

METHODOLOGY

Survey of water supply in South-Western Nigeria

The zone has six States out of which Ekiti State was selected as the pilot state for the research. The study approach involves the use of survey forms (questionnaire) designed the MIS consultant appointed by the Client. The forms are: Form 01 (Water Supply Facility Survey): To capture the location, attributes, and operational status of water supply facilities; Form 02 (Water Supply Agency Operational Survey): To collect data on the profile of water agencies in the state, in terms of production assets, capacity utilization, manpower; and financial sustainability; Form 03 (Sanitation Facility Survey): To capture the location, types and conditions of sanitation facilities; Form 04 (Water Related Diseases Survey): To collect data on reported cases of water related diseases from health institutions; Form 05 (Household Survey): To capture data on the proportion of households that have access to safe drinking water and sanitation facilities and prevalence of water related diseases in each community; Form 06: (Summary form for the Local Government Area).

Primary information was obtained through household survey carried out by recruited and well-trained enumerators. The survey was carried out in every ward in each of the six States of the geo-political zone. Within each ward, at least 24 houses were selected. Where the ward is a multi-community ward, the selected houses were shared among two randomly selected communities in the ward. However, for multi-ward communities, that is, communities with more than one ward within them, the selected houses were systematically spread among two randomly selected streets or quarters in the community. Facilities survey and determination of their coordinates were carried out by members of the project team with the aid of GPS. Secondary information on water supply and sanitation in the zone were obtained from the LGAs, State Water Boards/Corporations, State Ministries/Agencies of Environment, Ministries of Rural Development, Benin-Owena and Ogun-Oshun River Basin Development Authorities, water supply schemes, other sanitation offices and health institutions across the geo-political zone. Preliminary results of the study were discussed with stakeholders in each State de-briefing workshop where genuine concerns were addressed. State draft reports were circulated to respective State officials and a Zonal workshop organized to review the draft reports.

RESULTS AND DISCUSSION

Results of the water supply situation in the different settlement classes of the zone are summarized in the Table 1. With values mostly between 16 and 36%, water supply coverage is poor in the zone. The 49% value for urban Ogun State notwithstanding! However, access to improved water supply is much better all across the geo-political zone. Variations of these parameters within each Local Government Area are presented in individual State reports and in the zonal report. The results form the basis of calculating MDG targets as regards water supply by the year 2015. To meet this target, there is the need to substantially increase the water supply coverage from its present state all across the zone. In terms of sanitation, Table 2 presents a summary of percent access to sanitation facilities in the geo-political zone. Apart from Lagos, and to a lesser extent Ogun State, access to sanitation facilities is very poor in the zone. This result is further reinforced by the very little sanitation facilities mapped out during the survey as compared to water supply facilities. To accomplish the MDG target, there is a need to increase the number of sanitation facilities and pay more attention to people's access to the facilities. There are basically five categories of water supply promoters in the zone, with the State Governments being responsible for 100% of the surface water development. Even those developed by the Federal government are eventually handed over to their respective State governments. There are also the same five providers of sanitation facilities in the zone.

Disease survey

In the survey of more than 1,400 health institutions within the zone, malaria was found to be the most dominant water-related disease in each State of the zone. Typhoid, dysentery and diarrhea were found to be widely reported throughout the zone.

Strategies and techniques

Water supply schemes

Single-large and infective water schemes: In urban centres of developing countries with particular reference to Nigeria, Community water supply systems are

Table 2. Summary of access to sanitation facilities in Southwest Nigeria.

State	Total population	% Access to improved sanitation facilities
Ekiti	2,384,212	46.1
Lagos	9,013,534	84.8
Ogun	3,728,098	65.2
Ondo	3,441,024	36.7
Osun	3,423,535	36.5
Oyo	2,297,874	32.5

Source: Survey (2009).

fashioned after those that obtain in the industrialized countries with little or no adaptation. For example, Ado with a population of over 3.0 million is served from only a waterwork from Egbe with 180 million litres/day capacity. The water works combines Convectional treatment plant with mechanical pressure Filters in an arrangement that is very confusing resulting in frequent operational breakdowns. A disadvantage of this is that breakdown of the scheme will lay off all towns and villages supplied simultaneously. The distribution network is very scanty covering only about one-fifth of the entire city with complete neglect of the newly developed and economically viable areas of Omisanjana, Dallimore, Ajilosun, Opopogbooro etc. Only four reticulation reservoirs served the whole city with only three booster stations. Obviously, this cannot be an efficient system.

This same problem is likened to the old adage that “the strength of the chain is in the weakest link” in appraising the nature of the Ado water supply schemes. Ikere, Ise, Iju-Itaogbolu and many other villages are supplied from Ikere waterworks. Aramoko has only one waterworks, Irele, Itapaji, Ire, Oye, Agbado and Omuo were expected to be supplied from Ikole waterworks about 12 km from Irele. It is very clear and logical from the descriptions of some of the water scheme that acute water shortage has to be a citizen of our country. How do we “deport” this unwanted citizen?

Mini-water schemes

A study of 50 km radius of the city of Ado will reveal sources that could be harnessed separately for min-water schemes and which will meet the city’s ultimate demand if integrated together. Adesogan (2000) in projecting the potentials of mini-water schemes identified over 60 streams in Ado land most of which take their sources from springs. Adeniran (1997) has proposed the use of 6 mini-water schemes as supplements to the two gigantic water schemes in Ibadan. These include Olodo, Omi-Adio, Odo Ona Elewe, Ogunpa behind St. Patrick’s Grammar School at Idi-Ape Basorun, Tabielede at Ajibode and Sango/Oba at University of Ibadan. It is interesting to note that this report which was submitted at the end of Training course in the United States was never considered by the Water Corporation. It is doubtful if the report was ever brought to the notice of Government. It is however, gladdening that the same report was used by the University of Ibadan in developing the 6.0 millions litres/day mini-water scheme for the University. This scheme which serves a population of only 25,000 has made the University an oasis in the desert of Ibadan city. The U.I. scheme is maintained and operated by a total staff thus keeping overhead cost to the barest minimum. The scheme is also designed in modules such that any of the three modules can be operated without reference to others. This parallel arrangement makes water to be available at all times.

The importance of mini-water scheme can further be appreciated if an integrated water scheme is considered as is done in New York City. The entire city of New York with 5 Districts was discovered with 72 waterworks as at 1987. The largest of this waterworks only produced 20 Million litres/day. The water schemes are integrated in what was referred to as the “Pentagon Support Integration”.

Each of the mini-water schemes is completely independent serving only a population of between 10,000 and 30,000. Each water scheme is under instruction to produce about 25% more than the water demand of the area that it serves. This is to take care of emergency fire hazard and to render immediate “support” to a sister water scheme that might be having a “breakdown” problem. This way all areas are covered effectively on a 24 h basis either from “internal supply” or from “support supply” obtained from all nearby pentagons. The staff kept by each water scheme is scanty. Of course, the revenue collection is not the business of the water scheme; this is carried out by private entrepreneurs. These business organizations only receive a the bill from water supply management authority on the basis of the quantity of water supplied to their area. These organizations pay immediately and arrange to collect the bills from consumers in their area. Water is thus a business in its own case and not a social service. Adequate records are kept of industrial developments, population changes etc. Any new development or expansion is expected to be self financing.

Private sector partnership

At present, Government, through the State water agencies seems to be singularly saddled with the responsibility of providing public water supply to the people. Water is often made a political issue. Such central institutions alone are not generally able to support large numbers of water supply schemes with the technical, human and financial resources required for successful long-term operation and maintenance.

Funds

Data collection, designing and construction of water supply schemes are very capital intensive, so also its operation and maintenance costs are very high. The high cost makes many governments to shy away from embarking on provision of water supply. The National Policy on Water Supply and Sanitation stated that 404.522 billion would be needed to address the absolute demand gap and increase by about 25 billion per year to increase the existing capacity of waterworks and construct new ones.

Capital cost

Due to high capital costs and lacking of securing of loans, there are many completely designed schemes gathering dusts in our offices and waiting to be constructed. For example, Ijan, \Aisegba, Ode and other towns and villages' water supply scheme was completely designed in 1991 but could be constructed due to lack of fund. As a result, of time-lag, the design is now obsolete and had to be re-awarded to another consultant who promised to secure loan for the construction of the scheme. This is yet to be actualized.

Others are mini-water supply schemes for eight local government headquarters in Ekiti State. The National Water Supply and Sanitation policy suggested that the capital cost of project be shared amongst the Federal, State and Local Governments and the community in the percentages shown in Table 3.

The National Policy also advocated cost distribution for operation and maintenance as shown in Table 4.

Also “business as usual” for provision of water supply must stop and “business unusual” must be adopted if all citizens of this Nation must have access to potable water by involving private sector participation in water supply. There are various options of Private Sector Participation as service, management, lease, Build-Operate and Transfer (BOT) and concession contracts which are available and being used by many countries including developing countries in the world. However, there must be a very strong political leadership before some of the options could be used.

Involvement of entreprenuers

The general discussion in the Nigerian water industry today is commercialization. Lending agents continue to emphasize that the water agencies become economically sustainable. This is a laudable and welcome development. However, from experience elsewhere in the world it is established that this thrust towards commercialization along will not be sufficient to change the culture and improve the efficiency without the autonomy of the water agencies. Waller (1998) has suggested that without the commercial freedom to employ staff, but chemicals, maintain plant and operate as a business outfits the SWA's will remain hindered however efficient they manage to be.

The Government may not want to release SWA's from their control except it is to the private entrepreneurs. However, the World Bank experience indicates that management contracts suffer from a similar fate to commercial operation without autonomy. The output of an organization cannot be improved without the ability of the management to make its own decisions. Hence, the involvement of private sector is critical step in achieving independence and hence a proper commercial capability.

It is obvious, from performance indices, that most of the Water Agencies in Nigeria and the developing world are poorly established in terms of physical and human resources that development by Government and technical assistance are the only option left for them. However, if strong management is introduced, many of the agencies can ensure that operating expenditure is at least brought into balance with revenue collection. This will often necessitate the increasing of tariffs in accordance with a well determined unit cost of production. The options for involving the private sector in the Nigerian water supply industries can be addressed by focusing on the development of assets information, encouragement of the private sector, regulation and reduction of running costs.

Health engineering with minimal resources

One of the themes running through this paper will be the intension of a growing understanding that aid or the direct giving of help is not development, and tends to be detrimental in the long term. In countries of Africa, this includes giving by Central Government as well as giving by external agencies. But there is also the realization of the need for pump-priming by outsiders, the urgent need for a catalyst to release the inherent abilities of the people. This can be seen most clearly in the requirement which gradually became clear of the need to ``invest'' on occasion in expensive structures which apparently served no particular purpose in improving health. For example, permanent materials Primary Health Care Clinic might appear an unnecessary luxury when compared to an improved mud, wattle and thatch building with a 20 to 1

Table 3. Water supply scheme.

Agency	Rural (%)	Small town (%)	Urban town (%)
Federal Government	50	50	30
State Government	25	30	50
Local Government	20	25	10
Community	5	5	10

Source: Federal Ministry of Water Resources.

Table 4. Water supply scheme.

Agency	Rural (%)	Small town (%)	Urban town (%)
Federal Government	-	-	-
State Government	10	-	100
Local Government	20	-	-
Community	70	100	-

Source: Federal Ministry of Water Resources (2008).

cost difference. However, it could serve a vital purpose in proving to the people that development was coming and would benefit hem. The other major lesson learnt was that although it is so easy to look down on people in such a situation, considering them underdeveloped with little initiative and little willingness to help, they were survivors. They were the ones who had managed to live through a long time in a hostile environment. They were therefore canny and wise and manipulative and in a very reasonable way were out to get the best for themselves, their people and their District. Not surprisingly this meant they wanted to see the largest amount of money invested in their District in the shortest possible time. They wanted structures and hardware and goods and medicine and were not enthusiastic to hear about community participation and the need to use their own resources.

Community involvement in water supply

Now it became possible to discuss alternative forms of improvement to existing water sources, particularly in areas where the people were widely scattered. The Community Health Workers responded enthusiastically to the opportunity to carry out a survey of water resources in their area and, with the people, to recommend ways of improvement. In the areas where unlined hand-dug wells were used already, concrete culvert rings being used in feeder road upgrading could be given to seal off the well from surface water intrusions. In other areas where there is stream a couple of bags of cement could allow a small masonry dam to be built on a stream to increase the storage of water in the sand during the dry season. Such sand reservoirs gave natural filtration, limited evaporation, prevented mosquito breeding on stagnant pools and by reducing the frogs' habitat reduced the number of snakes.

In an area which had proved fruitless for drilling because of the un-weathered fresh rock, part of an outcrop could serve as a natural reservoir which could be cleaned out and enlarged by a small masonry wall. This rock catchment would enable them to use the results of the rains for their water uses. Community involvement does not always have instant result of course. News of failure in any development project appeared to spread very quickly through a community. News of success was less obvious but people were watching and gauging what was going on and when an idea worked it picked up momentum and schemes appeared to multiply exponentially.

Artificial recharge and recovery method

There are natural ground water replenishment or recharge methods. It was noticed that this increases the volume of water in the soil, and raised the ground water level. The phenomenon was particularly noticed in the arid and shore or coastal areas. The subsequent rise in: (1) population; (2) surface water pollution, and (3) water consumption.

Definition of artifical recharge

Artificial ground water recharge could be defined as planned activities of man whereby surface (streams, rivers, lakes) waters are made to percolate and infiltrate the ground at rates and in quantities many times in excess of natural recharge. By judicious design of recharge and recovery cycle, corresponding increase in the amount of ground water abstracted is possible with impeccable bacteriological quality.

Methods of artifical recharge (AR)

Ground water reserves in the aquifer can be increased in two major ways.

Natural / artificial method: Which is generally referred to as indirect method? In this case, increased replenishment is obtained by locating the means of ground water abstraction (infiltration gallery, large or small diameter well), close to any surface water (stream, river or lake with porous or pervious banks within a well accompanying abstraction (by pumping) will result in increased in flow of water from both the surface water and the aquifer sources through the pervious soil. This method is otherwise called induced recharge.

Direct method: This is the method by which water from a distant (or near) surface source (stream, river, lake, pre-treated sewage water, storm drainage) is transported or conveyed to areas or point where it is spread over the surface of previous soil basins, ponds, ditches or furrows and by pits, shafts, channels or by mere flooding in less pervious soil.

Induced or indirect artificial recharge: Criteria of design

As described previously, induced AR is the situation whereby water is drafted into the soil by locating as infiltration gallery or a (small or large diameter) well at small but carefully designed distance parallel to a surface water source (stream, river or lake).

At beginning of the water recovery to the rural area, the water pumped out $q_o = q_n$. This is the case when the ground water table is higher than the water level in the surface source nearby (where q_n is the natural underground water level in the surface rainfall P). As the water demand increases, pumping rate increase, the ground water level will fall below the surface water level. At this time recovered water q_o could be expressed as follows:

$q_o = + q_n$

Where q_s is the water induced by pumping from the surface source through the soil into the gallery or well at distance, L form the source. This is the artificial groundwater supplied by downward percolation of the river water which infiltrates the pervious soil into the gallery or well or a battery of them.

Use of well

Induced ground water recharge with gallery is not only possible when the ground water is not at a great distance single well bear a surface may suffice but when the demand is large a line of wells parallel to the streamed is used.

Single well for small demand

When a single well is used, the only design factor is the distance L between the well and the shore line. The drawdown S_o is small and it is localized. Thus, it des not form a design limiting factor. Also, the entry rate V_e of the surface water into the aquifer is not a boundary condition as the aquifer is deep down. Thus detention time T for the flow of surface water to well is the only design requirement, the distance L must satisfy. And minimum required distance L of the well to the shore line. Therefore with the notion, the elevation h of the ground water is expressed as (using Darcy and continuity equations as applied to unconfined/and semi confined aquifer).

Battery of parallel wells for large capacity

When is needed to supply large amount of a cluster of villages or rural communities, urban segmented communities, or about 100,000 to 200,000 people, whose water demand is in the order of 0.23 m^3/s (about 20,000 m^3/day) and above, induced recharge and recovery by battery of wells is the right solution. All the wells must be located at a distance “L” parallel to the shore line or streambed.

Design assumptions

The wells are each at a distance L from the shoreline/streambed. The distance of the wells from each other is a small distance, “b’’ compared with their distance L from the streambed. In the above two conditions, the flow pattern is assumed equal to that of a gallery with capacity. These three conditions simplify the design of this artificial induced recharge scheme to be exactly the same as for a gallery. A constant value of coefficient of transmissibility KH is assumed and that the river fully penetrates the aquifer thickness.

Conclusion

It is therefore not out of reason for water resources and environmentalengineerstore-access theabovesubmission (a mere reminder of what exists), then enlist the artificial recharge and recovery (AR & R) method in the list of water supply options to rural or small communities.

Mini water supply option based on small communities in all the local government area should replace the ineffective and inadequate gigantic option that is the vogue now. Decentralization of water supply scheme with monitoring, administrative, financial and technical authority shared between the community users (stakeholders), local and state governments. This will give and ensure efficient method for effective production of adequate hygienically reliable water that can ensure and give preventive medicine for the local/rural dwellers against water-borne disease.

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Review

Integrated water resources management in Iran: Environmental, socio-economic and political review of drought in Lake Urmia

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In recent years Lake Urmia, the largest saline lake in the Middle East located in northwestern Iran has undergone severe environmental changes. As a result of drought and anthropogenic impacts, the area of the Lake has been shrunk and the water level has been dropped. In this article the environmental, political and socio-economic impacts of drought in Lake Urmia basin has been reviewed and the obstacles regarding institutional water frameworks in national and regional levels has been studied and assessed. Furthermore, lack of sufficient mitigation and adaptation policies and inadequate attention to the environmental impact assessment during megaprojects has been discussed. The most crucial impacts have been realized as ecological and environmental consequences of lake drying up on all over the Lake Urmia catchment. In associated with these consequences, several scarce species of flora and fauna are exposed to the danger of extinction, and polluted air ensued by the salt storms affect the daily life of people in the region. In addition, this event has a direct influence on the economy of the region. Therefore, the implementation of a holistic institutional-based remediation program to accomplish lake restoration seems to be inevitable.

Key words: Lake Urmia management, Lake drought, human activities, climate change, environmental impact assessment.

INTRODUCTION

Lake Urmia (formerly called Rezaiyeh) is a shallow landlocked hypersaline lake located in northwestern corner of Iran close to the border with Turkey. It is known as one of the largest continental salt lake in the world and the largest one in the Middle East (Figure 1) (Hassanzadeh et al., 2012). Recently, area and volume of the lake have been shrinking seriously. The lake was declared a Wetland of International Importance by Ramsar Conversation in 1971 and designated a UNESCO Biosphere Reserve in 1976 (Chander, 2012).

Lake Urmia is one of the hyper saline lakes throughout the world. In addition, this basin is an endorheic basin that retains water and does not allow any outflow to other external bodies of water. According to the information issued by The Ramsar Convention on Wetlands, the primary outflow of Lake Urmia is evaporation and the primary inflows are precipitation, freshwater discharge from the rivers and getting fed by springs. Increase in evaporation and decrease in rainfall, freshwater inflow and springs inflow has led to salinization and water level decline.

The surface area of Lake Urmia has been estimated about 5200 km^2 and the area of the basin is estimated 51,876 km^2. Lake Urmia possesses more than 102 rocky

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Figure 1. Location of the Lake Urmia.

saline islands and its ecosystem is the habitat for more than 212 species of birds, 41 reptiles, 7 amphibians, and 27 species of mammals which most of them are endemic species (Rezvantalab et al., 2011).

According to the U.S. Geological Survey anticipation, the Lake Urmia is sharply drying, and it may completely vanish in just two years (USGS, 2012). If this scenario happens just a vast salt desert will remain from this lake which is an undeniable treat to the local ecosystem. Therefore two main problems have been recognized and defined lately based on water quantity and water quality.

In terms of water quantity, according to the official statistics, more than 60% of Lake Urmia is disappeared since 1960s (Karmi, 2011). The water level decline is another drought indicator. Based on current investigations, in a recent drought of the Urmia basin, started in 1999, the water level of Lake Urmia dropped from 1277.80 masl to 1273.35 masl (Tabari et al., 2012). During August 1998 to August 2001, water level of Lake Urmia declined up to three meters and caused serious decrease in the area of the lake, approximately from 6000 to 5200 km^2.

In terms of water quality, the lake has been decayed and sudden change in salinity regime has been occurred. Currently the amount of the salt, dissolved in the lake water, increased from 160 to 170 gL^{-1} up to 400 gL^{-1} (Zarghami, 2011). The mentioned disaster has affected the biota of the lake. In these conditions, water with so high salinity is no longer a suitable and sustainable environment for fauna and flora and has caused to destroy the ecology of the lake.

Figure 2 represents shrinking in the area of the Lake and severe drought has been observed (left picture) and the trend to this drought is likely to be continued (right picture). As a plausible consequence, the eastern and southern areas of the lake would be completely dried up until 2019 and this can be associated with irreparable environmental impacts in the ecosystem of the Lake Urmia catchment.

Objective

This article aims to develop a holistic review on ecological and environmental impacts and political and socio-economic implications of Lake Urmia basin drought in response to anthropogenic drivers such as increased water demand due to population growth (Statistical Center of Iran, 2012) and environmental pressures (e.g. climate variability and climate change) within the context of current institutional set-up. Political and institutional obstacles will be presented and comprehensively discussed in this review. Thus the final conclusion of this review reflects the previous and the current river basin's characteristics and the impacts of human activity and climate change on the status of water bodies in the basin and the possible measures. For this aim, this study will also address how the water quantity and quality and ecological states of Lake Urmia Basin has been changed over the past decades. The ultimate objective of this review paper is to create and develop a recommended list of measures that might improve the management of the Lake Urmia Basin.

LITERATURE REVIEW

Main drivers and pressures

Two major aspects of drivers which are responsible for this environmental crisis are anthropogenic driving forces and natural driving forces. In this occurrence, anthropogenic drivers are more effective than environmental drivers. Sharp population growth during 1980 to 2011 and intensive immigration towards big cities raised the food and water demand. Regarding to the amount of water which is consumed instead of being discharged in the Lake Urmia, these participations can be obtained that agriculture sector is responsible for 91% of the water consumption, whereas industry and domestic consumption are responsible for 6 and 3% of the water consumption respectively (Faramarzi, 2012). Raise of demand for water forced the government and farmers to provide numerous damming and water diversion projects and groundwater pumping stations to supply water demand.

The main freshwater resource is Zarrineh River, located in the south of the lake, supplying more than 50% of the annual inflow. Simineh River and Ghadar River are providing 35% of the inflow (Mohaggeg, 2002). Some of the freshwater from these sources flows unimpeded to Lake Urmia, but much of it is impounded within reservoirs or water diversion dams for the sake of irrigation, drinking water, power generation (hydro-power plant) and industrial usage of water. For instance, Bukan dam was constructed on Zarrineh River in order to launch hydropower plant and supply water demand. The location of the Bukan Dam is specified in Figure 3. In addition, several damming and water projects are currently under

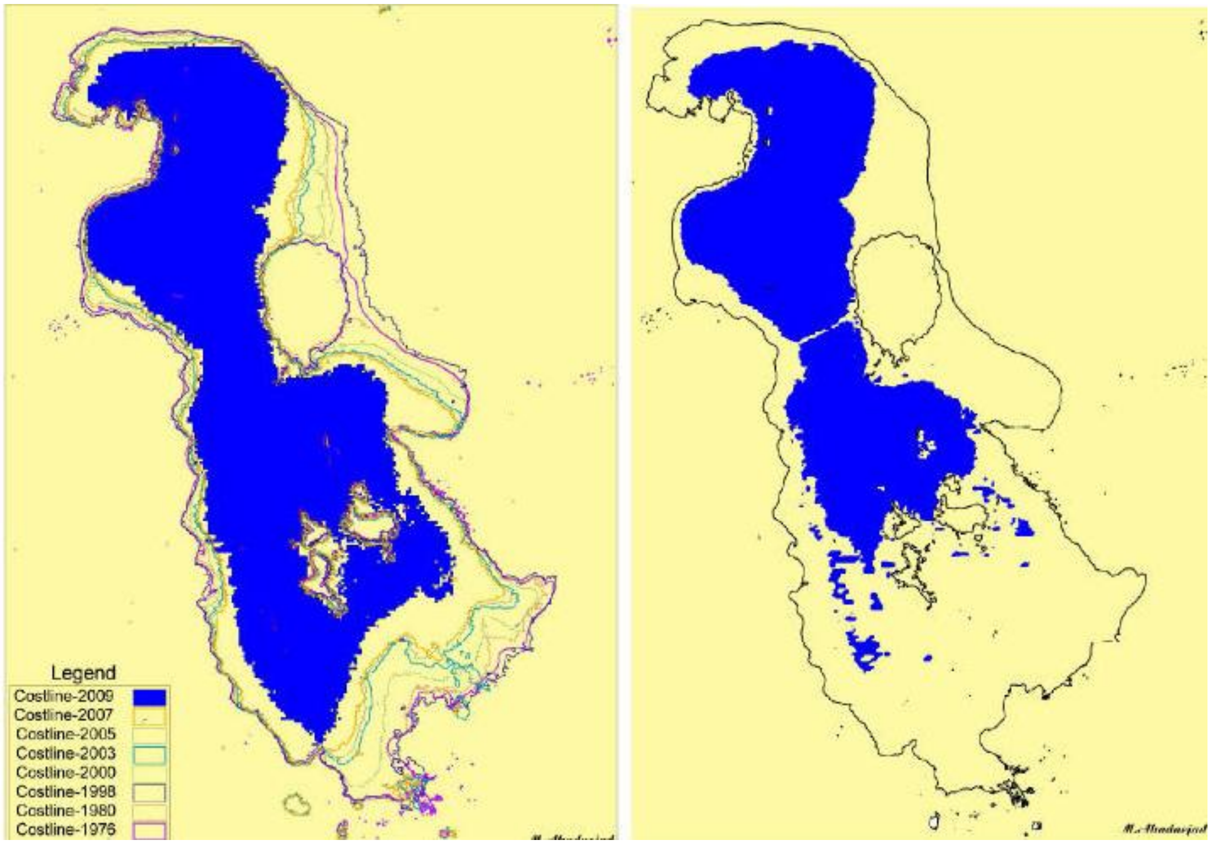

Figure 2. Lake Uremia water level changes in period 1976-2009 (left) and predicted change map by 2019 (right) (Ahadnejad Reveshty, 2010).

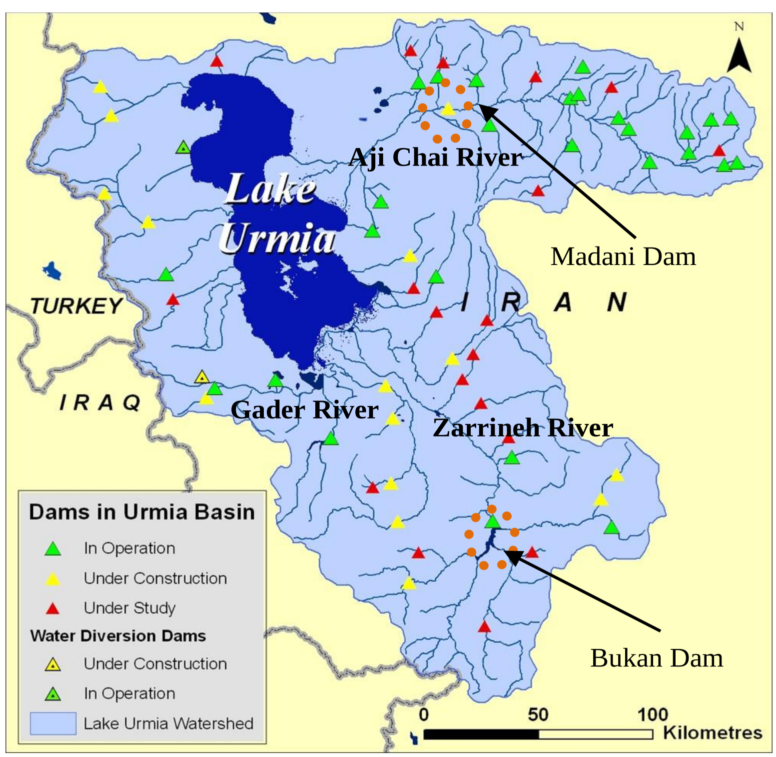

Figure 3. Dams location in Urmia Basin.

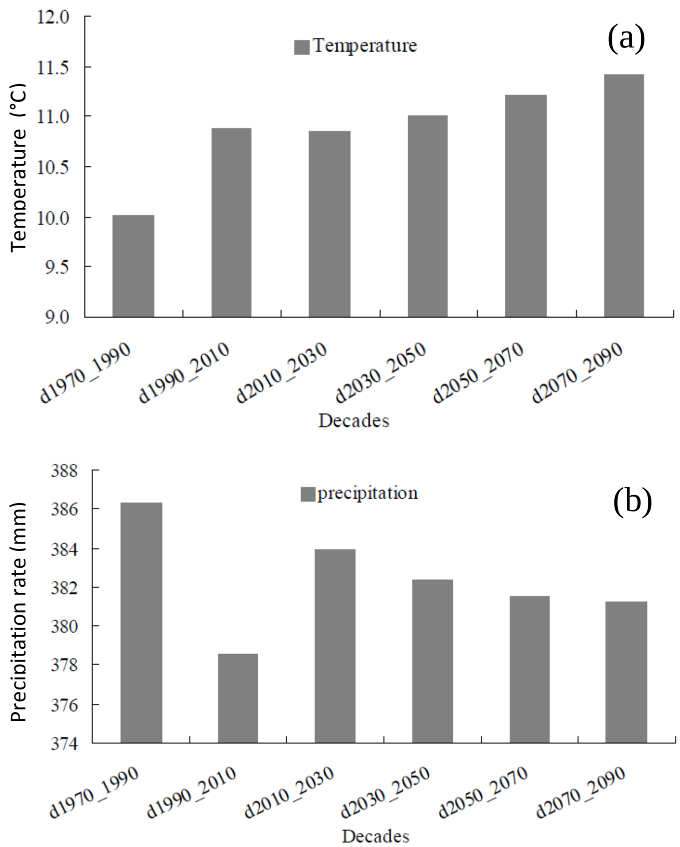

Figure 4. (a) Ten-year average (1970-2100) of trend of changes in temperature components of the Lake; (b) the ten-year average (1970-2100) of trend of changes in precipitation components of the Lake.

study and under construction. Since large number of dams and water diversion projects are already in operation on the rivers feeding the lake, Lake Urmia is shrinking, getting shallower and extremely drying, and a salt desert has been remained which can lead to several environmental consequences. Furthermore, groundwater excessive unsupervised overuse caused groundwater depletion which decreased the amount of water that is fed into the lake by the springs. This event may lead to the salt intrusion in the catchment of Lake Urmia.

Moreover, the construction of a causeway, from 1999 until 2007, in order to decrease the distance between Tabriz city, capital of East Azerbaijan province, and Urmia city, capital of West Azerbaijan Province, was believed to pressurize the flow and salinity regime of the lake. Various studies has shown the influence of the causeway construction on the lake’s hydrodynamics and water quality by using two-dimensional and three-dimensional numerical models (Zeinoddini et al., 2009). The necessity to build a new road is the direct effect of population and trade growth as the main drivers and consequently increasing transportation demand is the main pressure (Khosravifard, 2010). This bridge divides the lake into two parts. The severe drying of the lake was simultaneously coincided with the project construction duration and has been intensified after running the project. The flow and salinity regimes are affected by the presence of this new causeway (Zeinoddini et al., 2009).

Furthermore, due to climatic variability and climate change the quantity of water flowing into the lake varies annually. Higher temperature and less precipitation have led to higher evaporation from the lake and less water yield into it. As evaporation is the primary output and precipitation is the input, salinization will increase dramatically due to less dilution.

Figure 4 shows the trend of the average temperature and precipitation changes which two time scales of the past and future are considered. To characterize the changes in climate components for time scale of the past and future the longitudinal data set between 1968 and 2011 and between 2012 and 2100 considering the climate change effect have been used respectively. The changes of annual average of precipitation display a decreasing trend every decade from 1968 to 2011 which is equal to -14.8 mm/decade. The trend of changes in average temperature between 1968 and 2011 displays a significant rise which is equal to 0.59°C/decade. Also the increasing trend of annual temperature considering climate change scenario, indicates an increase in temperature of +0.88°C by the year 2100 in the Lake Urmia region. Furthermore, it is expected that the average of precipitation is projected equal to -0.37 mm/decade. Totally it will decrease as 3.3 mm by the year 2100 (Tisseuil et al., 2013).

These results of latter study are fully compatible with the map given in Figure 5. It shows that areas around Lake Urmia are being threatened by drought.

The decreasing factor in precipitation rate is estimated between 50% (severe drought) to 80% (weak drought). The map is based on the percentage of rainfall from September 2010 to January 2011 in comparison with the long-term average.

Therefore it is concluded that the precipitation (primary inflow of Lake Urmia) will decrease and the evapotranspiration will increase (primary outflow the Lake) by increase in the temperature.

States

All of these drivers and pressures have led to the current lake situation. As the Lake Urmia basin is an internal drainage system, the climatic factors have driven the lake to the more evaporation and less precipitation and the anthropogenic factors have led to less freshwater input. Less freshwater inflow and higher evaporation have led to higher salinity and water level decline.

Figure 6 represents the gradual change in surface area of the lake. After fluctuations between 1963 and 1998, sharp drop of surface area has been observed.

As shown in Figure 7, in terms of water quantity, although there are fluctuations in water level over the past

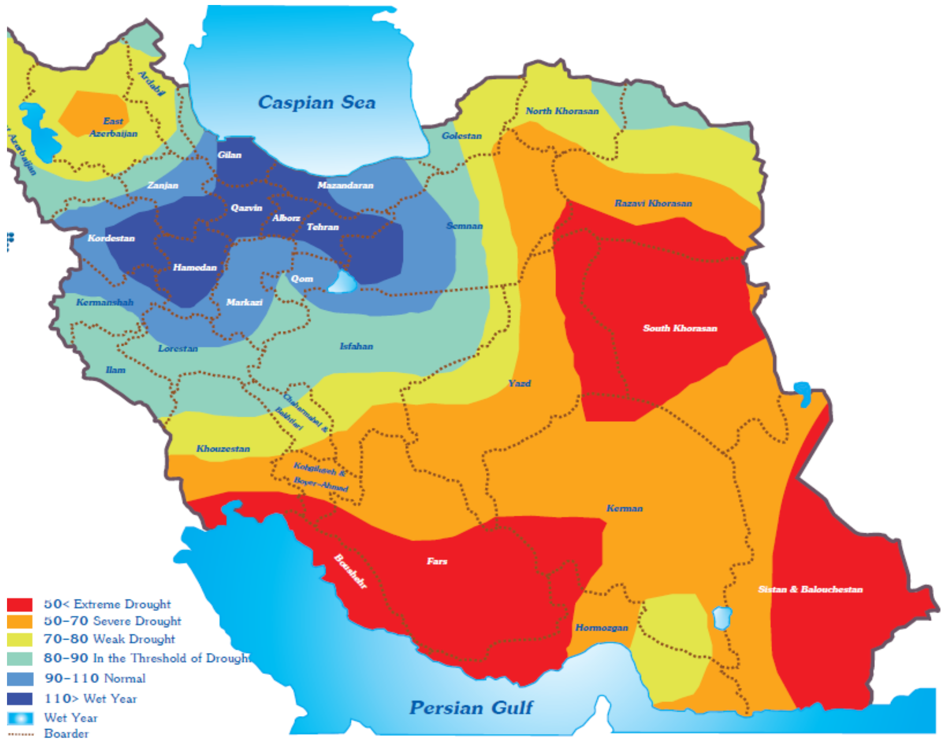

Figure 5. Drought map of Iran.

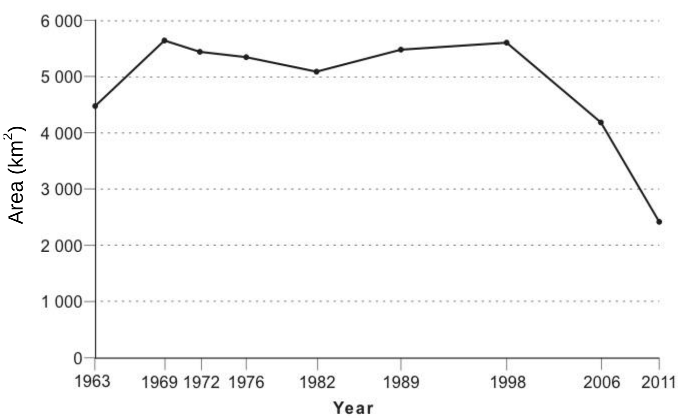

Figure 6. Lake Urmia surface area, 1963-2011 (Chander, 2012).

100 years, the trend line slope is negative which implies that the lake situation is getting worse.

In terms of water quality, recent investigations denotes that in early 2003 salinity of the lake has been raised up to 250 g/L in the southern part, whereas salinity was as high as 280 g/L in the northern part. More recent studies illustrate the amount of salt in the lake water increased from 160 to 170 g/L up to 400 g/L (Zarghami, 2011).

Environmental and ecological Impacts

Environmental campaigners claim that the construction of dams on rivers and the recently built causeway across the narrowest part of the lake have reduced the water level, affected the water circulation, increased the water salinity and jeopardised animals as well as aquatic organism. The most important flora and fauna which are presently endangered and may extinct in the future are aquatic organisms, regional vegetation, flamingos and Iranian yellow deer. Lake Urmia possesses more than 102 rocky islands. The islands and the wetlands around the lake are major staging areas for migrating flamingos, however their numbers have recently declined (Zafarnejad, 2010) (Figure 8).

Significant alterations in the biota of the lake endangered aquatic organisms such as Artemia, a kind of brine shrimp which is a unique cosmopolitan anostracan living in hypersaline and saline lakes. Artemia serve as food source for the migratory birds such as flamingos and is also used in aquaculture sector. Because of high salinity, Artemia was not able to fully recover in the lake's water (Abbaspour and Nazaridoust, 2007). The other consequence on the biota of the lake is fish mortality. Due to the high level of salinity, the Lake Urmia is no longer able to sustain any fish species.

The hydrological pressures on the lake have profound impacts not only on the lake itself, but also on the land cover and the water quality and the ecosystem of surrounding wetlands especially those located in estuary parts. Water quality conditions differed among the wetlands and ranged from mostly freshwater, nutrient-rich (eutrophic) conditions to more saline, nutrient-poor

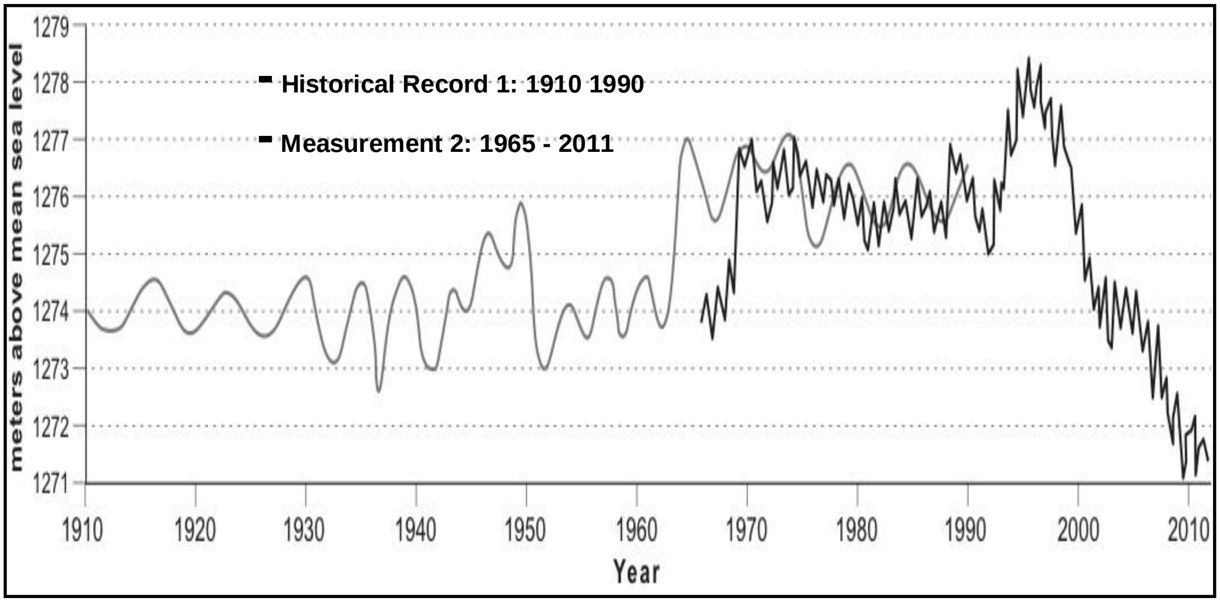

Figure 7. Lake Urmia water level change and its fluctuations, 1910-2011 (Chander, 2012).

Figure 8. Environmental Impact of Lake Urima Drying on biota of the lake basin: (Left: flamingos, right, and a dead flamingo).

(oligotrophic) conditions. One principal example is the aquatic macroinvertebrates living in Zarrineh River which are currently endangered upon poor nutrient conditions and highly saline water (Ahmadi et al., 2011).

Socio-economic impacts

The use of Artemia in fish and shrimp aquaculture is commercially important and recently has been restricted. Due to fish kill in Lake Urmia no fishing benefits can be expected which has led to reduce economic benefits.

Increase in the number of salt storm events is noticed over the last few years. Destructive effects of chemical pollutants of salt storms on bridge constructions and other infrastructures such as harbor and port facilities, cargo warehouses and passenger boats have been observed lately. In addition, when the toxins and minerals from the salt flats are blown into the air by these storms and inhaled, the toxins and minerals may cause throat and lung cancer, infant mortality, decreasing the life expectancy and increase in birth defects. Vice president of the Iranian Department of Environmental Protection believes that the consequences may lead to exacerbate air pollution in adjacent regions (Fazel, 2012; Interview).

The environmental specialists call these events “Salt Tsunami” (Khabbaz, 2012). The other impact on the social life is related to the mud bathing properties of Lake Urmia salt marshes. This is a medicinal bath in heated mud to treat some diseases such as Rheumatism.

Recently due to severe drought and unsatisfactory environmental conditions, this region may not be as a target for patients.

Political and Institutional implications

Integrated Management Plan for Lake Urmia Basin was signed by Ministry of Agriculture, Ministry of Energy, Chief of Iran's Department of Environment Protection and the governors of provinces responsible for the Lake Urmia basin. This IWRM plan consists of two main programs which are currently under implementations by Ministry of Energy, the main client for projects related to supplying water demand, and Ministry of Agriculture, the main responsible for irrigation sector.

The first and main suggested plan is to reduce agricultural water use to provide 3100 MCM Lake Urmia's water demand by expanding pressurized irrigation and changing cropping pattern (Morid, 2012). The proposed duration is 3 years and Ministry of Agriculture is the main supervisor of this plan.

As the second plan, constructing dams in the Lake Urmia basin will be suspended, and the possibility of transfer water from out of the basin for instance from Aras River and Caspian Sea will be explored. Water transfer from Aras River has started from February 2012, through this way annually 600 MCM water can be transferred into the basin, but the ecological consequences have seriously concerned ecologists (Chit Chian, 2013; Interview).

Prospective barriers of current Lake regenerative programs are insufficient collaboration between corresponding responsible ministries and organizations, mismanagement in responsible regional institutions and inconsistency in other administrative sectors which are leading to a notable delay in ongoing projects.

Furthermore, most studies on Lake Urmia are based on a few limited samples, so investment on research by universities and research institutes are crucial. Lack of government supervision and inadequate attention to environmental issues and human activities impacts is undeniable.

In terms of obstacles caused by publics due to overconsumption and lack of sufficient information, an educational program for public awareness about how the potential volunteers can cooperate to lake restoration programs is inevitable. Volunteers can be involved directly in Non-Governmental Organizations (NGO), charity foundations and public companies to maintain a public-private partnership structure (PPP) in order to save Lake Urmia.

RECOMMENDATIONS

The authors recommend the current restoration plans for saving Lake Urmia could include some other measures. We have integrated our new proposals and categorized the program of measures into three main procedures.

Procedure A is adjusting water allocation in the basin to allow an adequate flow for sustainable management of the Lake Urmia basin. Full descriptions on the proposed measures for water allocation adjustment (Procedure A) are given in Table 1. It has been presumed that the combination of all measures given in this procedure would be the best ecological option to save the Lake Urmia.

Procedure B could be carried out by importing water from outside the basin to supply water demand and let more water flow to the lake (Kordavani, 2012, Reiisi, 2011). Although procedure B as transferring the water has been proposed by many specialists as a time-efficient way to rescue the lake, the head of Iran's Environmental Protection Organization, noted that the corresponding Organization does not consent with the idea of transferring water from Caspian Sea or Aras River to Lake Urmia. Due to this prospective view, the following plans are detrimental to the ecosystem of the basin and may bring severe environmental degredation. Regarding to the remarkable economic costs for the government and the unbeneficial impact on the agronomy of the neighboring catchments, the procedure B cannot be justified. Therefore, Instead of procedure B, Iran's Environmental Protection Organization is intended in strategies more compatible with region's ecology (Ebtekar, 2013; interview).

Procedure C is proposing investment on research, designing and implementing novel techniques e.g. cloud seeding. That would be possible by providing the artificial rains on the Urmia Lake basin. Although the limited cloud seeding projects are under study, but the operation of these projects are still controversial.

CONCLUSION

Lake Urmia located in northwestern of Iran has experienced the severe drought over the past years, where over 70% of the lake water has dried up. Studies show the water level has declined since 1960s. Climate change and climatic variability in climatic patterns, increase in sowing areas, construction of dams and occurrence of excessive water wells around the lake are the main natural and anthropocentric reasons which caused the lake to diminish. These driving forces result in major changes in the area's ecosystem and significant changes in economy of the region.

On August 2013, the Iranian president established a working group to tackle the issue of saving the Lake Urmia. The work group was commissioned to use the background of the already conducted studies and technical research works to resolve this environmental problem and to present their proposals for saving the Lake Urmia to the government. However, in a long-term vision, more studies have to be accomplished on establishing an innovative and holistic IWRM framework

Table 1. Full description on the proposed measures for water allocation adjustment (Procedure A).

S/N	Proposition	Remarks
1	Stopping under construction dams and all ongoing surveys	Pros: Providing sustainable ecosystem for future More budget will be saved Cons: Unemployment at consultancy sector Farmers dissatisfaction
2	Opening remaining dams permanently or temporarily during wet periods	Pros: Providing water for restoring the Lake periodically Cons: Farmers dissatisfaction
3	Reducing agricultural water demand: 3.1) Deficit irrigation, 3.2) Reducing cropped area 3.3) Elimination of some of the annual crops 3.4) Changing the cropping patterns 3.5) Expanding pressurized irrigation 3.6) wastewater reuse 3.7) Enhancing agricultural drainage system	Pros: Accomplish more than 3000 MCM/year to the lake Cons: Social tension Unemployment Endangering food security Consuming huge budget Stakeholder management and engagement is needed Subsidies for supporting frames are required
4	Reducing municipal and industrial water demand: 4.1) Studying modern approaches regarding to drinking water supply and distribution systems, urban drainage and sewage collection and disposal systems 4.2) Public participation programs 4.3) Water and wastewater reuse	Pros: Can accomplish more than 600 MCM annually Cons: Lack of education High budget is required No studies are implemented so far
5	Reducing available Lake Urmia basin water quota for different sectors in each province only in drought spells	Pros: Sustainable allocation during drought spell Cons: Stakeholder participation More collaboration between regional sectors
6	Enhancing the water quality of the lake towards a proper ecological status: 6.1) Enhancing water and wastewater treatment techniques to lower salt loads into the water bodies (e.g. membrane filtration) 6.2) Salt and minerals extraction from accumulated salts around the lake	Pros: Sustainable management of ecosystem of basin Minerals extraction from the lake is profitable Cons: High budget Insufficient studies

to study the casual relations between the different drivers and responses of this crisis within the catchment. Once these frameworks are established, a work plan of remediation consisting of structural and non-structural measures can be conceptualized and implemented for sustainable management of Lake Urmia basin.

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Full Length Research Paper

Assessment of discharge and sediment transport from different forest cover types in lower Himalaya using Soil and Water Assessment Tool (SWAT)

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The present study was carried out to examine the applicability of Soil and Water Assessment Tool (SWAT) in estimating daily discharge and sediment delivery from mountainous forested watersheds and to assess the impact of forest cover types on stream discharge pattern and sediment load. The study watersheds namely Arnigad and Bansigad, comprising of dense Oak forest (80%) and degraded Oak forest (83%) respectively, are located in lower Himalaya (India). Apart from hill topography, deforestation in the watersheds results in huge loss of productive soil and water as runoff. Daily discharge, sediment concentration and other hydro-meteorological data were monitored at the outlet of each watershed. SWAT was calibrated and validated for daily discharge and sediment concentration using the observed data. The performance of the model was evaluated using the statistical measures of coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E_{NS}). The statistical analysis of calibration results for Arnigad watershed showed very good agreement between observed and simulated daily values, with an R^2 value of 0.91, and an E_{NS} of 84.48% in discharge simulation; and an R^2 value of 0.89, and an E_{NS} of 83.11% in sediment simulation. The model also exhibited high performance on Bansigad watershed with an R^2 value of 0.91, and an E_{NS} of 89.74% in discharge simulation; and an R^2 value of 0.86, and an E_{NS} of 82.07% in sediment simulation. The model performed equally well on validation data and estimated the discharge and sediment yield very close to the observed data. The simulated mean annual water yield and sediment yield were also comparable to observed values in both the watersheds. The mean annual surface runoff and water yield over the entire study period were simulated as 6 and 59.4% respectively of the mean annual rainfall in Arnigad watershed; and 6.9 and 63.7% respectively in Bansigad watershed. The results of the study indicated that SWAT is capable of estimating the discharge and sediment yield from Himalayan forested watersheds and can be a useful tool for assessing hydrology and sediment yield response of the watersheds in the region.

Key words: Oak forest, soil and water assessment tool (SWAT), discharge, sediment concentration, calibration, water yield.

INTRODUCTION

In mountainous watersheds, especially in Himalayan region, the spatial and temporal variability in terms of soil, land use/land cover, topography, rainfall and biotic forest cover, as well as young geologic materials have interventions is large. The steep slopes along with depleted been major factors in soil erosion and sedimentation in river reaches (Jain et al., 2004). Runoff and sediment yield data is scarcely available for Himalayan watersheds

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which are often required for operation and management of irrigation and hydropower projects in the region. Reliable measurement of various hydrological parameters including runoff and sediment yield is also a difficult task in remote and inaccessible areas. The use of simulation models can partially solve the problem of hydrologic evaluation of watersheds in conditions with limited and unavailable data of discharge and sediment yield. A suite of physically based, spatially distributed hydrological models are now available. The USDA-Agricultural Research Service (ARS) developed CREAMS model (Knisel, 1980) to simulate the long-term impact of land management on water leaving the edge of a field. Several other distributed models for hydrologic and pollutants transport modelling include ANSWERS (Beasley et al., 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1983), OPUS (Smith, 1992), AGNPS (Young et al., 1989) and SWRRB (Williams et al., 1985). These models were all developed for specific problems and have limitations for modelling watersheds with hundreds or thousands of sub-watersheds.

The soil and water assessment tool (SWAT) (Arnold et al., 1998), a physically based, spatially distributed model overcomes these limitations and is being increasingly used to assess the hydrological behaviour of large and complex watersheds. Rapid parameterization of hydrologic models can be derived using remote sensing (RS) and geographic information systems (GIS) as remotely sensed data provides valuable and up-to-date spatial information on natural resources and physical terrain parameters. Numerous studies have described the potential benefits and use of RS and GIS in hydrologic modelling (Hession and Shanholtz, 1988; Maidment, 1993; Srinivasan and Engel, 1991; Bhaskar et al., 1992; Pandey et al., 2005, 2009). Among others, the SWAT model has proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of environmental conditions. The model has been widely used in various regions and climatic conditions on daily, monthly and annual basis (Arnold et al., 1998; Mulungu and Munishi, 2007; Muttiah and Wurbs, 2002; Srinivasan et al., 2005; Tolson and Shoemaker, 2007) and for the watershed of various sizes and scales (Kannan et al., 2008, 2007). Rosenthal et al. (1995) tested SWAT predictions of stream flow volume for the Lower Colorado River basin (8927 km^2) in Texas. A GIS-hydrologic model link was used to aid in forming input files. Stream flow was simulated for nine years for four stream gauge locations with 60 sub-watersheds. With no calibration, the model closely simulated monthly stream flow with a regression coefficient (R^2) of 0.75. Bingner (1996) evaluated the SWAT model in the Goodwin Creek Watershed (21.31 km^2) located in northern Mississippi over a 10-year period. The land use of the watershed was primarily pasture and cultivated field. The Nash-Sutcliffe coefficients (E_{NS}) and R^2 values computed with observed monthly flow were all around 0.80. Srinivasan et al. (1997) used the SWAT model to simulate hydrology from 1960 to 1989 in the Rio Grande/Rio Bravo river basin (598,538 km^2) located in parts of the United States and Mexico. The simulated average annual flow rates were compared against USGS stream gauge records. Visual time-series plots and statistical techniques were used to evaluate the model performance.

In one of the few applications to study daily streamflow, Peterson and Hamlett (1998) used the SWAT model to simulate discharge in the Ariel Creek watershed (39.5 km^2) of north eastern Pennsylvania. Model evaluation of daily flow prior to calibration revealed a deviation of runoff volume of 68.3% and a R^2 of -0.03. Spruill et al. (2000) evaluated the SWAT model and parameter sensitivities were determined while modelling daily stream flow in a small central Kentucky watershed comprising an area of 5.5 km^2 over a two year period. Stream flow data of 1996 were used for calibration and of 1995 were used for evaluation of the model. The E_{NS} for monthly total flow was 0.58 for 1995 and 0.89 for 1996, whereas for daily flows it was observed to be 0.04 and 0.19. Oeurng et al. (2011) used SWAT to simulate discharge and sediment transport at daily time steps within the intensively farmed Save catchment in south-west France (1,110 km^2) and concluded that simulated daily values matched the observed values satisfactorily. Ayana et al. (2012) applied SWAT model to Fincha watershed (3,251 km^2), located in Western Oromiya Regional State, Ethiopia and estimated monthly sediment yield with R^2 of 0.82 and E_{NS} of 0.80 during calibration and R^2 of 0.80 and ENS of 0.78 during the validation period. SWAT has also been successfully used for simulating runoff, sediment yield and water quality of small watersheds for Indian catchments (Pandey et al., 2009, 2005; Tripathi et al., 1999).

Tripathi et al. (2003) applied the SWAT model for Nagwan watershed (92.46 km^2) with the objective of identifying and prioritizing of critical sub-watersheds to develop an effective management plan. The model was verified for monsoon season on daily basis for the year 1997 and on monthly basis for the years 1992 to 1998 for both surface runoff and sediment yield. Jain et al. (2010) calibrated and validated SWAT for estimating runoff and sediment yield from part of the Satluj river basin lying between Suni and Kasol in Western Himalaya. The R^2 values in estimating daily runoff and sediment yield were 0.33 and 0.26 respectively, while for monthly runoff and sediment yield these were computed as 0.62 and 0.47 respectively. They considered these values reasonably satisfactory for estimating runoff and sediment yield from remote watershed with limited data. The review of literature, in general, indicated that SWAT is capable of simulating hydrological processes with reasonable accuracy. However, studies related to applicability of SWAT to the watersheds located in Himalayan region of India are rarely available in literature. The present study

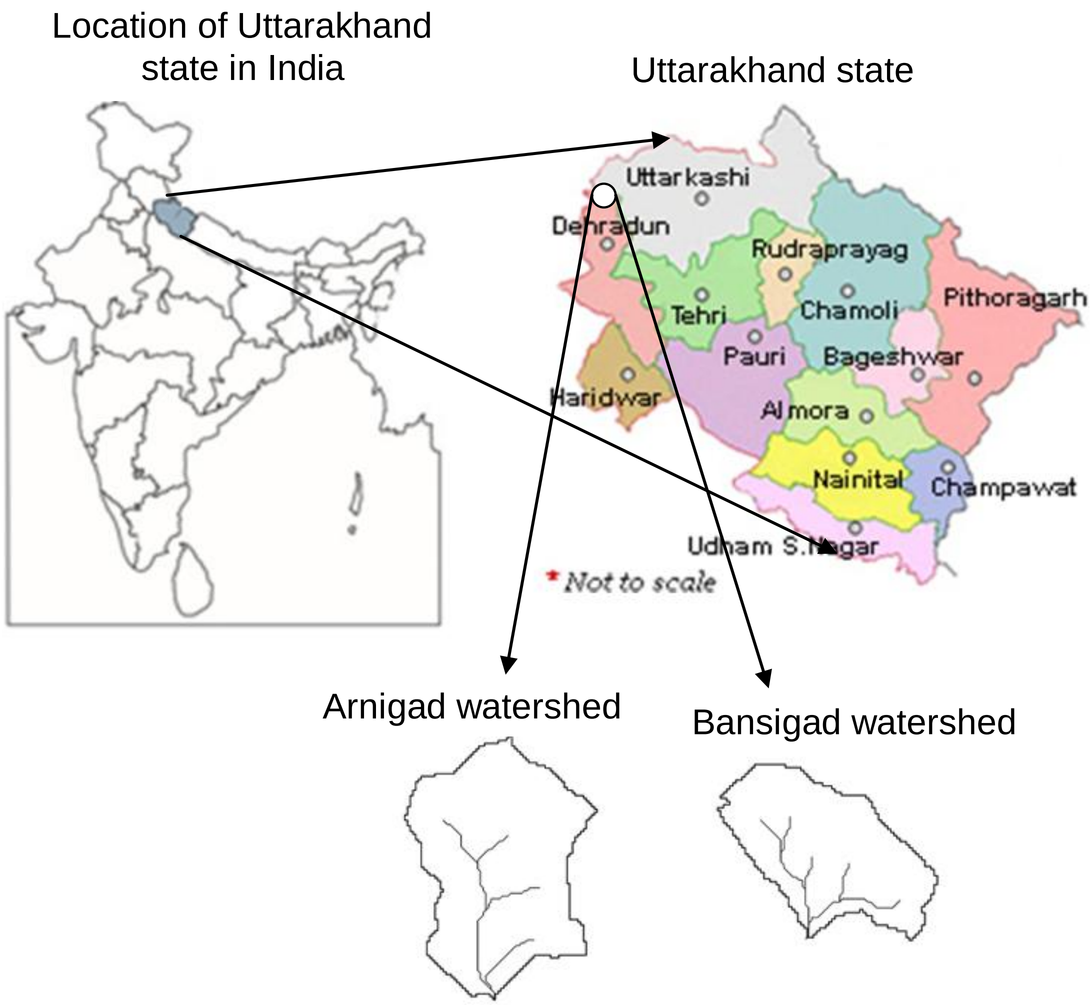

Figure 1. Location of study watersheds.

aims at examining the applicability of SWAT in simulating the hydrological and sediment response of dense and degraded Oak forest covers that predominantly occupy Arnigad and Bansigad watersheds respectively in lower Himalaya (India).

The Specific objectives of the study were to: i) measure rainfall, runoff and sediment concentration and other hydro-meteorological parameters in the watersheds, ii) calibrate and validate SWAT for the study watersheds using the measured data and assess its applicability in simulating daily discharge and sediment transport from forested mountainous watersheds, and iii) assess the impact of different forest cover types on stream discharge pattern and sediment yield.

STUDIED WATERSHEDS

Two small watersheds namely, Arnigad (30° 26’ 13.9” N, 78° 05’ 37.4” E) and Bansigad (30° 27’ 9.1” N, 78° 02’ 45.9” E), located 36 km North of Dehradun near Mussoorie (situated on the first mountain ridge beyond Dehradun) in Uttarakhand state of India were selected for the present study (Figure 1). The Arnigad (304.4 ha) and Bansigad (209.8 ha) watersheds are predominantly covered with moderately dense Oak forest and moderately degraded mixed Oak forest, respectively. The landform of both the watersheds consists of rugged, mountainous terrain with steep slopes. The elevation in Arnigad and Bansigad ranges between 2,220 to 1,640 m above msl and 2,160 to 1,620 m above msl, respectively. The mean orientation of both the watersheds is south. The drainage pattern of both the micro-watersheds is of dendritic type. The annual rainfall in Mussoorie is about 2005 mm of which 60 to 85% is received during monsoon season (June to September). In Mussoorie, the mean annual air temperature is 13.7°C. The hottest month is June with an average (1961 to 1995) air temperature of 19.8°C, and the coldest month is January with an average air temperature of 6°C.

The Mussoorie range, constituting the Proterozoic to lower Cambrian rocks of the lesser Himalaya is separated from the Cainozoic Siwalik Group and the Dun gravels by the MBT (Thakur and Pandey, 2004), that is a north–northeast dipping thrust along which the lesser Himalayan rocks are thrust over the Siwaliks (Rautela et al., 2010). The main parent material in this area consists of quartzite, schist, slates, phyllite, hard sandstones, limestone and dolomite (Bartarya, 1995).

BRIEF DESCRIPTION OF SWAT MODEL

SWAT 2005 with ArcSWAT interface was used in the present study. SWAT is a continuous, physically based distributed model that operates on a daily time step at watershed scale for long-term simulation of hydrology, sediment and agricultural chemical movement (Arnold et al., 1998). SWAT can analyse small or large catchments by discretising into sub-basins, which are then further subdivided into hydrological response units (HRUs) with homogeneous land use, soil type and slope. The SWAT system embedded within ARCGIS can integrate various spatial environmental data including soil, land cover, climate and topographical features. SWAT estimates daily volume of overland rainfall excess over each HRU by solving the water budget components of precipitation, runoff, evapotranspiration, percolation and return flow from subsurface and groundwater flow (Arnold et al., 1998). The model uses the Green-Ampt method or the modification of the SCS curve number method (USDA Soil Conservation Service, 1972) to compute surface runoff volume. Peak runoff rate is estimated using a modification of the 'rational method' (Chow et al., 1998). The measured daily potential evapotranspiration can be loaded directly for the watershed or determined using the Penman–Monteith method, the Priestley–Taylor method or the Hargreaves method (Arnold et al., 1998). Lateral subsurface flow is simulated using kinematic storage model, whereas empirical approaches are adopted for groundwater (Arnold et al., 1998; Borah and Bera, 2003; Neitsch et al., 2005).

In SWAT, Manning's equation is used to estimate flow rate and velocity through channels. Flow routing is based on either the variable storage or the Muskingum routing method (Neitsch et al., 2005). In the present study, SCS curve number and Muskingum routing methods, along with daily climate data, were used for surface runoff and streamflow computations. The Penman method was used to estimate potential evapotranspiration. SWAT uses the modified universal soil loss equation (MUSLE) (Williams, 1975) for computing the soil loss for each HRU. The sediment concentration is obtained from the sediment yield, which corresponds to flow volume within the channel on a given day. The transport of sediment in the channel is controlled by simultaneous operation of two processes: deposition and degradation. Whether channel deposition or channel degradation occurs depends on the sediment loads from the upland areas and the transport capacity of the channel network.

MODEL INPUT DATA

The basic spatial input datasets used by the model include the digital elevation model (DEM), land use/cover data, soil data and climatic data. The brief methodology for preparation of the data is described as follows:

Digital elevation model

DEM is one of the main inputs of the SWAT model to define topography of the study area. Elevation contours at 20 m interval were digitized from Survey of India toposheet (no. 53 J/3) at 1:50,000 scale using ARCGIS software. The digitized contours were used to generate DEM (Figure 2a and 2b) with a grid cell resolution of 30 m. The DEM was used to delineate the boundary of the watershed and analyze the drainage patterns of the land surface terrain. Terrain parameters such as slope gradient and slope length, and stream network characteristics such as channel slope, length and width were derived from the DEM.

Land use/cover data

Land use is one of the most important factors that affect runoff, soil erosion and evapotranspiration in a watershed during simulation (Neitsch et al., 2005). As per the Survey of India toposheet, major land use in Arnigad and Bansigad watersheds consists of oak forest with small areas under habitation and barren lands. The extent of various land use classes shown in the Survey of India toposheet (1:50,000 scale) was verified in the field and minor modifications were made in the boundaries of land use classes as per actual extent. For preparation of land use map, the field surveyed land use classes were digitized and converted to raster format with grid cell size of 30 m. The generated land use maps of Arnigad and Bansigad watersheds are shown in Figure 3(a and b). The various land use categories and their coverage in both the study watersheds are presented in Table 1.

Soil data

The soil textural and physicochemical properties required by SWAT model include soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for each soil type. Undisturbed soil samples were collected from the depths of 0 to 15 and 15 to 30 cm using core samplers from five locations in each watershed. The collected soil samples were analysed in a standard soil laboratory for particle size distribution, bulk density, soil organic carbon and hydraulic conductivity. The available water content was calculated by subtracting the moisture content at wilting point from that at field capacity. Texturally, the soils in both the study watersheds were sandy loam soils. The average values of soil properties for Arnigad and Bansigad watersheds are presented in Table 2.

Weather data

Meteorological observatories were established within each watershed to monitor daily rainfall, temperature, humidity and wind velocity. Rainfall was measured using tipping bucket rain gauge linked with a data-logger system, and also with ordinary rain gauge for cross check. Maximum and minimum temperature, relative humidity and wind velocity were measured with the help of maximum to minimum thermometers, dry-wet bulb thermometers and anemometer respectively. The meteorological data was collected from March 2008 to February 2011.

Hydrological and sediment yield data

The daily discharge and suspended sediment concentration for the period of March 2008 to February 2011 were measured at the outlets of each study watershed. A sharp-crested weir with apex angle of 120° was constructed at the medial line of flow and a digital stage level recorder was used to measure stream stage. Daily discharge was calculated using appropriate weir formula. The water samples were collected using Punjab bottle samplers and analysed in the laboratory for sediment concentration. Sediment

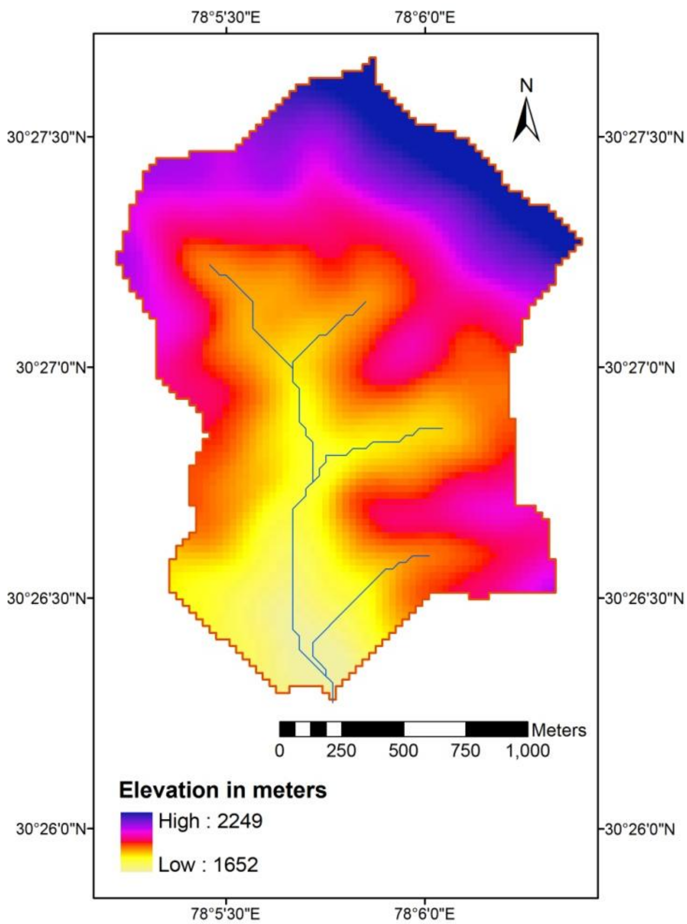

Figure 2a. DEM of Arnigad watershed.

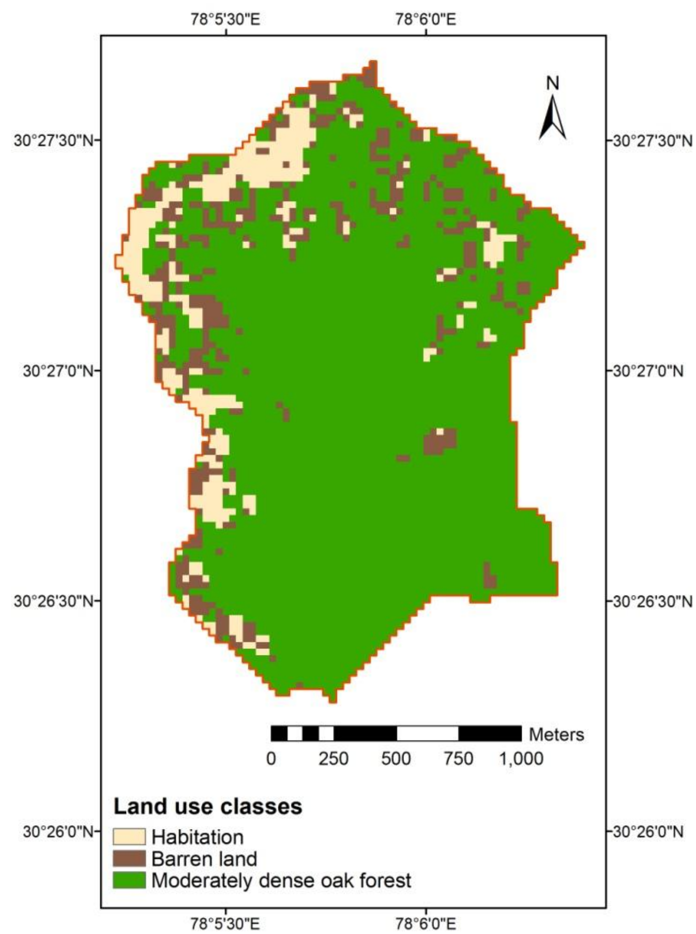

Figure 3a. Land use map of Arnigad watershed.

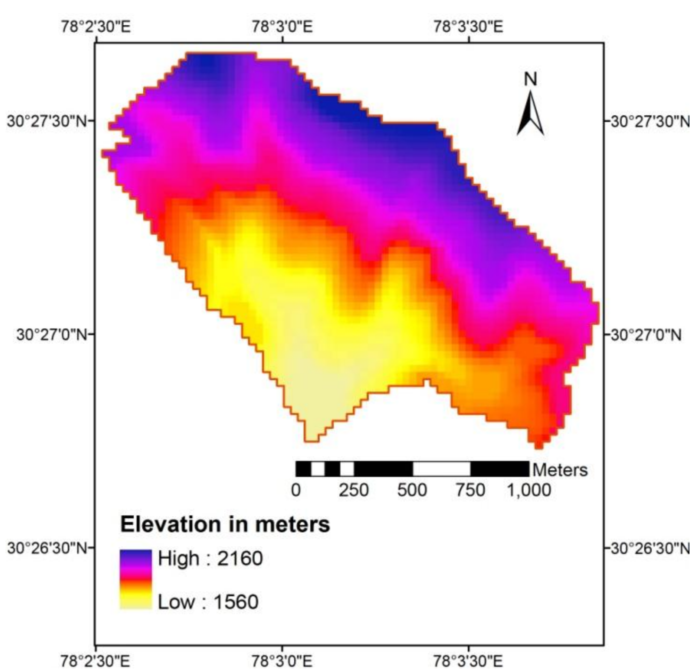

Figure 2b. DEM of Bansigad watershed.

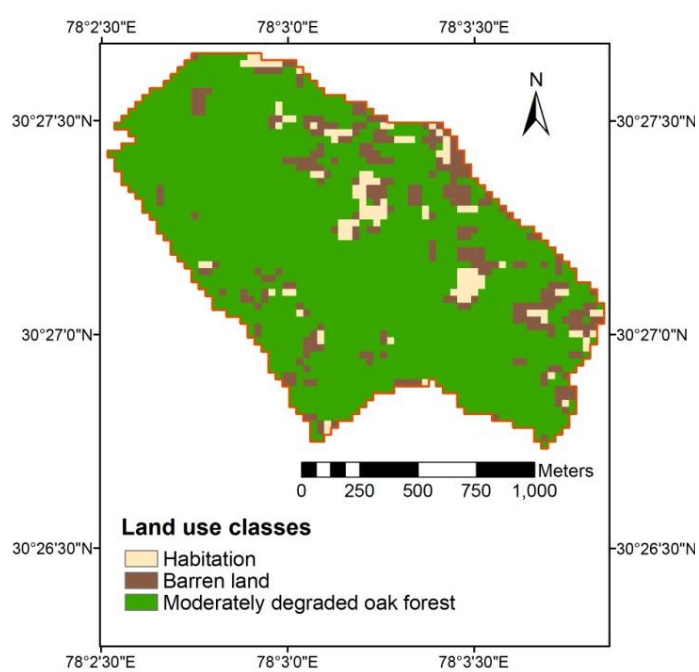

Figure 3b. Land use map of Bansigad watershed.

Table 1. Major land use classes in Arnigad and Bansigad watersheds

Land use	Arnigad watershed		Bansigad watershed	
	Area (ha)	% total	Area (ha)	% total
Dense Oak forest	244.2	80.22	0	0
Degraded Oak forest	0	0	174.2	83.03
Barren	33.8	11.10	25.7	12.25
Habitation	26.4	8.68	9.9	4.72
Total	304.4	100	209.8	100

concentration was measured by filtering samples through Whatman filter paper no. 42. The flow and suspended sediment concentration were measured over a range of hydrological conditions and daily values were calculated from the mean of instantaneous values for a given day.

APPLICATION OF SWAT

Model set-up

The ArcSWAT interface was used for the setup and parameterization of the model. A digital elevation model (DEM) was imported into the SWAT model. A masking polygon (in grid format) was loaded into the model in order to extract the area of interest, delineate the boundary of the watershed and digitize the stream network in the study area. The minimum threshold area for generation of streams was taken as 20 ha that divided Arnigad and Bansigad watersheds into seven and nine sub-watersheds (Figure 4a and 4b) respectively. The land use/cover and soil maps of the study watersheds (in grid format) were also imported into the model and overlaid to obtain a unique combination of land use, soil and slope. Multiple HRUs with 10% land use and 10% slope thresholds were set to eliminate minor land uses and slope classes in each sub-watershed as recommended in the SWAT user manual (Neitsch et al., 2002). A total of 15 and 21 HRUs were delineated in Arnigad and Bansigad watersheds respectively. The daily data of rainfall, minimum and maximum temperature, relative humidity, wind speed and solar radiation were prepared in the appropriate file format and imported into the model.

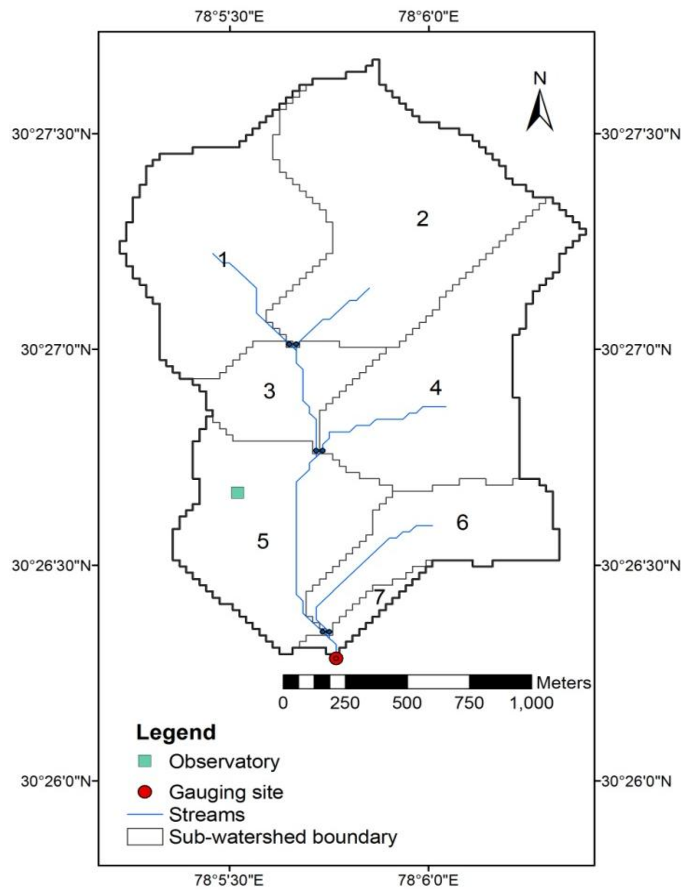

Figure 4a. Sub-watershed delineation in Arnigad watershed.

Model calibration and validation

The calibration and validation were carried out at daily time steps using flow and suspended sediment concentration data. The calibration was performed using the data from June 2008 to May 2010. The data for the period of March 2008 to May 2008 were utilized for warming up and initialization of the model variables. The warm up period was not used for evaluation of the model predictions. The SWAT model includes a large number of parameters that describe different hydrological conditions and characteristics across the watershed. These parameters need to be calibrated to adequately simulate streamflow and sedimentation processes in the study watersheds. Parameters can either be calibrated manually or automatically. In this study, the calibration was done manually based on physical catchment understanding and sensitive parameters from published literature (Bärlund et al., 2007; Xu et al., 2009) and calibration techniques from the SWAT user manual. The hydrological component and the erosion component of the model were calibrated sequentially until the average simulated and measured values were in close agreement. Results of many studies have indicated that SCS curve number (CN_2), a function of soil permeability,

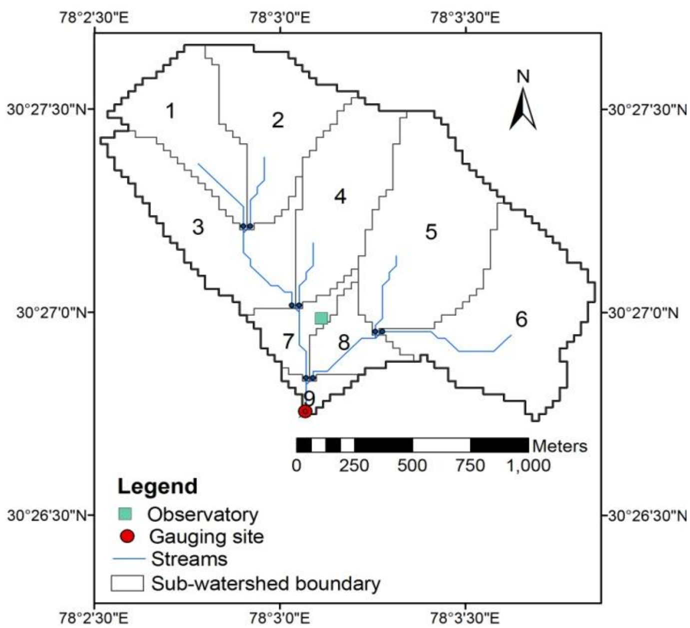

Figure 4b. Sub-watershed delineation in Bansigad watershed.

landuse and antecedent soil water conditions, is an important parameter for surface runoff (Oeurng et al., 2011; Das et al., 2007; Parajuli et al., 2007; Arabi et al., 2008; Wang et al., 2008). Since the base flow forms a significant part of the total flow in the study watersheds, the baseflow recession coefficient (ALPHA_BF) was calibrated for simulation of base flow.

The other important parameters that were calibrated for prediction of flow included 'soil evaporation compensation factor' (ESCO), 'plant water uptake compensation factor' (EPCO), 'surface runoff lag time' (SURLAG), 'groundwater delay' (GW_DELAY), 'deep aquifer percolation factor' (RCHRG_DP), 'Manning's ''n'' value for tributary channels' (CH_N1), 'Manning's ''n'' value for main channel' (CH_N2) and 'Maining's ''N'' for overland flow' (OV_N). SWAT uses MUSLE (Williams, 1975) for prediction of sediment concentration. Therefore, the MUSLE "crop cover and management factor' (C) and the channel sediment routing variables, namely, a linear parameter for calculating the maximum amount of sediment that can be entrained during channel sediment routing (SPCON), an exponential parameter for calculating the channel sediment routing (SPEXP) were adjusted during the calibration. In the validation process, the model was run with calibrated input parameters and the model predictions were compared with an independent set of observed data of the period of June 2010 to February 2011.

Criteria for model evaluation

Several statistical measures are available for evaluating the performance of a model. In the present study, the performance of the model in simulating discharge and sediment was evaluated graphically and by Nash–Sutcliffe efficiency (E_{NS}) and coefficient of determination (R^2). The Nash and Sutcliffe (1970) efficiency is one of the most frequently used criteria and is expressed in percentage form as:

$$E_{NS} = \left\{1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right\} \times 100$$

Where O_i and S_i are the observed and simulated values, n is the total number of paired values and $\bar{O}$ is the mean observed value.

The efficiency varies from 0 to 100 with 100 denoting perfect fit. Generally, E_{NS} is very good when E_{NS} is greater than 75%, satisfactory when E_{NS} is between 36 and 75%, and unsatisfactory when E_{NS} is lower than 36% (Nash and Sutcliffe, 1970; Krause et al., 2005). However, a shortcoming of the Nash–Sutcliffe statistic is that it does not perform well in periods of low flow, as the denominator of the equation tends to zero and E_{NS} approaches negative infinity with only minor simulation errors in the model (Oeurng et al., 2011). This statistic works well when the coefficient of variation for the data set is large.

The coefficient of determination (R^2) is the proportion of variation explained by fitting a regression line and is viewed as a measure of the strength of a linear relationship between observed and simulated data. It is computed as:

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})}{[\sum_{i=1}^{n}(O_i - \bar{O})^2]^{0.5}[\sum_{i=1}^{n}(S_i - \bar{S})^2]^{0.2}}\right\}$$

Where $\bar{S}$ is the mean of simulated values, R^2 ranges between 0 and 1. The value of 1 implies that the computed values are in perfect agreement with the observed data.

RESULTS AND DISCUSSION

Assessment of calibration results

The observed and simulated daily runoff and sediment concentration during calibration period of June 2008 to May 2010 are graphically presented in Figure 5(a, b) for Arnigad and Figure 6(a and b) for Bansigad watershed. It can be observed that the simulated discharge generally followed the trend to observed discharge in both the watersheds. A critical comparison of the runoff hydrographs of Arnigad watershed (Figure 5a) shows that the flow peaks are simulated slightly higher than the observed peaks during monsoon seasons both in 2008 and 2009. However, the low flows simulated by the model

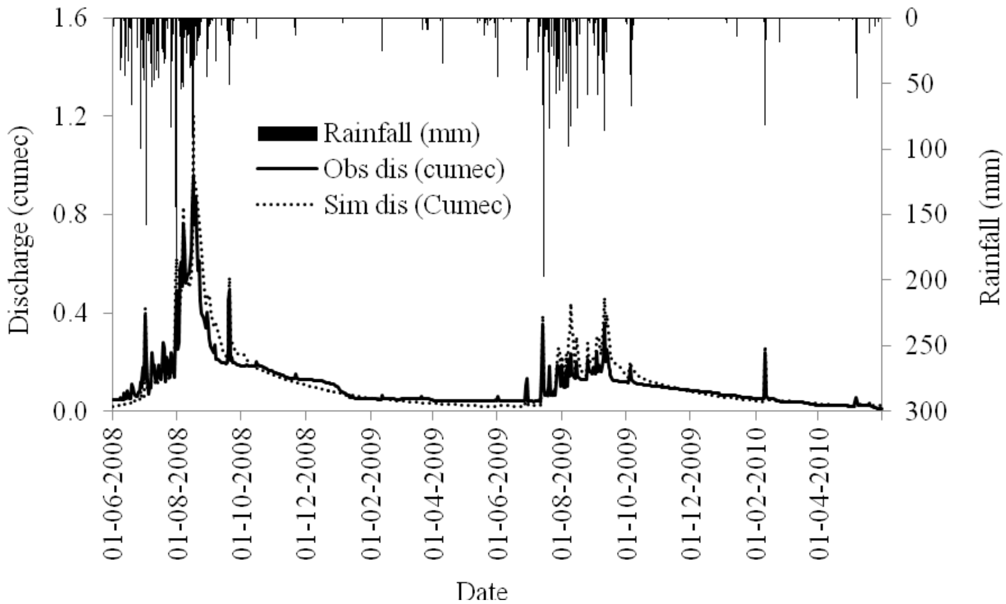

Figure 5a. Observed and simulated daily discharge during calibration in Arnigad watershed.

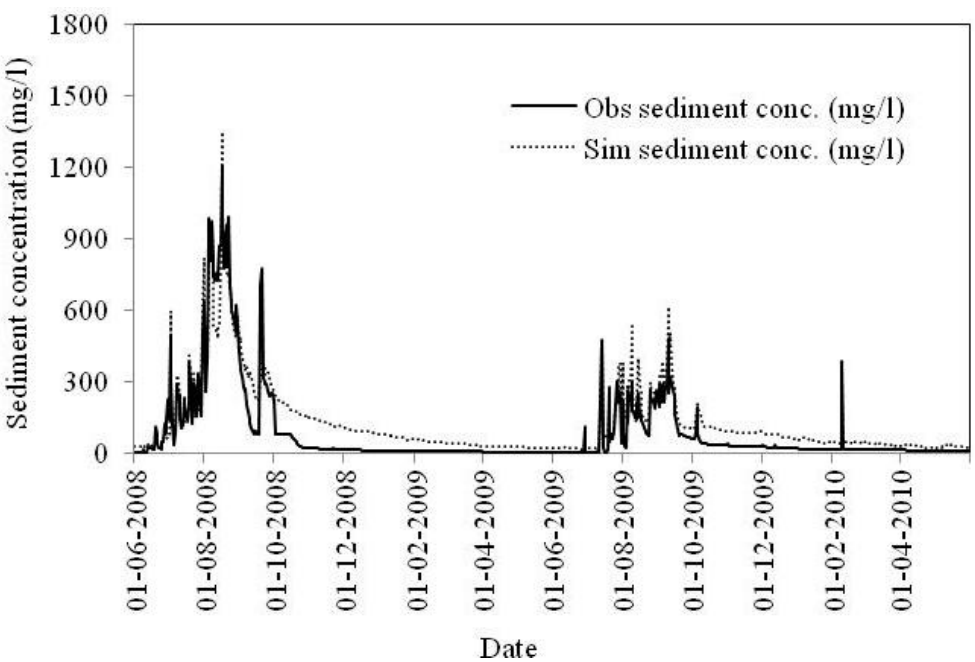

Figure 5b. Observed and simulated daily sediment concentration during calibration in Arnigad watershed.

generally match well with the observed values. In Bansigad watershed, a mixed trend is observed in simulating flows during 2008 and 2009; while, high and low flows are simulated reasonably well during 2008; the high flows appear to be underestimated and low flows overestimated during 2009. A comparison of observed and simulated suspended sediment concentration (Figures 5b and 6b) shows that simulated sediment concentration also generally followed the observed trend in both the watersheds. Although, model predicted peak values were found both higher and lower than the observed values at different times in both watersheds, the difference was within reasonable limits. The difference in simulated and observed values could occur due to the fact that in

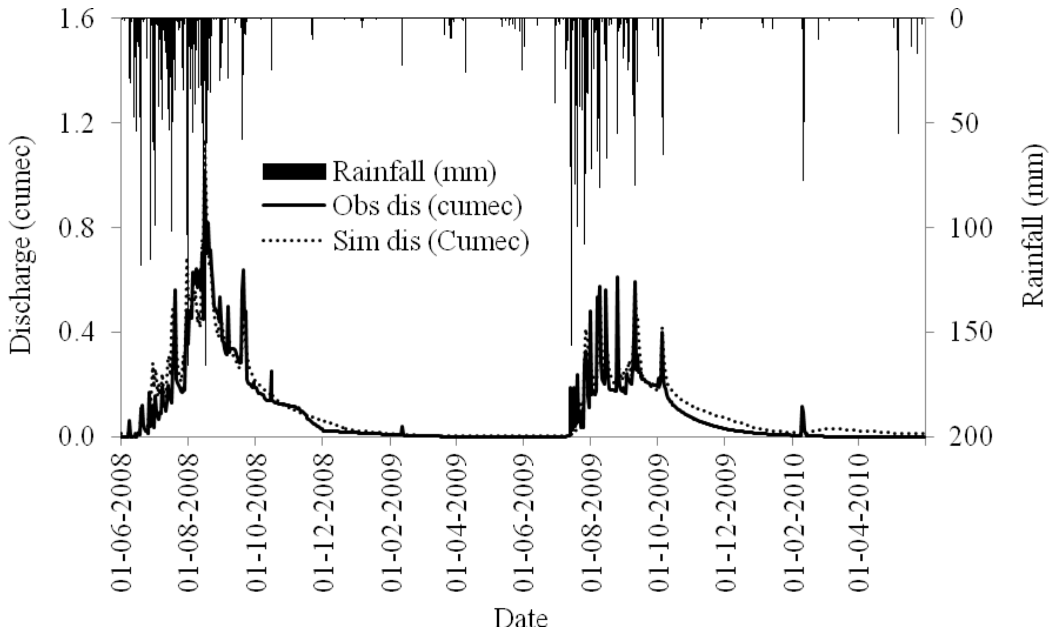

Figure 6a. Observed and simulated daily discharge during calibration in Bansigad watershed.

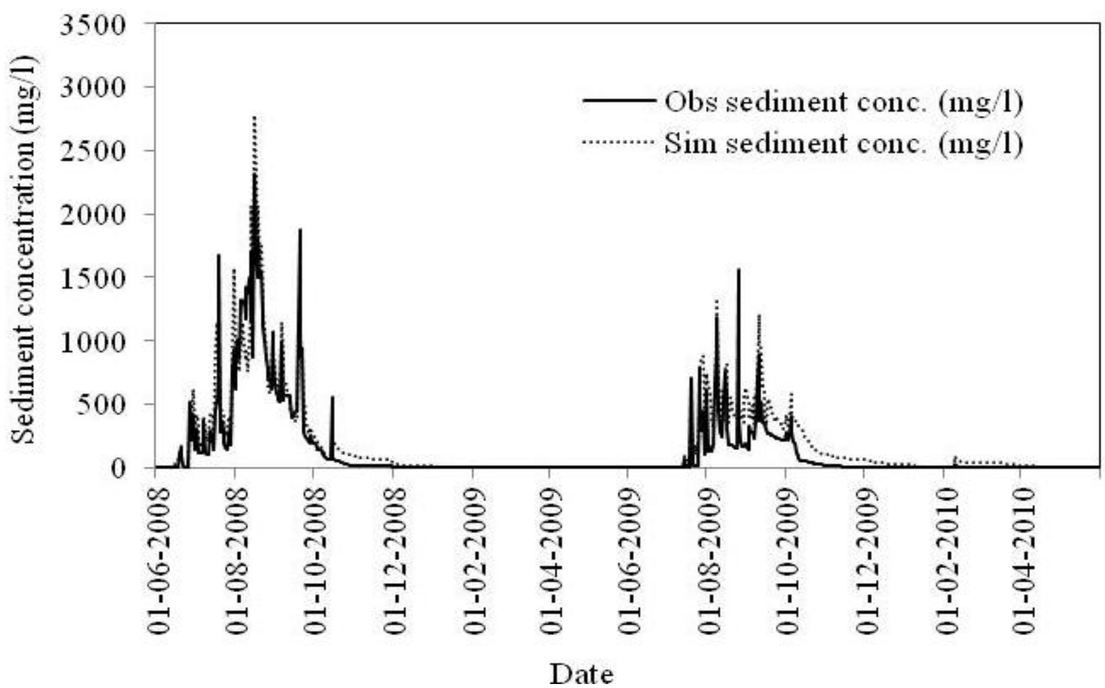

Figure 6b. Observed and simulated daily sediment concentration during calibration in Bansigad watershed.

practice, high-intensity and even short duration rainfall can generate more sediment than simulated by the model on the basis of daily rainfall (Xu et al., 2009). The simulated sediment concentration during non monsoon seasons was higher than the observed values in Arnigad watershed.

The obvious reason for higher sediment simulation is that the sediment response follows the simulated runoff rate as the sediment generation is largely determined by the runoff quantity. In Bansigad watershed, the simulation of sediment concentration during non monsoon seasons was reasonably good. The observed daily flows and sediment concentration were plotted against simulated daily flows and sediment concentration along with 1:1 line

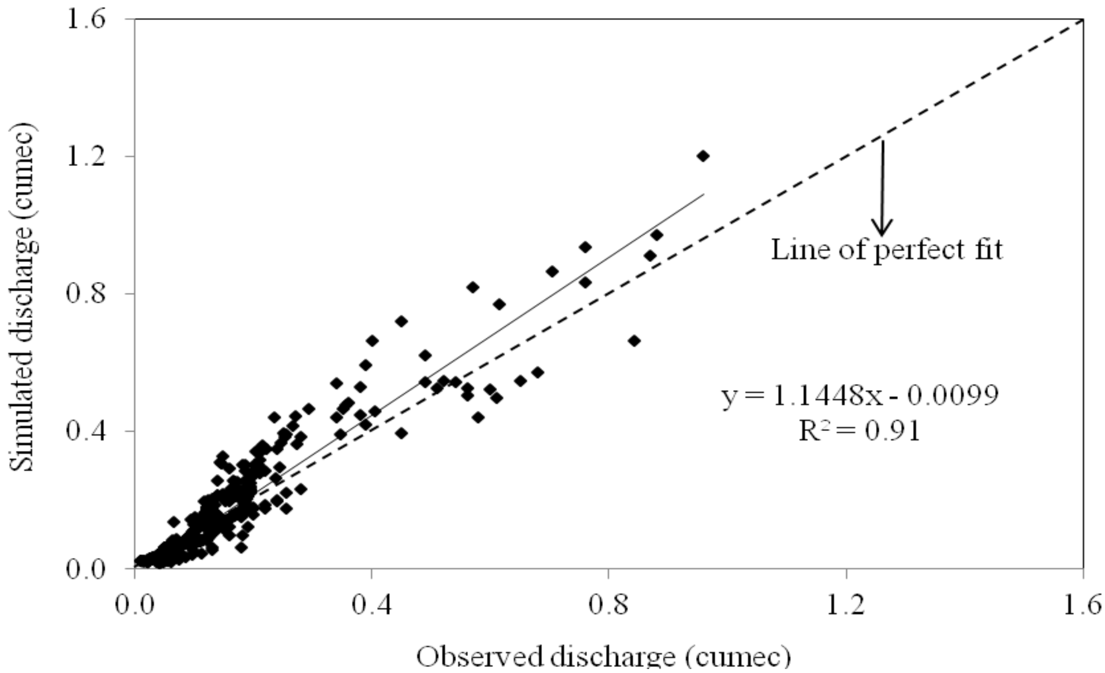

Figure 7a. Scatter plot of observed and simulated daily discharge during calibration in Arnigad watershed.

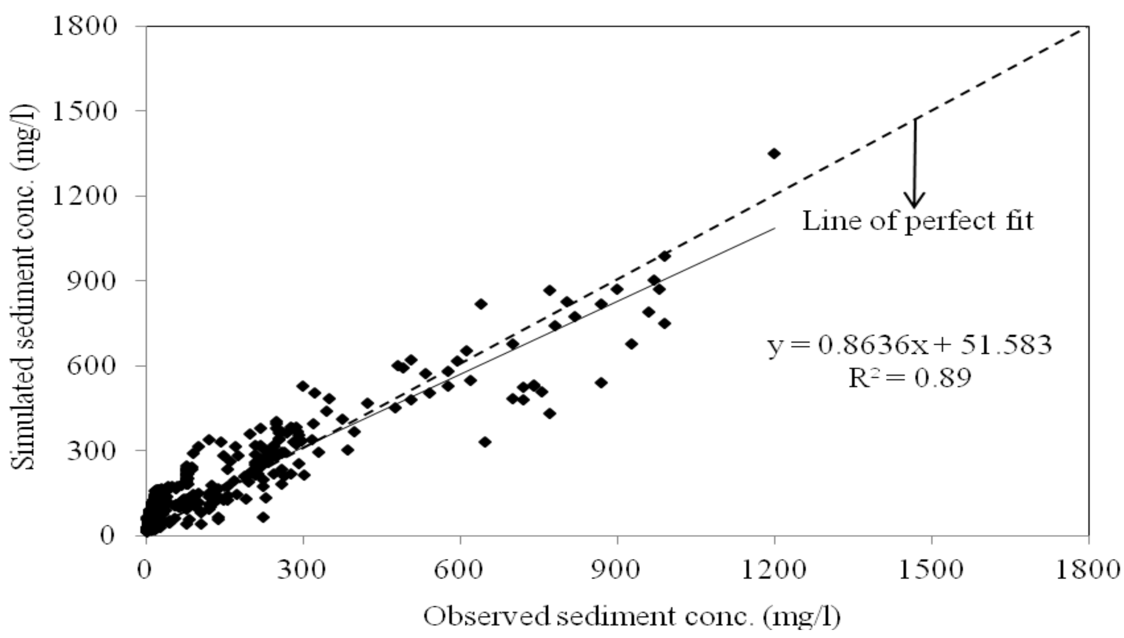

Figure 7b. Scatter plot of observed and simulated daily sediment concentration during calibration in Arnigad watershed.

(line of perfect fit) as shown in Figure 7(a, b) for Arnigad and Figure 8(a and b) for Bansigad watershed. It is observed from Figure 7a that the simulated runoff values are distributed uniformly about the 1:1 line for low values of observed runoff. For high values of observed runoff, majority of the simulated values are slightly above the line of perfect fit, indicating that the model over-predicts the high values of runoff. A close observation of Figure 8a shows two clusters of data scatter, one cluster for low flows where most data lie above line of perfect fit indicating overestimation, and another cluster for high flows where most data lie below line of perfect fit that

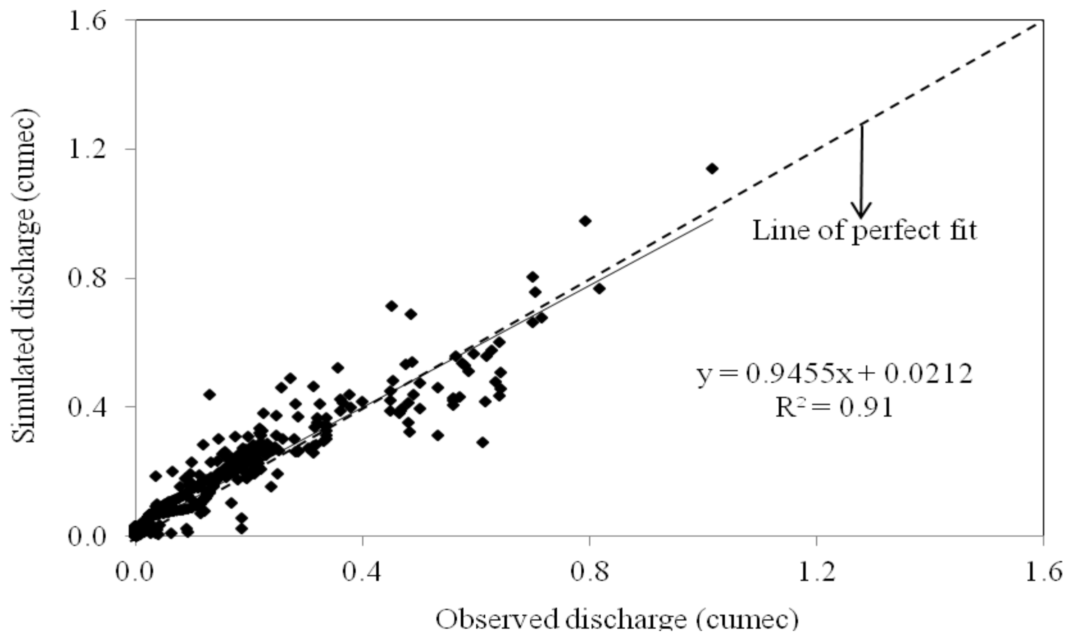

Figure 8a. Scatter plot of observed and simulated daily discharge during calibration in Bansigad watershed.

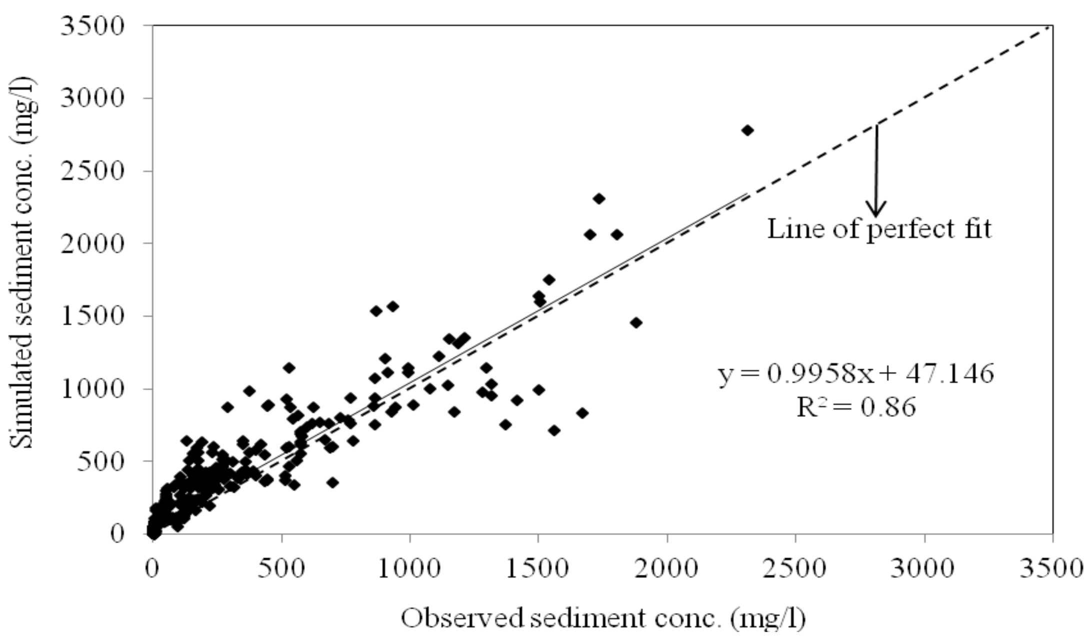

Figure 8b. Scatter plot of observed and simulated daily sediment concentration during calibration in Bansigad watershed

indicates under-prediction of the flows. Similar interpretations can also be made from the scatter plots of sediment concentration (Figures 7b and 8b).

The statistical indices of model performance are presented in Tables 3 and 4 for Arnigad and Bansigad watersheds, respectively. The analysis for Arnigad watershed showed very good agreement between observed and simulated daily values, with an R^2 value of 0.91, and an E_{NS} of 84.48% in discharge simulation; and an R^2 of 0.88, and an E_{NS} of 83.11% in sediment simulation. In Bansigad watershed too, the model exhibited a very good performance in simulating the discharge (R^2 = 0.91, and E_{NS} = 89.74%) and the sediment concentration (R^2 = 0.86 and E_{NS} = 82.07%).

Table 2. Soil properties of study watersheds.

Depth (cm)	Soil organic carbon (%)	Available water content (mm water mm soil^{-1})	B. D. (gm cm^{-3})	Hydraulic conductivity (mm h^{-1})	Sand (%)	Silt (%)	Clay (%)	Soil texture
Arnigad watershed (dense oak forest)								
0 - 15	3.31	0.142	1.01	71.42	67.75	14.00	18.51	Sandy loam
15 - 30	2.30	0.136	1.05	62.35	66.07	13.33	20.51	Sandy loam
Bansigad watershed (degraded oak forest)								
0 - 15	2.37	0.131	1.06	65.39	74.27	11.33	14.40	Sandy loam
15 - 30	1.91	0.124	1.09	58.36	72.93	11.33	15.83	Sandy loam

Table 3. Goodness of fit statistics for Arnigad watershed for calibration period.

Description	E_{NS} (%)	R^2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge (m^3 s^{-1})	84.48	0.91	0.111	0.118	0.120	0.143
Sediment concentration (mg l^{-1})	83.11	0.89	82.485	122.820	172.944	158.658

Table 4. Goodness of fit statistics for Bansigad watershed for calibration period.

Description	E_{NS} (%)	R^2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge (m^3 s^{-1})	89.74	0.91	0.092	0.108	0.153	0.152
Sediment concentration (mg l^{-1})	82.07	0.86	132.128	178.717	309.983	332.161

Assessment of validation results

For validation, the observed daily discharge and sediment concentration data of the period of June 2010 to February 2011 were utilized and compared with the model simulated values. A visual comparison of the observed and simulated daily discharge and sediment concentration is presented in Figure 9(a, b) for Arnigad and Figure 10(a and b) for Bansigad watershed. These results show a good general agreement between observed and simulated trends of discharge and sediment concentration in both the watersheds. Further, it is observed that similar to calibration results, the peak flows are slightly overestimated in Arnigad watershed and underestimated in Bansigad watershed. The flows during non monsoon season are simulated reasonably accurate in both the watersheds. In estimating suspended sediment concentration (Figures 9b and 10b), the peak values are observed to be overestimated in both the watersheds. The model also overestimated the sediment concentration during non monsoon period which is possibly due to the reason that the quantity of sediment generation also depends on the simulated discharge rate as mentioned earlier.

The scatter plots of observed and simulated daily discharge and sediment concentration are shown in Figure 11(a, b) for Arnigad and Figure 12(a and b) for Bansigad watershed. Although, the data points lying above and below the line of perfect fit show some overestimation and underestimation respectively, the closeness of the data points to the line of perfect fit indicates a very good performance of the model in estimating both discharge and sediment concentration for the study watersheds. It can be seen from Tables 5 and 6 that the R^2 of 0.94 and E_{NS} of 82.78% in discharge estimation, and R^2 of 0.88 and E_{NS} of 83.28% in sediment estimation are computed for Arnigad watershed; and R^2 of 0.92 and E_{NS} of 92.5% in discharge estimation, and R^2 of 0.94 and E_{NS} of 80.67% in sediment estimation are computed for Bansigad watershed. These R^2 and E_{NS} values are of the same order as obtained during calibration which explain that model has performed equally well on the data set used for validation purpose. The model performance with these high values of statistical indices can be rated as more than satisfactory in simulating discharge and sediment concentration from the study watersheds. The aforementioned results can be viewed in the light of the fact that the runoff and soil erosion process in hilly and mountainous forested catchments are highly complex phenomena and affected by interaction among rainfall, runoff, soil texture and structure, land use, land slope and conservation measures. Therefore, magnitude of randomness in daily simulated values may be large in mountainous catchments

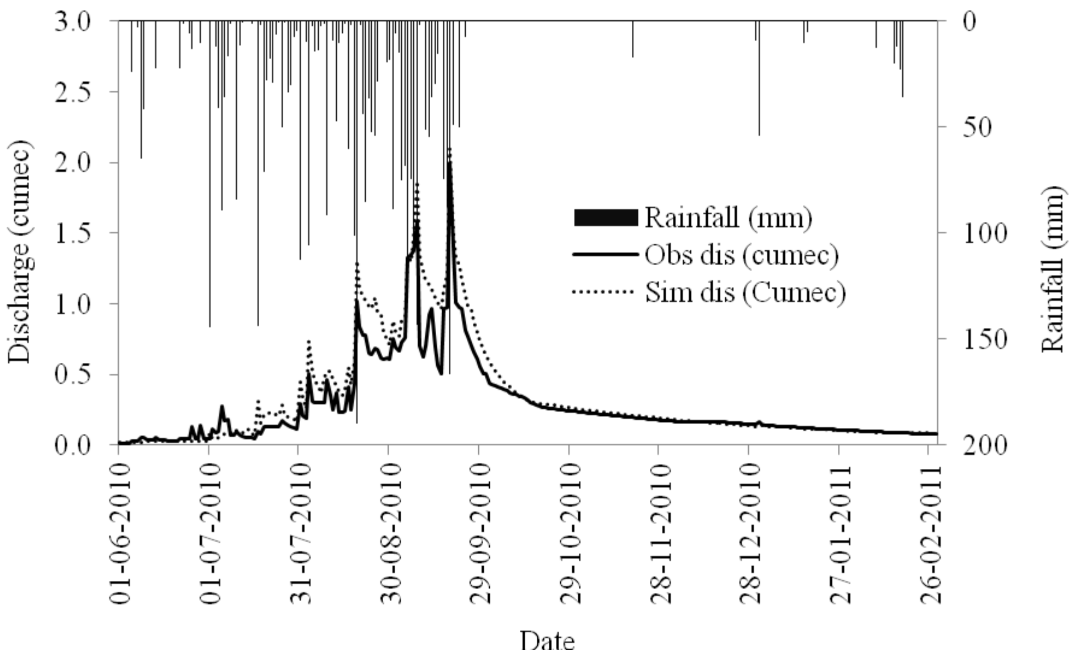

Figure 9a. Observed and simulated daily discharge during validation in Arnigad watershed.

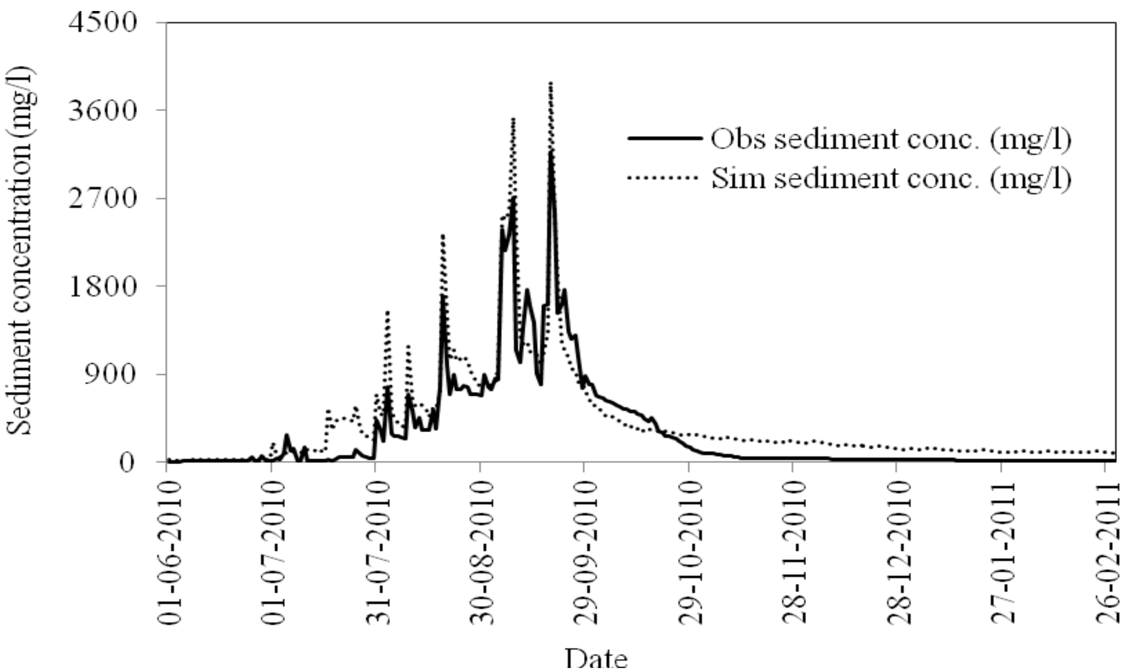

Figure 9b. Observed and simulated daily sediment concentration during validation in Arnigad watershed.

(Singh et al., 2011). Generally, poor correlation among daily values in SWAT simulation has been reported in literature (Peterson and Hamlett, 1998; Varanou et al., 2002; Spruill et al., 2000).

The results of the present study, however, indicate that SWAT can be used for estimation of daily discharge and sediment from forested watersheds in lesser Himalayas.

Assessment of the impact of forest cover types on stream discharge pattern and sediment yield

The assessment of runoff and sediment yield was made based on the total simulation period of three years. The model predicted that mean annual rainfall of 2925 mm over Arnigad watershed was mainly partitioned among

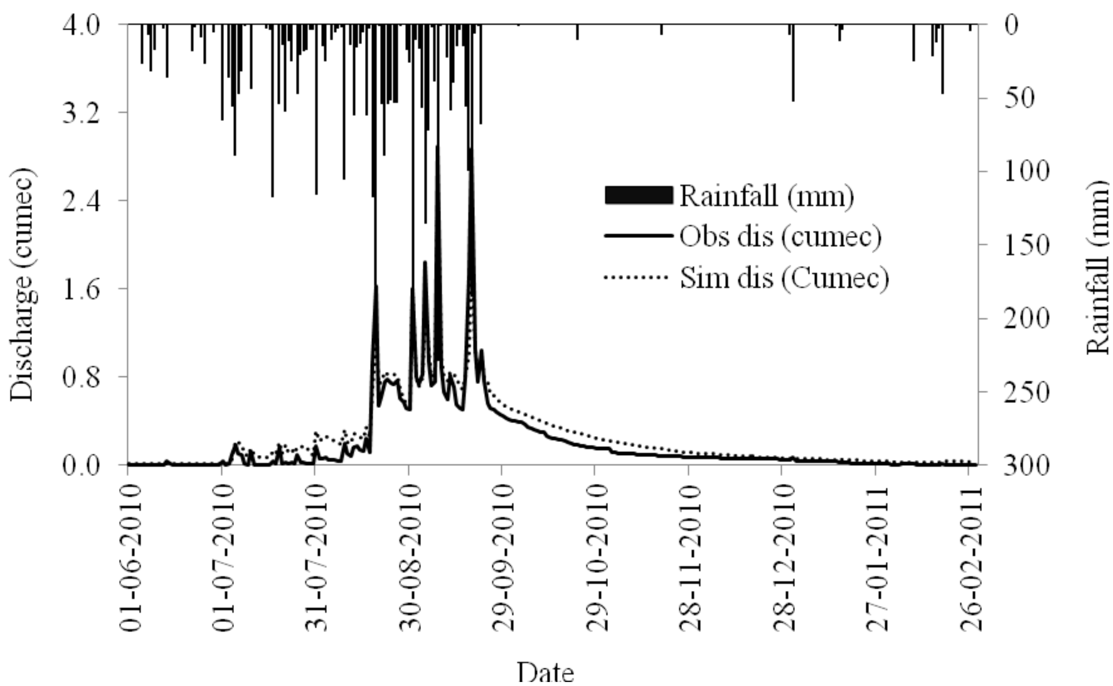

Figure 10a. Observed and simulated daily discharge during validation in Bansigad watershed.

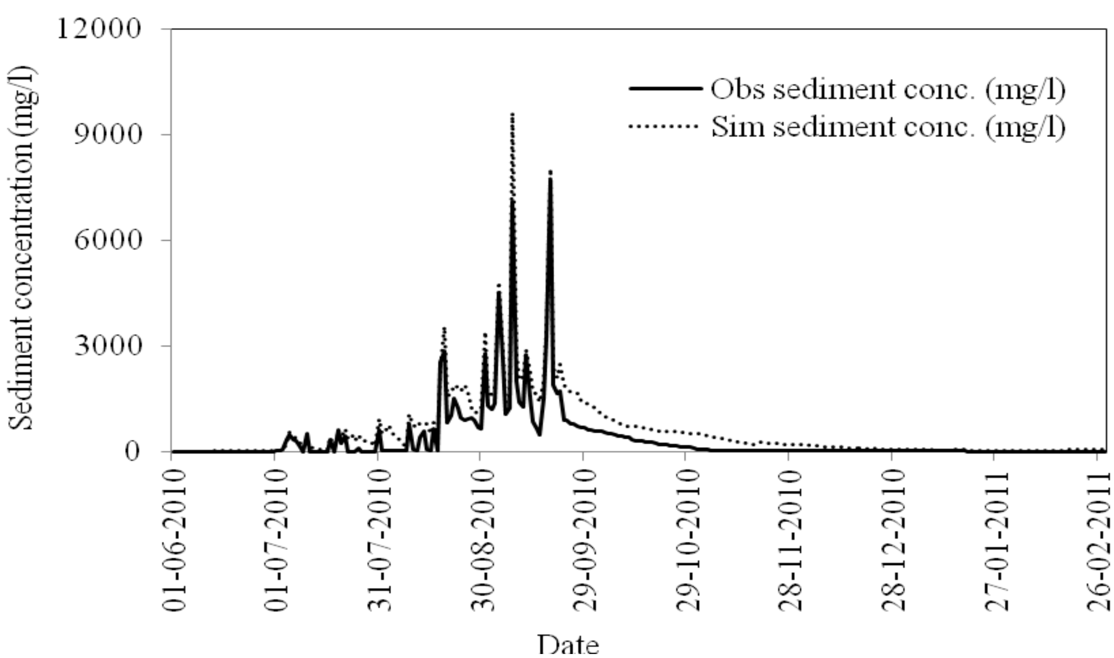

Figure 10b. Observed and simulated daily sediment concentration during validation in Bansigad watershed.

evapotranspiration, ET (27.3%), percolation/ groundwater recharge (62.2%), transmission loss/abstraction (4.5%) and surface runoff (6%). The simulated mean annual water yield amounted to 1738.5 mm (59.4%) against the observed water yield of 1622.4 mm (55.5%). In Bansigad watershed, the mean annual rainfall of 2926.5 mm was partitioned among ET (22.1%), percolation/groundwater recharge (65.8%), transmission loss/abstraction (5.2%), and surface runoff (6.9%) and the mean annual water yield was simulated as 2030.1 mm (69.3%) against the observed value of 1863.6 mm (63.7%). These values indicate that the water balance components in both catchments are almost identical. These results can be supported by the fact that the distribution of land use and

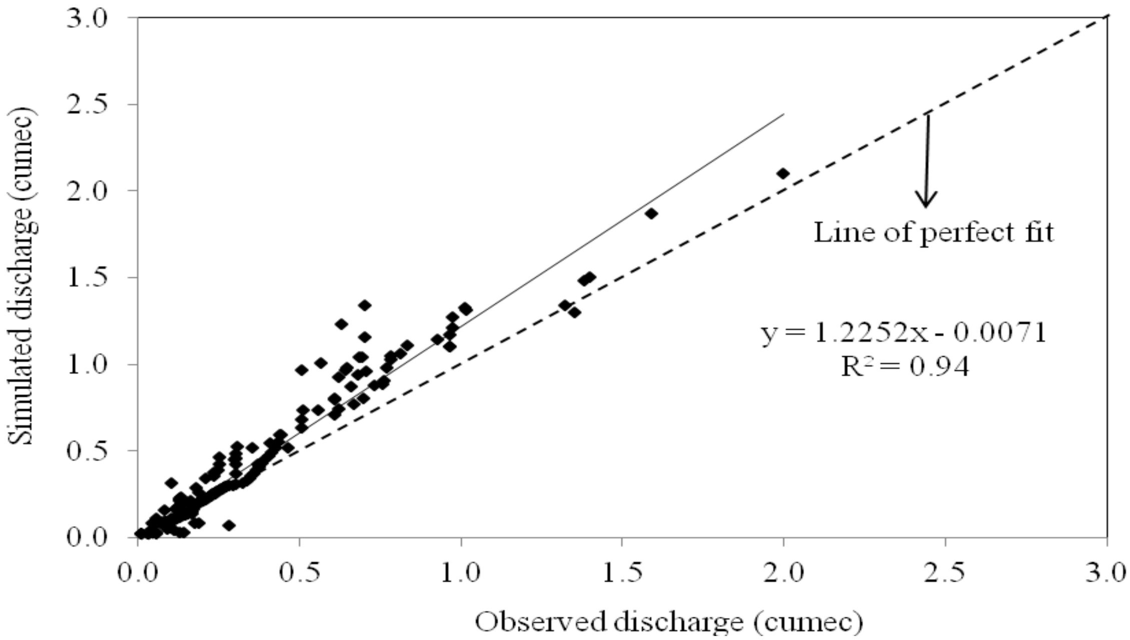

Figure 11a. Scatter plot of observed and simulated daily discharge during validation in Arnigad watershed.

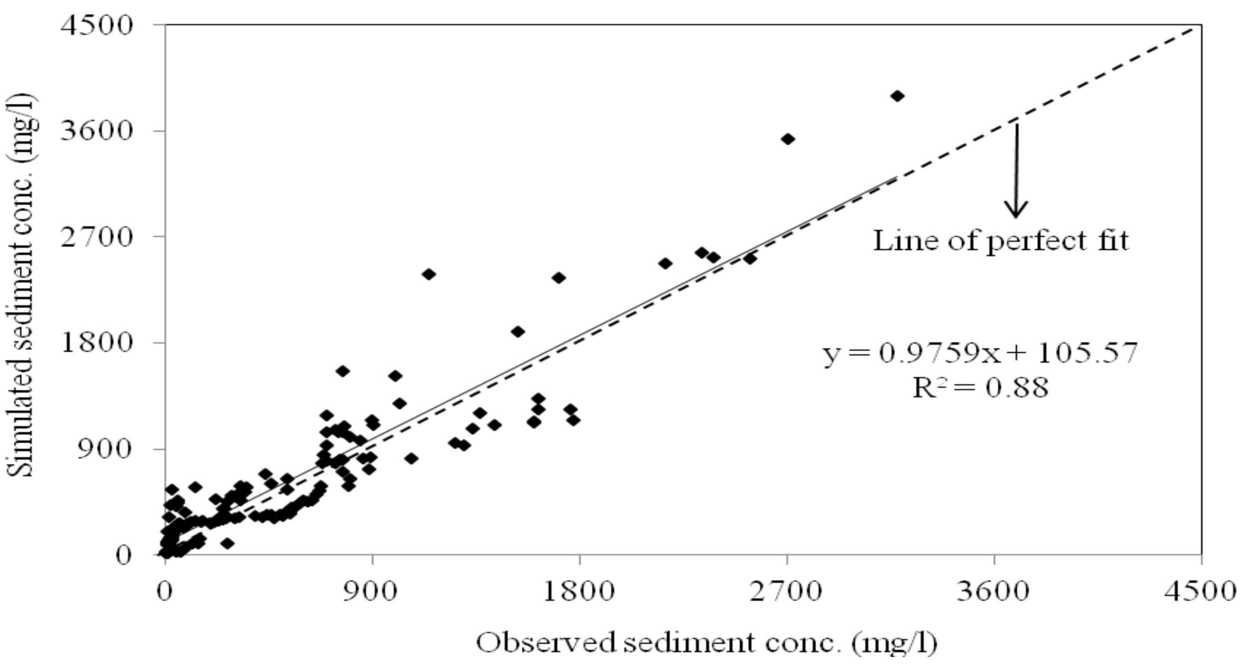

Figure 11b. Scatter plot of observed and simulated daily sediment concentration during validation in Arnigad watershed.

soil types in both the watersheds is almost similar. Higher ET and lower surface runoff in Arnigad than the Bansigad watershed is obvious due to the difference in forest cover types in Arnigad (dense Oak forest) and Bansigad watershed (degraded Oak forest). Although, higher water yield is obtained in Bansigad than the Arnigad watershed, the river flow in Bansigad ceases in the month of February or during early March, while Arnigad sustains the river flow throughout the year. Sharda and Ojaswi (2006) reported that root system of an oak tree is very extensive and soil-root complex system of each mature oak tree has a capacity to store several hundred litres of water, which is released as base flow during the lean season.

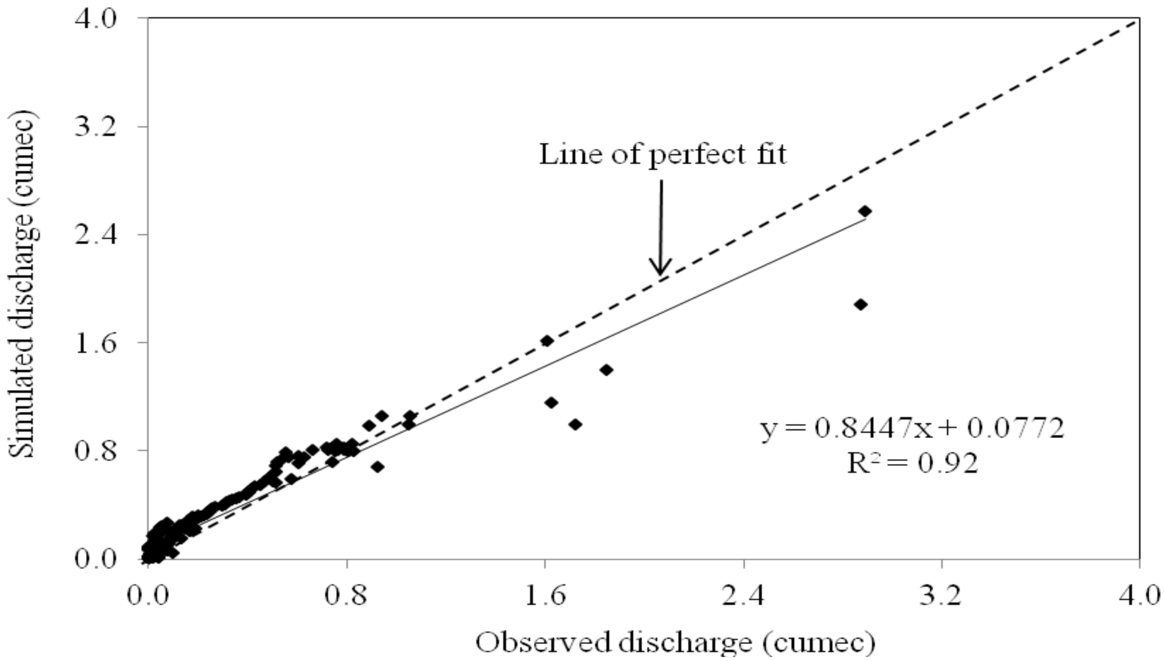

Figure 12a. Scatter plot of observed and simulated daily discharge during validation in Bansigad watershed.

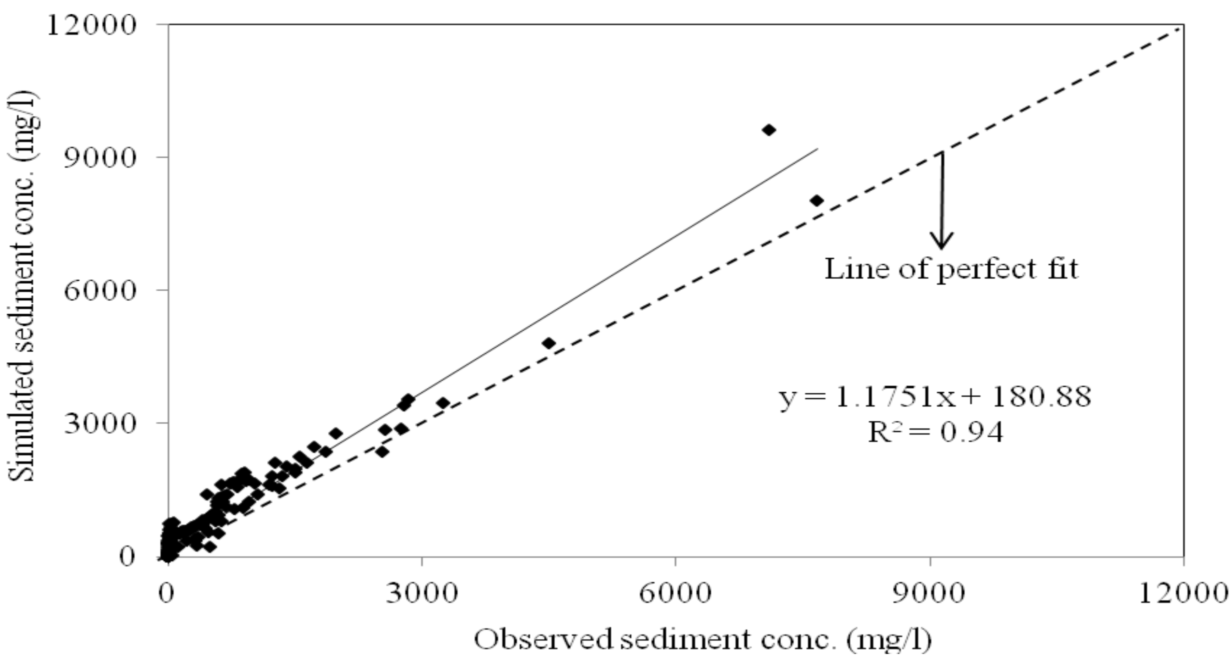

Figure 12b. Scatter plot of observed and simulated daily sediment concentration during validation in Bansigad watershed.

Table 5. Goodness of fit statistics for Arnigad watershed for validation period.

Description	$E_{NS\,(\%)}$	R^2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge ($m^3\ s^{-1}$)	82.78	0.94	0.273	0.327	0.293	0.369
Sediment concentration ($mg\ l^{-1}$)	83.28	0.88	298.989	397.358	520.740	541.964

Table 6. Goodness of fit statistics for Bansigad watershed for validation period.

Description	E_{NS} (%)	R^2	Mean		Standard deviation	
			Observed	Simulated	Observed	Simulated
Discharge ($m^3 s^{-1}$)	90.50	0.92	0.205	0.250	0.378	0.331
Sediment concentration ($mg l^{-1}$)	80.67	0.94	337.922	577.961	853.365	1032.541

The mean annual sediment loading from the Arnigad and Bansigad watershed was simulated as 8.45 and 21.97 t ha^{-1} respectively against the mean observed sediment yield of 10.70 and 24.46 t ha^{-1} in respective watersheds. The simulated sediment yield is comparable to observed values in both the watersheds. The high sediment yield in Bansigad watershed can be attributed to degraded forest cover and other anthropogenic activities in the watershed.

Conclusions

The present study was carried out to evaluate the applicability of physically based, distributed parameter SWAT model in estimating discharge and sediment yield from two forested watersheds in lower Himalaya (India) and to assess the impact of forest cover types on stream discharge and sediment yield. The following were drawn based on the results of the study:

1) The model simulated daily discharge and suspended sediment concentration followed the trend of observed values in both the watersheds.
2) R^2 values of 0.91 and above and E_{NS} values of 82.8% and above both in calibration and validation exhibited high performance of SWAT in simulating the discharge from the study watersheds.
3) Similarly, the model also performed more than satisfactory on both the study watersheds in simulating the sediment concentration with R^2 values of 0.86 and above and E_{NS} above 80%.
4) The model also simulated the mean annual water yield and sediment yield close to the observed values in both the watersheds. The mean annual surface runoff and water yield over the entire study period were simulated as 6 and 59.4% respectively of the mean annual rainfall in Arnigad watershed; and 6.9 and 63.7% respectively in Bansigad watershed. The mean annual sediment yield from the respective watersheds was simulated as 8.45 and 21.97 t ha^{-1} respectively.
5) The higher ET, lower mean annual surface runoff, lower water yield and lower sediment yield from dense oak forest than that from the degraded oak forest clearly indicated the effect of forest cover types on these hydrological variables.
6) The water balance components simulated by the model provided a useful insight for examining the hydrological behaviour of study watersheds, especially the ET needs and water delivery from the watersheds which are dominated by two different forest cover types.
7) The results indicated that SWAT is capable of estimating the discharge and sediment yield from Himalayan forested watersheds, the estimates of which are often required for operation and management of irrigation and hydropower projects in the region.

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