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Full Paper

MODELLING AND SIMULATION OF EPHEMERAL STREAMFLOW IN IBADAN, NIGERIA

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ABSTRACT

Flow variability of ephemeral rivers due to spatial and temporal distribution of rainfall and unregulated exploitation of water resources is a major cause of severe water supply shortages. With appropriate conservation planning of surface water resources through hydrological modelling, timing of extraction of large volume without adverse effects on downstream requirement can be predicted. This study attempts to develop water balance components for evaluating flow characteristics essential for conservation planning of ephemeral streams. Daily Meteorological data spanning 1973-2006, obtained from the International Institute of Tropical Agriculture, Ibadan weather station were used in developing predominant water balance model components of Ona Stream. Daily infiltration values were obtained using Crawford and Linsley's model and interflow based on soil moisture levels. Data were statistically analyzed and developed models validated using 10 years meteorological data. Analyses showed that 93.4, 91.5 and 55.0 % variability in runoff was due to precipitation, groundwater storage and interflow respectively. Precipitation, interflow and groundwater storage were significant while evapotranspiration was insignificant ($P<0.05$) for runoff prediction. The water balance models simulated acceptable hydrologic processes such as interflow and groundwater storage which are generally difficult to measure directly. The R2 values obtained from validation range from 0.79 to 0.99. The water balance model thus improved the reliability of streamflow computation and other flow characteristics of the ephemeral Ona stream. It would appear that the ephemeral streamflow investigated depended more on the magnitude of precipitation, interflow and groundwater flow while evapotranspiration (a major source of water loss in hydrologic water balance model) has relatively little effect on streamflow characteristics.

Keywords: Ephemeral streamflow, Water balance model, Statistical analyses, Monte-Carlo Simulation.

I. INTRODUCTION

Beyond the impact of population growth in developing countries, demand for freshwater has been rising in response to industrial development, increased reliance on irrigated agriculture, massive urbanization, and rising living standards. (Hinrichsen et al, 1998). Lack of economic and financial resources needed to tap freshwater efficiently in developing countries makes the region to be economically water scarce (Molden et al, 2001). Problems such as the geographical redistribution of water resources due to climate change, the ecological consequences of large-scale water transfers, the effect of land use changes on the regional hydrological cycle, the effect of non-point sources of pollution on the quality of surface water at the regional scale and the possibility of changing regimes of regional floods and droughts have been neglected (Slaymaker, 2000). The need for research into the connectivity of components of the hydrological cycle in the developing countries can not be over emphasized. Hydrological data available in African tropical regions usually consist of long precipitation records, rather short water level and discharge records and very short data for small, separated experimental catchments. In some cases, daily rainfall data will not be available or will not span 15-year periods, which is the recommended minimum in hydrologic studies (Mutsaers et al, 1997). Hydrological modeling simulates the conversion of precipitation to runoff through evaporation, infiltration, transpiration, percolation, surface flow, groundwater flow and interflow. Wilson (1990) gave four processes with which hydrologists is mainly concerned as precipitation, evapotranspiration, surface runoff or stream flow, and groundwater flow. The general water balance for watershed scale applications equates basin inputs with outputs and changes in storage (Sheridan, 1997). As climate models are presently not able to give reliable estimates of the hydrological responses to climatic changes, most studies use hydrological models instead (Kite and Droogers, 2000; Kite et al, 2001, Jayatilaka et al, 2001; Ines et al, 2001).

In the past decades a wide range of hydrological models have been used to assess the impact of climate change on a variety of water resources. For large drainage basins, conceptual water balance models are often believed to be appropriate (Arnell, 1999). In terms of data demands, accuracy, flexibility and ease of use, the conceptual water balance models offer significant advantages over process-based distributed parameter models (Gleik, 1986). The use of models according to Kite and Droogers (2000) gives two advantages compared with reliance on collected data viz, models can be used to understand processes that are difficult to measure because of complexity or temporal and/or partial scale, and models can be used to study the effects of changes.

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Simulation models such as Hydrologic Simulation Program FORTRAN (HSPF) and the Soil and Water Assessment Tool (SWAT), according to Van Liew et al (2003) are applied to large watersheds in a distributed fashion to represent spatial variations in climatic, topographic, soils and land use features across the watershed. Distributed hydrological models are often used to investigate basin water resources but such models generally require a large amount of data, which are not always available in developing countries (Lacroix et al, 2000).

This paper focuses on developing water balance components for evaluating flow characteristics essential in conservation planning of ephemeral or intermittent streams. There is need for proper and improved understanding of the ephemeral nature of stream flows as some are dammed or impounded into reservoirs for use during acute water shortage. Hence, model to be developed is limited to the analyses of daily meteorological data for two months of the year with decrease in flows due to transition between the rainy and dry season. This is to allow for comprehensive and in depth study of the dependent and independent variables responsible for the stream flow of the study location.

2. METHODOLOGY

Ona River is in Ibadan, south-western region of Nigeria lies roughly between latitude 07° 29' 16 N and longitude 03° 54' 44 E, at an altitude of about 213.4 m above mean sea level (Eze, 1997). International Institute of Tropical Agriculture (IITA) meteorological station is about 500 m northwest of Ona River (Figure 1). Study location lies between Ojoo-Moniya roads with localized outcrops of pre-Cambrian basement complex rocks resulting in the establishment of quarry industries. The land use pattern of study location in Ibadan is of built up area with residential and industrial areas. The average elevation of study location near IITA is 210 m above mean sea level.

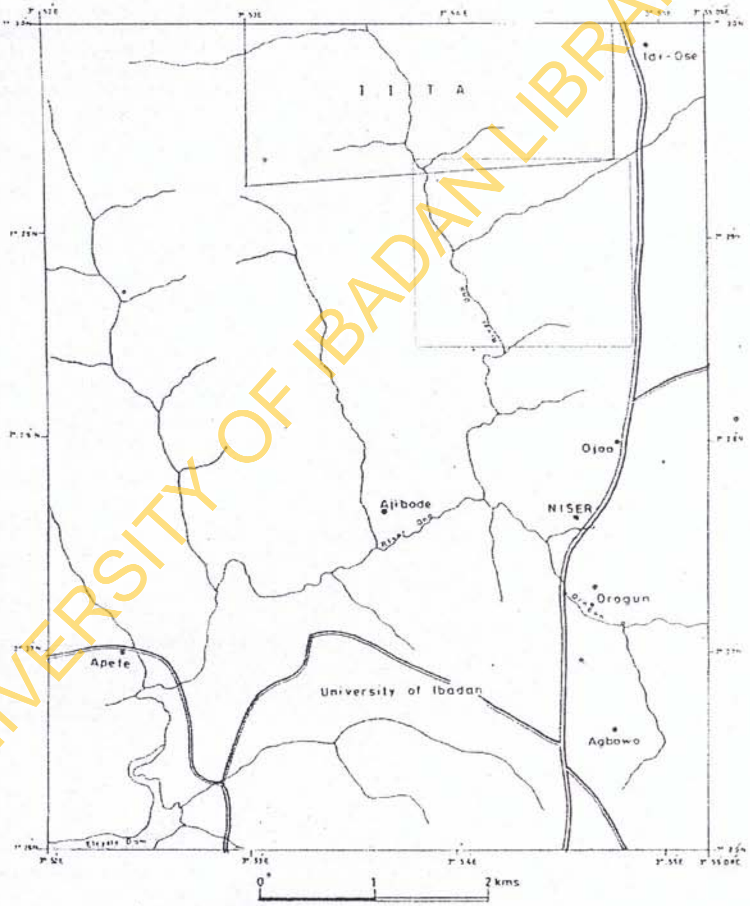

Figure 1: Ona River Geographical Location Highlighted in Study Area Map

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Annual rainfall for Ibadan was between 1000-1600 mm, with the mean around 1270 mm per annum (Lal, 1993). Approximately, 50 % of the average annual rainfall occurs between April and July while 40 % occurs between August and October. November to March is usually the driest months and temperatures tend to be higher. Mean day length of this latitude is 12 hours, ranging from a minimum of 11.5 in December to a maximum of 12.7 hours in June. Maximum values of long term average solar radiation are recorded in April *(18.16 MJ/m²/day) while minimum values are recorded in August* (12.63 MJ/m²/day).

The percentage composition of topsoil with depth between 0–30 cm and subsoil with depth greater than 30 cm of topsoil samples were characterized as Sandy Clay Loam while subsoil was Clay textured when percent sand and percent clay of soil samples were inputted into an interactive Soil Moisture Triangle of the National Water and Climate Center Irrigation Water Management model. Topsoil belongs to National Resources Conservation Service (NRCS) soil hydrologic group A while subsoil is clay with 120mm soil moisture available at Field capacity (Raudkivi, 1979).

The water balance time-dependent relationship was computed as a continuous function in order to fully understand catchment response. The components are based on concepts of the hydrologic cycle and a generalized water balance equation written in the form:

$$P_t = (E_t + R_t + G_t + \Delta S_t)_{time} \qquad (1)$$

where P_t = total precipitation over land and water surfaces

E_t = total evaporation from land and water surfaces

R_t = total runoff from land surface

G_t = total subsurface runoff from land to stream

ΔS_t = change in storage of water in the atmosphere, land or stream.

$(\ldots)_{time}$ = a function of time

Runoff was calculated using the NRCS procedure known as "Curve Number Technique". Description of the four hydrologic groups was given in ICRISAT (2004). The NRCS estimate of storm runoff using the Curve Number (CN) of the watershed was applied thus:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad (2)$$

where: Q = runoff volume

P = precipitation

S = surface storage measured in depth of water before the onset of runoff; estimated from:

$$S = (1000/CN) - 10 \qquad (3)$$

Infiltration was determined using Crawford and Linsley (1966) infiltration equation:

$$\bar{f}_t = \frac{INF}{(LZS_{t-1}/LZSN)^b} \qquad (4)$$

Where: $\bar{f}_t$ = Segment mean infiltration capacity in mm at time, t (Sec.)

INF = a parameter representing an index infiltration level. This is physically related to the characteristics of Catchment. Typical value ranges between 0.25 – 1.27 mm.

LZS_{t-1} = actual soil moisture storage at time (t-1) in the lower soil zone (mm).

LZSN = nominal soil moisture storage in lower soil zone equivalent to field capacity (mm)

b = exponent; a value of 2 adopted following numerous trials by Crawford and Linsley.

The total subsurface runoff from land to stream is a combination of the interflow and groundwater flow (G_w). Interflow (Int) is routed back to the streams that are ephemeral while the groundwater flow is lost to deep percolation. This is reflected in the following equation:

$$G_t = G_w + I_{nt} \qquad (5)$$

To obtain the total runoff from land surface, equations 1 - 4 was rearranged, assuming total change in storage (ΔS_t) to be zero *and the infiltration capacity f was evaluated thus:*

$$R_t = P_t - E_t - G_w - I_{nt} \qquad (6)$$

$$\bar{f}_t = \bar{f} + \bar{f}(c-1) \qquad (7)$$

where; $\bar{f}_t$ = total mean infiltration capacity

$\bar{f}$ = Mean infiltration capacity

and

$$I_{nt} = C/2^{(LZS/LZSM)} \qquad (8)$$

The soil moisture entering groundwater storage is a complex phenomenon. A simplification of the process is to obtain a fraction of water accumulating in the lower zone from direct infiltration and percolation from upper zone. This fraction expressed in percentage was calculated as follows:

$$P_g = 100\frac{LZS}{LZSN}\left(\frac{1.0}{1.0+Z}\right)^Z for \frac{LZS}{LZSN} < 1 \qquad (9)$$

$$P_g = 100\left[1.0 - \left(\frac{1.0}{1.0+Z}\right)\right]^Z for \frac{LZS}{LZSN} > 1 \qquad (10)$$

$$Z = 1.5\left(\frac{LZS}{LZSN} - 1.0\right) + 1.0 \qquad (11)$$

where P_g is the percentage of moisture entering groundwater storage.

The following daily values were entered into the CropWat 4 Windows programme: mean maximum and minimum temperature (°C), air humidity (%), wind speed at 2 m height (km/hr), daily sunshine (hrs), latitude and longitude, location altitude (m), and station location. The programme uses FAO (1992) Penman-Monteith (Smith et. al., 1999). Daily precipitation data were obtained from International Institute of Tropical Agriculture (IITA) weather station, which is located approximately 200 m from 'Ona' River gauging point.

Average absolute deviation or mean absolute error was used to assess differences associated with regression model parameters and this can be effective for model calibration (Spruill et. al., 2000). Other model performance statistics used includes the regression based correlation coefficient and hypothesis tests methods with the use of sample t statistic. More than one model performance statistical tests were applied in this study based on recommendations of Coffey *et al* (2004). Uncertainty and sensitivity analysis of the stream flow was quantified using the standard deviation of the Monte Carlo simulation outputs. Monte Carlo was selected because it provides a truly global measure of uncertainty and also enable the use of simple regression techniques to calculate sensitivity (Bekesi and McConchie, 1999). The calibrated regression models were validated using ten years (1997 to 2006) daily weather data of the study location. Field data was obtained by standard methods as recommended by WMO (1983). Physiographic characteristics of study location determined included Catchment

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Area, River Length, Average slope and height of the Catchment area, and Average and smoothed river slope.

3. RESULTS AND DISCUSSION

Substituting parameter values of water balance equation and rearranging, the water balance model runoff/streamflow of the location of study are obtained. For the NRCS method (which takes into consideration effects of soil and surface vegetation on the runoff) estimates with CN method are detailed as seen in Table 1. Flows of actual and model runoffs were plotted to compare trends and also to examine the shape and timing of the hydrographs. Figures 2 and 3 show that the shape of the daily flows; timing of the actual and model runoff hydrograph compare reasonably well

Table 1: Ona River Runoff Estimates using the Water Balance and Curve Number (CN) Techniques

	September							October						
Days	Pt (mm)	Et (mm)	Int (mm)	Gw (mm)	Gt (mm)	Rt (mm)	R_{CN} (mm)	Pt (mm)	Et (mm)	Int (mm)	Gw (mm)	Gt (mm)	Rt (mm)	R_{CN} (mm)
1	0.05	3.8	0.27	0	0.27	0	0.29	2	4.21	1.02	0.76	1.78	0	0.07
2	0	3.4	0.21	0	0.21	0	0.32	2.6	3.2	0.89	0.97	1.86	0	0.23
3	60.6	2.76	0.17	5.62	5.79	52.05	53.55	0	4.07	0.89	0	0.89	0	0.32
4	0	3.95	1.09	0	1.09	0	0.32	0	4.45	0.86	0	0.86	0	0.32
5	0.05	2.64	1.09	0	1.09	0	0.29	2.9	3.54	0.78	0.96	1.74	0	0.33
6	17.8	2.35	1.03	2.29	3.32	12.13	11.91	0	4.29	0.73	0	0.73	0	0.32
7	24.2	2.2	1.1	2.18	3.28	18.72	17.93	0	4.1	0.67	0	0.67	0	0.32
8	69.5	2.74	1.23	2.07	3.3	63.46	62.38	0	3.48	0.6	0	0.6	0	0.32
9	0	4.01	1.34	0	1.34	0	0.32	31.2	3.94	0.52	3.39	3.91	23.35	24.66
10	0	2.63	1.34	0	1.34	0	0.32	18.2	3.5	0.71	2.9	3.61	11.09	12.28
11	25	3.5	1.23	2.07	3.3	18.2	18.69	7.2	3.84	0.83	2.07	2.9	0.46	2.85
12	35.5	2.7	1.34	1.91	3.25	29.55	28.84	49.2	2.94	0.92	2.41	3.33	42.93	42.28
13	43	2.46	1.38	1.93	3.31	37.23	36.18	4	4.85	0.99	1.38	2.37	0	0.81
14	0.05	3.09	1.38	0	1.38	0	0.29	0	2.49	1.06	0	1.06	0	0.32
15	1	3.54	1.31	0.42	1.73	0	0.01	13.5	3.96	0.95	2.35	3.3	6.24	8.03
16	0	3.77	1.2	0	1.2	0	0.32	0.05	2.3	1.07	0	1.07	0	0.29
17	17	3.78	1.06	2.25	3.31	9.91	11.18	0	2.82	1.01	0	1.01	0	0.32
18	17	3.73	1.16	2.13	3.29	9.98	11.18	17.9	4.96	0.98	2.37	3.35	9.59	12.01
19	2	2.98	1.16	0.8	1.96	0	0.07	1	4.79	1.06	0.41	1.47	0	0.01
20	0.05	2.77	1.17	0	1.17	0	0.29	0	3.87	0.91	0	0.91	0	0.32
21	13	3.79	1.14	2.11	3.25	5.96	7.59	18.5	4.13	0.79	2.7	3.49	10.88	12.56
22	1	2.55	1.26	0.44	1.7	0	0.01	0	4.5	0.9	0	0.9	0	0.32
23	0.05	1.97	1.09	0	1.09	0	0.29	0	4.59	0.76	0	0.76	0	0.32
24	0	3.61	1.02	0	1.02	0	0.32	12	4.28	0.71	2.72	3.43	4.29	6.72
25	10.5	3.21	0.99	2.28	3.27	4.02	5.45	25.5	4.47	0.77	2.74	3.51	17.52	19.17
26	7.8	3.72	1.03	2.12	3.15	0.93	3.29	3.5	3.84	0.83	1.17	2	0	0.57
27	0	3.79	1.11	0	1.11	0	0.32	0	4.75	0.77	0	0.77	0	0.32
28	0	4.03	1.03	0	1.03	0	0.32	0	4.34	0.69	0	0.69	0	0.32
29	0	4.26	0.91	0	0.91	0	0.32	0	4.58	0.6	0	0.6	0	0.32
30	42	2.92	0.85	2.6	3.45	35.63	35.20	0	4.01	0.53	0	0.53	0	0.32
31								1	3.81	0.45	0.26	0.71	0	0.01

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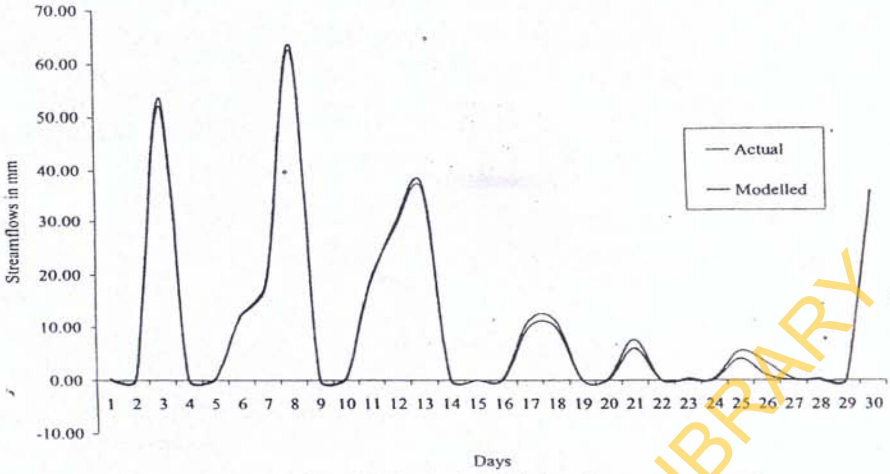

Figure 3: September Actual and Modelled Streamflows

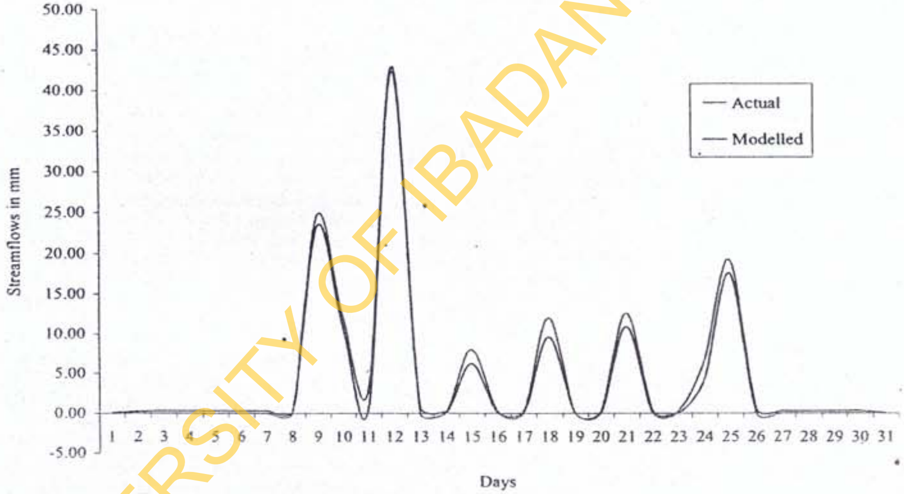

Figure 3: October Actual and Modelled Streamflows

The peak runoff values of the actual flows are slightly higher than the model values, but in terms of their timing they are almost the same. From the water balance Table 1, large magnitude rainfall events corresponds with peak runoff values while consecutive days of no rainfall events correspond to little or no runoff values.

Components of water balance of the location of study for September and October were used in the development of first-order multiple regression models. From summary output of multiple regression analysis, explained variability SSR (8359.79) accounts for almost all of total variability SST (8388.75), the model appears to fit the data well. The low SSE (29.0) indicated that error inherent in model data is negligible.

Statistical concepts of null and alternative hypothesis were applied to the data and the absolute values of t Stat of three of the four independent variables is greater than the tabulated value. The exception was Et (evapotranspiration) which has $|t| = 1.5069$ which was less than 2.060. Hence, we reject the null hypothesis, which states that the fitted regression goes through the origin ($\beta_1 = 0$) when Pt (precipitation), Int (interflow), and Gw (groundwater flow) were taken into consideration. It does appear that Pt, Int, and Gw were useful in predicting runoff in multiple regression models. The first-order multiple regression model for September is:

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$$Y_{sept} = 0.9982X_1 - 0.5227X_2 - 2.1944X_3 - 2.4162X_4 + 3.7214 \qquad (12)$$

where X_1, X_2, X_3, and X_4, are Precipitation (Pt), Evapotranspiration (Et), Interflow (Int), and Groundwater flow (Gw) respectively. The coefficient values of the quantitative independent variables lies between the lower and upper 95 %, thus indicating that multiple regression model coefficients are true estimates of the population data.

Similar results were obtained in October.

Table 2: Uncertainty and Sensitivity Analysis from Monte Carlo Simulations

	INPUTS				OUTPUT	
	Pt (mm)	Et (mm)	Int (mm)	Gw (mm)	Rt (mm)	b_0
Y	9.8302	3.5527	0.7161	0.8805	5.8467	
S	16.0007	0.7161	0.2721	1.3659	15.1461	
b (September)	0.9982	-0.5227	-2.1944	-2.4162		3.7214
b (October)	1.018	-0.2239	-1.4001	-2.9279		2.0165
U_{SCR} (September)	1.054521	-0.024714	-0.039425	-0.21789		
U_{SCR} (October)	1.0754382	-0.010586	-0.025155	-0.264035		

$$Y_{oct} = 1.018X_1 - 0.2239X_2 - 1.4001X_3 - 2.9279X_4 + 2.0165 \qquad (13)$$

The regression coefficients (bi) measure the linear sensitivity of the output to the input variables. Considering the coefficients in September; for every millimetre increase of precipitation (Pt) there is an average increase of 1.05 mm of runoff estimated over the entire range of other input variables. Similarly, a millimetre increase of evapotranspiration (Et), interflow (Int), and Groundwater flow (Gw) causes an average decrease of 0.52, 2.19, and 2.42 mm in runoff respectively. Similar results were observed in October and this further corroborates the hypothesis tests methods. The standardized regression coefficients which compares the effects of all input variables on a single scale shows that the output runoff is more sensitive to the input variables in the listed order of precipitation, groundwater flow, interflow, and evapotranspiration.

4. MODEL VALIDATION

There was a good relationship between measured and predicted runoff (figures 4 and 5), with R^2 values range of 0.79 to 0.99. Similar results were obtained when Gowda *et al* (1999) used the SWAT model to study hydrologic budgets for three watersheds.

Stepwise regression analyses indicated that 93.4 and 91.5 % of the variability in runoff was explained by the variation in precipitation and groundwater storage (figures 6 and 7). These figures show that the effect of precipitation and groundwater storage is directly proportional to resulting runoff. Slope of figure 6 implied that every millimetre of precipitation resulted to 0.56 mm of runoff, while in figure 7, every millimetre of groundwater storage resulted to 0.55 mm of runoff. Similarly, 55.0 and 5.3 % of the variability in runoff was explained by the variation in interflow and evapotranspiration components of the water balance as seen in figures 8 and 9. From the slope of figure 8, it was observed that as interflow increases, resulting runoff decreases. When there was no runoff, interflow components of the water balance continue to increase and this may be attributed to flows that are observed even when there are consecutive days of no precipitation.

5. CONCLUSIONS

Regression models developed were able to stimulate the conversion of precipitation to runoff through natural processes of precipitation, evapotranspiration, infiltration, interflow, and ground water flow. This findings was in line with Sheridan (1997) which recommended the use of linear rainfall-streamflow regression models for estimating annual water yields on humid, flatland watersheds with low-gradient drainage networks as obtained in this study. By considering the precipitation, interflow, and ground water flow, the developed regression models from statistical analyses were useful in making predictions since regression coefficient values lie within the lower and upper 95% confidence interval, the multiple regression model coefficients are true estimate of the population data. Also, large relative difference between the Sum of Squares due to regression (SSR) and Sum of Squares due to Error (SSE) indicated that error inherent in the model data is negligible.

In summary, developed Water Balance models showed that the streamflow characteristics investigated depended more on magnitude of precipitation, interflow and ground water flow. The magnitude of evapotranspiration, a major source of water loss has relatively little effect on the characteristics of stream flow. This may be due to the fact that long-term evapotranspiration weather data of the study location investigated showed consistent constant values when compared with random nature of rainfall during the period of study.

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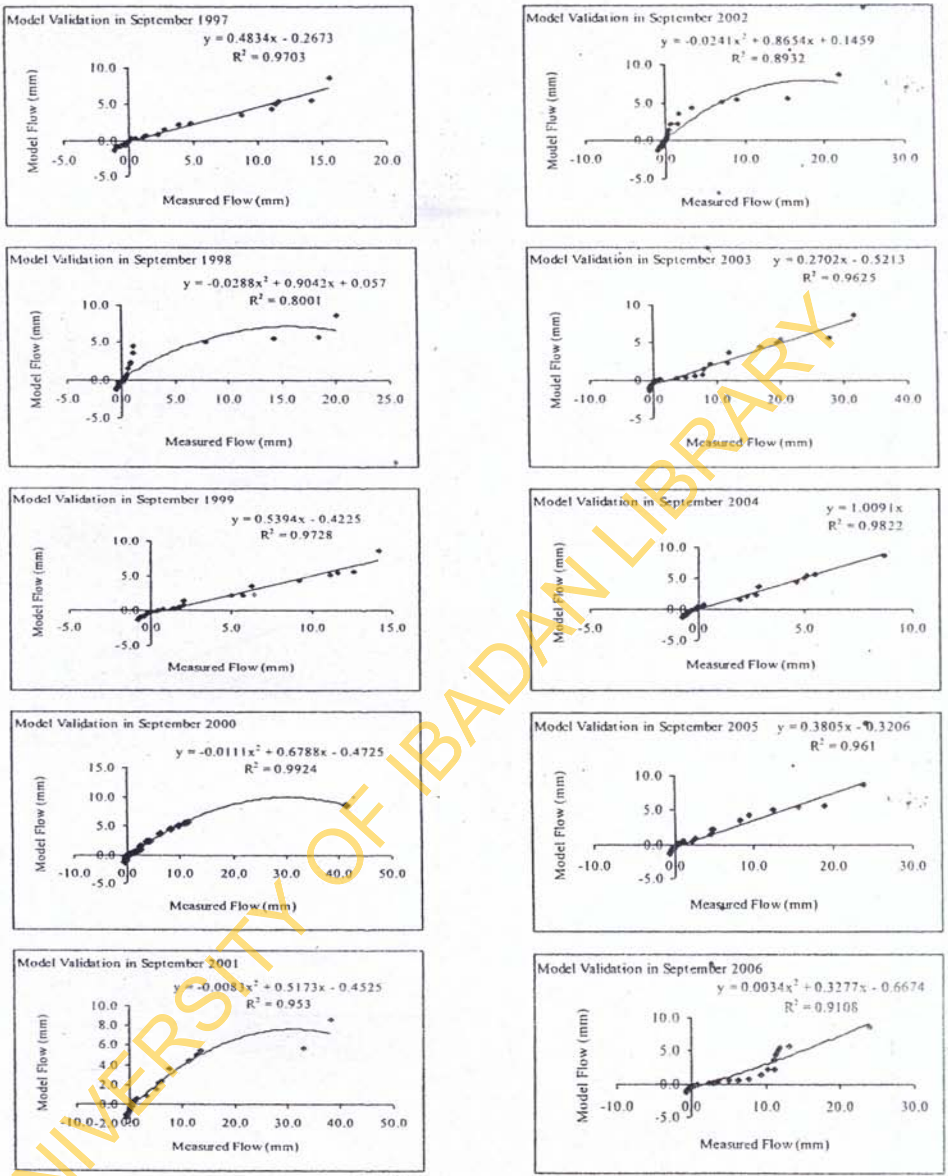

Figure 4: September Model Validation

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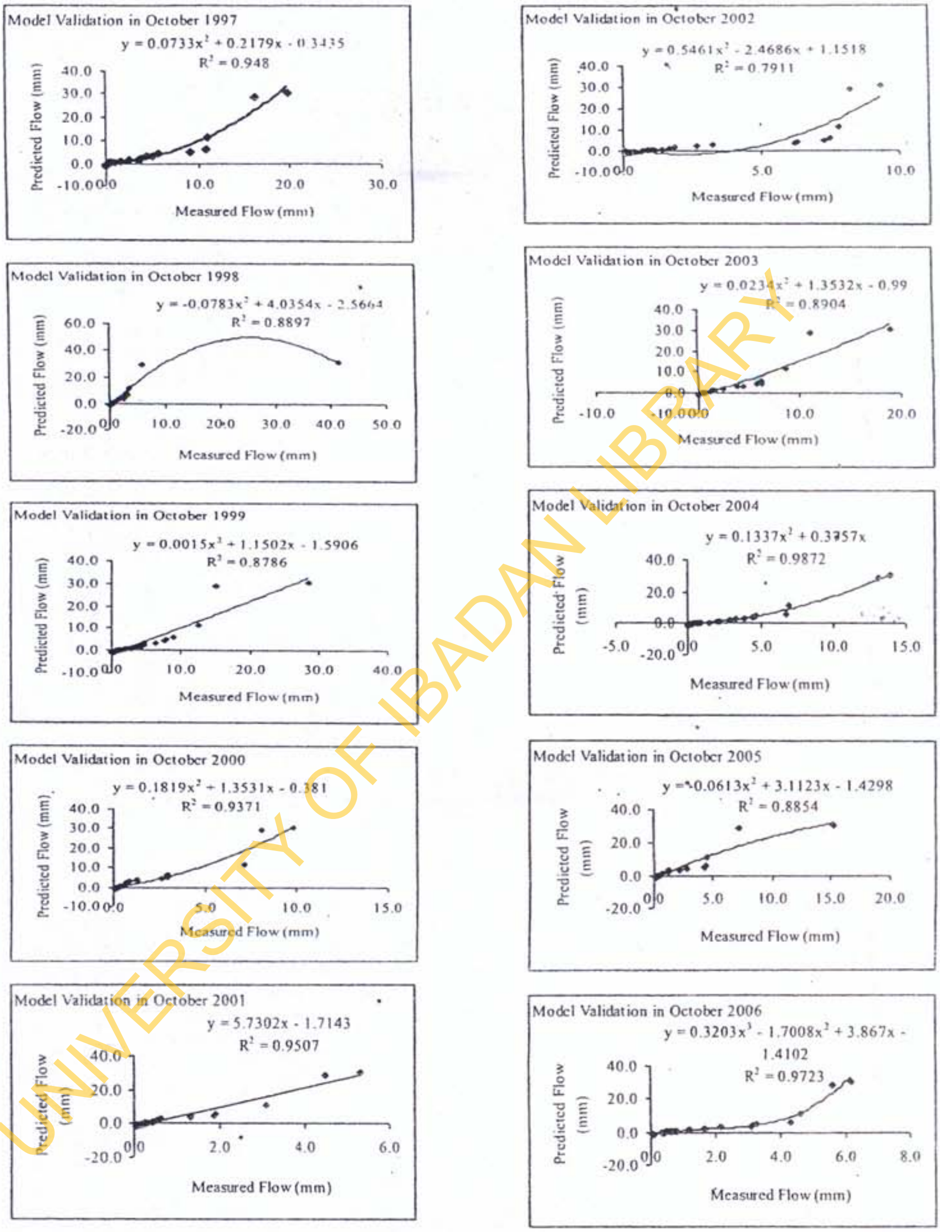

Figure 5: October Model Validation

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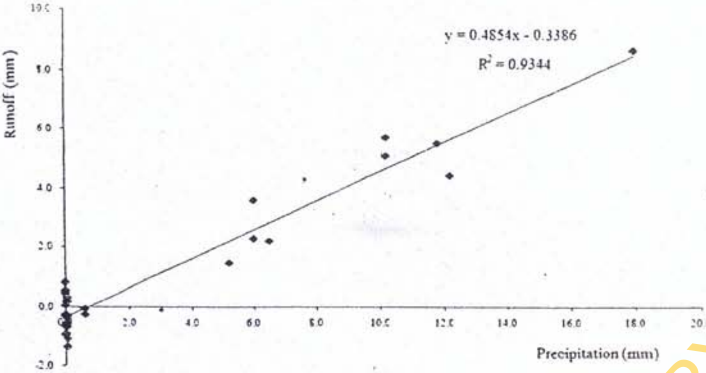

Figure 6: Effects of Precipitation on Runoff

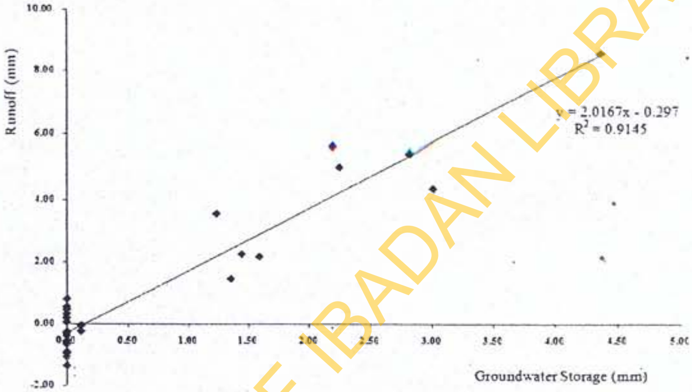

Figure 7: Effects of Groundwater Storage on Runoff

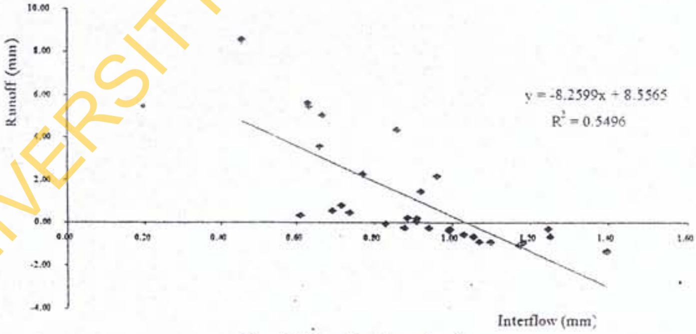

Figure 8: Effects of Interflow on Runoff

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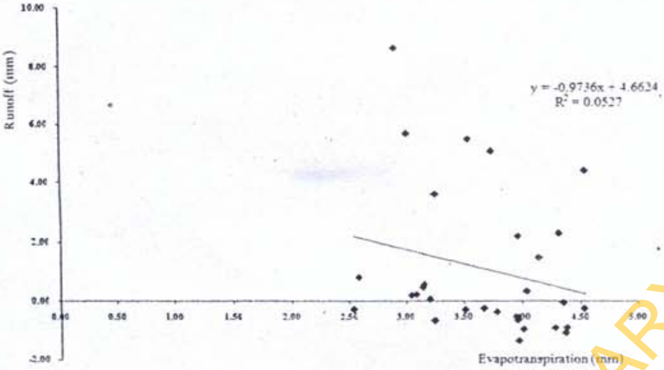

Figure 9: Effects of Evapotranspiration on Runoff

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