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Spatial Variation in Surface Runoff at Catchment Scale, the Case Study of Adigela Catchment, Tigray, Ethiopia

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Abstract

The study was conducted in Adigela catchment with specific objective to examine surface runoff variation in relation to factors affecting runoff processes. Four representative units were selected where runoff data in terms of depth is collected while runoff hydrograph analysis was made to determine runoff volume. The hydroraph at all gauging station was indicated with a trend of rising before the runoff reached peak and started to faill quickly on the recession limb. The discharge in terms of volume at the outlet was then determined using Hydrochan after surveying (Total station) the channel cross section. The study indicated that on average a peak discharge of 0.73, 2.14, 0.47 and 1.53 m^3/sec from Maykaebo, Mengediweste, Nushteyshintro and Abayshintro were measured respectively. The statistical result has showed that spatial pattern of the origin of runoff is complex and varies significantly between sub catchments. From the field experiments, it was found that the key controls on runoff hydrograph and runoff generation at the catchment scale are shape of the catchment, vegetation cover, and slope gradient, soil type, area coverage and amount of rainfall. It was also found that SCS CN method was efficient and can be used to predict runoff in the catchment. Based on the result, it has been recommended to identify similar hydrological response units in the catchment so as to compare runoff difference among homogenous units.

Keywords: Catchment, Runoff, Infiltration and Hydrograph.

Introduction

Effective watershed management requires a detailed understanding of hydrologic processes within the watershed so as to identify management options (Kansheng, 2003). Surface runoff is mainly generated by two mechanisms, infiltration excess runoff and saturation excess runoff; and the spatial variability of soil properties, antecedent soil moisture, topography, and rainfall will result in different surface runoff generation mechanisms. Runoff is thought to be generated mainly by infiltration excess overland flow, and predominantly with in the short burst of intense rainfall. During these storm bursts, runoff is generated almost everywhere but, when rainfall intensity declines, overland flow re-infiltrates so that only flow generated close to channels contributes to their flow (Zhenghui et al, 2003). Infiltration is the process flow of water into the soil profile vertically through the soil surface and it remains crucial in modeling surface runoff (Suresh, 2008).

The amount of water which leaves a slope is controlled by the connectivity of the runoff generating areas (Reaney, 2003). Response of the landscape to intense rainfall events is a complex and poorly understood problem. An understanding of the spatial variability of runoff generated by such storms at the hill slope scale is a necessary goal if patterns of runoff and soil erosion are to be understood at the field and catchment scale also (Wainwright et al, 2001). The objective of this study was to evaluate surface runoff variation at catchment scale.

Methodology

The study area (Adigela catchment) is geographically located at $13^0 7'$ to $13^0 10'$ N Latitudes and $39^0 30'$ to $39^0 34'$ E Longitudes with an Average annual rainfall and temperature about 477mm and 18.5^0c respectively and having an area of around 8 km^2.

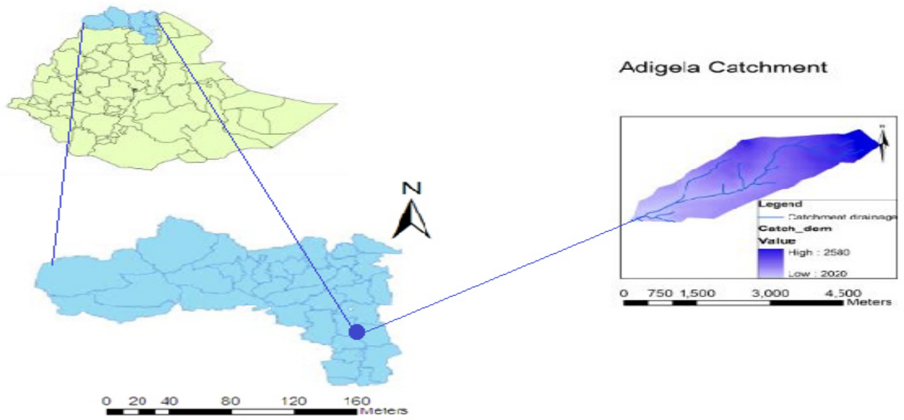


Figure 1. Study area map

Data collection techniques and analysis

Selecting gauging station and Runoff measurement

The study area had four gauging stations. On the first (Maykaebo) and forth (Abayshintro) sub catchments construction of masonary structures were made to conduct stage measurement while flood mark was used on second (Mengediweste) and third sub catchments (Nueshteyshintro). Runoff events from June to September, 2010 were specifically monitored. Indeed, daily rainfall was collected from three meteorological stations which are located nearby and within the study catchment and Runoff data were collected interms of stage from four monitoring stations namely. Total station was used to measure stream cross-sectional area and then to compute velocity by using hydrochan software. The hydrochan requires Manning coefficient ('n' value) for the channel as an input. The runoff depth was converted in to discharge using runoff rating curve table produced using hydrochan software.

The infiltration measurements were made by means of double-ring infiltrometer (DRI). Because infiltration excess overland flow is considered to be the dominant runoff process, infiltration test units have been mapped within each sub catchment and classified according to relevant catchment characteristics at each monitoring stations.

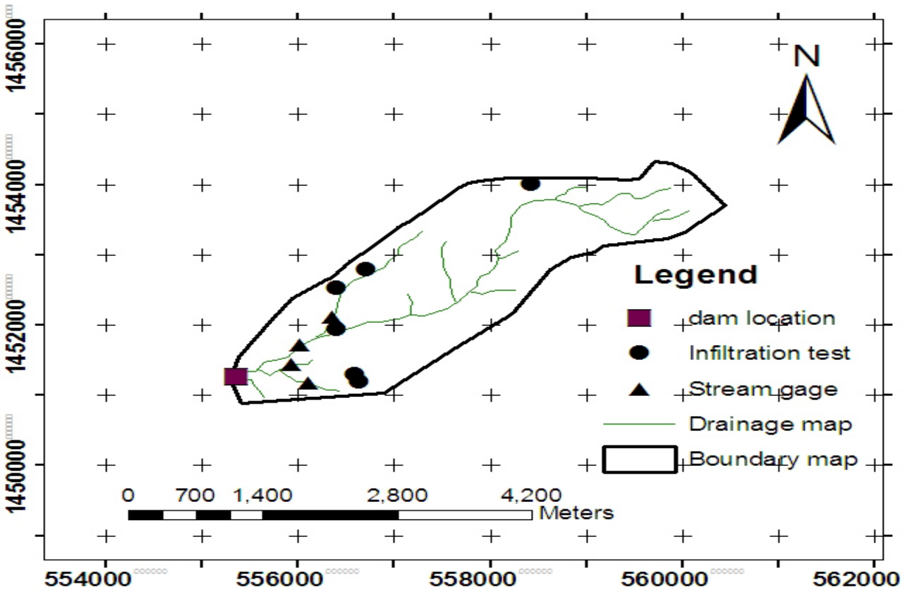


Figure 2. Infiltration test and runoff monitoring station/stream guage map

Flow path connectivity and Watershed boundary and Land Use

Connectivity was investigated through personal observation and field mapping of major flow paths using Trimble GPS. Moreover, average slope of each sub catchment were measured using clinometers. The catchment boundary and land use was mapped and site for the experiment was selected by land surveying using Navigation GPS and topographic map. Adigudom topographic sheet was used and exported to ArcGIS interface for analysis.

The projection was set to Universal Transverse Mercator (UTM) projection system, zone 37 while the spheroid and datum was referenced to WGS 1984.

Data analysis

Runoff data were analyzed with the help of hydrochan software. Hydrochan requires data on channel slope and roughness coefficient while velocity, area and discharge was calculated. Area of flow section was measured for each runoff gauging station. These measurements allowed calculating the runoff discharge for each specific runoff gauging station. In simulating runoff, SCS CN was used where the CN for each land use and hydrologic soil group were assigned. The model efficiency and relative root mean square error (RRME) was analyzed using Nash and Sutcliffe (Van Rompaey et al., 2001). Area under the hydrograph was calculated and summed to obtain total runoff volume at the outlet of the sub catchment and descriptive statistics were also used for comparison. Infiltration capacity was analyzed using Horton model that says the infiltration capacity as a function of time, so the infiltration rate is determined by the initial conditions of soil moisture at the time of soil infiltration is started to happen while soil textural class was examined using hydrometer. Finally, ArcGIS 9.3 was used to create layer, analyze the map and conduct spatial analysis.

Results and Discussion

Catchment Land Use

As indicated from the table below the catchment is mainly dominated by various land uses like cultivable, area closure, grazing, and waste land having area coverage and nearly 2% of the catchment is covered by the dam as presented below in the table.

Table 1. Classes of Land Use/Cover of the Study Area

S no.	Land use type	Area (m^2)	Percentage (%)	Description
1	Cultivable land	4508855	57.18	Agricultural land with cereal crops
2	Area closure	1107325	14.04	An area covered with grasses and small shrubs (Accacia species).
3	Waste land	1524822	19.34	Steep and rocky area (bare land).
4	Grazing land	588003	7.46	Land under grazing.
5	Water body	156446	1.98	Dam area

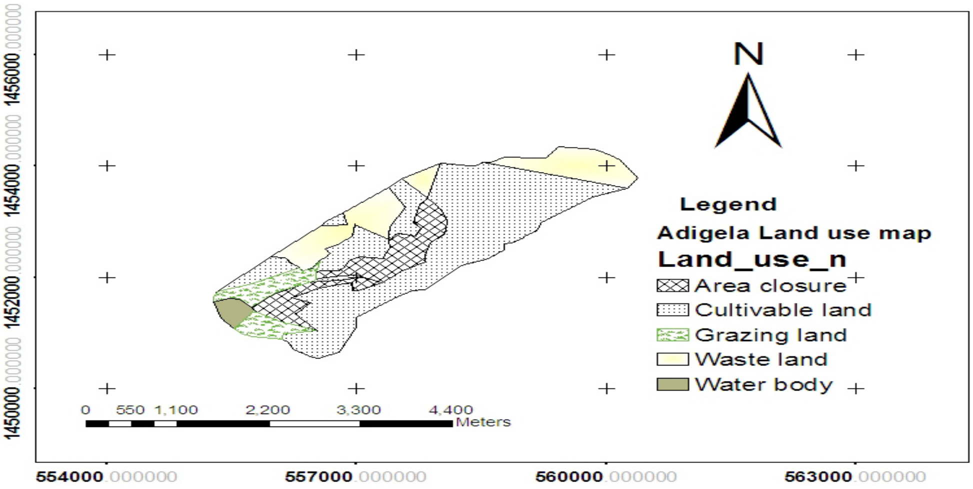


Figure 3. Adigela Land use map

Catchment characteristics and Hydrological connectivity

The major geological units in the study area are dolerite, shale, limestone and shale intercalation. Limestone is found at the base overlying by shale. The shale is exposed in the lowlands along the river beds. It consist intercalations of limestone, lime and marl. It has a multicolored color, and is highly weathered and fractured. Most of the dolerites occur as sills and dykes occupying the hills and mountains of the area dominantly occurred in Maykaebo sub catchment and not common on the other sub catchments.

The distribution of landscape elements in relation to each other in influencing transfer pathways and flow patterns are due to physical connection of water flows through landscapes (Marc et al., 2003). The study has indicated that the catchment is hydrologically connected to the flow paths. The connectivity of the runoff generating areas has been mapped and it was observed that each tributary have transferred flow to the outlet. The catchment is drained by intermittent rivers. It originates from the northern parts towards the southern flatlands and finally joins Adigela dam. The streams are dense at areas of higher slopes and sparse where the slope is relatively flat. There are still newly formed flow path often originated from poorly maintained soil and water conservation measures (terraces) and such structures are one of the sources for runoff initiation. In general, Abayshintro has the highest drainage density (4.7 km/km^2) followed by Maykaebo (2.5 km/km^2) and Mengediweste (2 km/km^2) with the least in Nushteyshintro (0.56 km/km^2). The study area has a dendritic drainage pattern (Figure 1).

According to (Table 2), Mengediweste covers the highest area coverage proportion with an average slope of 32.5%. The sub catchment is covered with cultivable land and to some extent area closure and waste land. Maykaebo sub catchment is ranked as second based on area coverage with its land use dominated by waste land and it is topographically undulated. The upper hill of Maykaebo is geologically basaltic type and has loam soil texture. Nushteyshintro and Abayshintro have similar land use, geology, soil and vegetation type. The upper flat land in both sub catchments is cultivable land while the sloppy part is area closure.

Field observation shows that in Mengediweste sub catchment the upper hill is not well connected in terms of transferring water to the out let. The reason is underlined with the hydrological network; the undulated topographic setup has put the ridges to disconnect the flowing water. Moreover, infiltration areas and slope change were also somehow disconnecting the flow.

Table 2. Sub catchment characteristics

S.no	Sub catchment	Area (m^2)	Average slope (%)	Drainage density (km/km2)
1	Maykaebo	638760	25.33	2.5
2	Mengediweste	5926241	32.5	2
3	Nushteyshintro	476515	17.25	0.56
4	Abayshintro	519818	17.75	4.7

Infiltration capacity

Hortonian overland flow is applicable for impervious surfaces in urban areas, and for natural surface with thin soil layers and low infiltration capacity as in semiarid and arid lands. Horton suggested the following form of the infiltration equation, where rainfall intensity $I > f$ at all times:

$$f = f_c + (f_o - f_c)e^{-kt}$$

Where: f = infiltration capacity (in/hr), fc = initial infiltration capacity (in/hr) at t = 0, f_o = final capacity (in/hr), and k = empirical constant (hr^{-1}) (Horton, 1933).

Table 3. Infiltration capacity of soil from infiltration test

S.no	Code	Infiltration capacity (mm/hr)	Sub catchment	Textural class (USDA)
1	A	30	Maykaebo	Sandy Loam
2	B	24	Mengediweste	Sandy clay loam
3	C_1^*	9	Nushtey and Abayshintro	Clay loam

A=Maykaebo, B = Mengediweste and C_1^*=Nushtey and Abayshintro

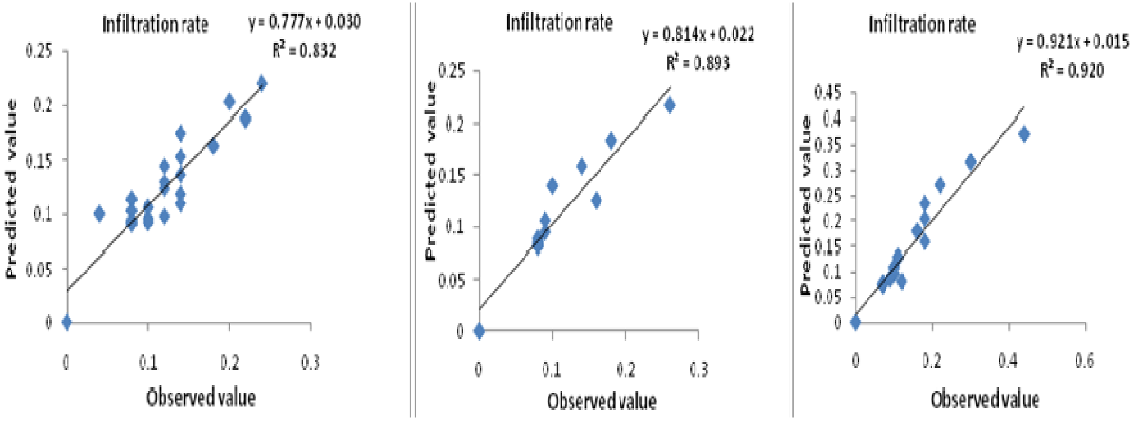


Figure 4. Comparison of observed and predicted infiltration values

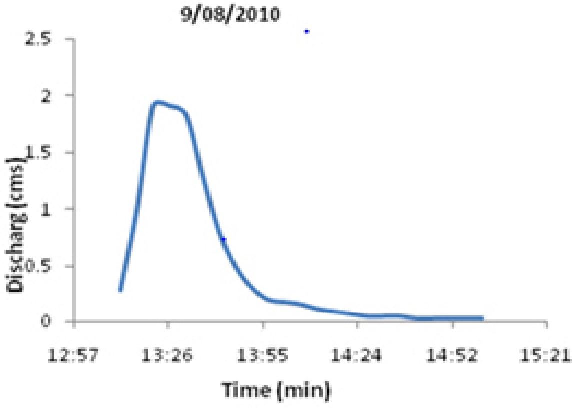
The field measurement of infiltration rate and estimation of infiltration rate (Horton Model) decreases up to a maximum limit of the soil to absorb water; the soil infiltrability is high early in the process and then gradually decreased to a constant. The cumulative infiltration and the time required to achieve constant infiltration are affected by initial soil water content, soil texture and uniformity of soil profile and roughness of land surface

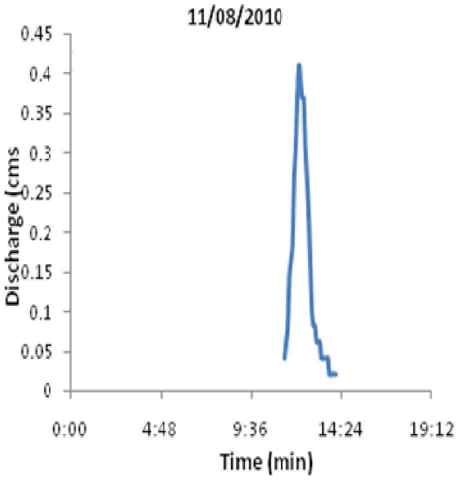
According to USDA textural classification the infiltration test sites in the catchment are categorized in to sandy loam, sand clay loam and clay loam. The result has obtained variation in infiltration rate with the highest infiltration capacity in Maykaebo sub catchment and lowest infiltration capacity in Nushteyshintro and Abayshintro sub catchments. The soil type on Nushteyshintro and Abayshintro are similar and texturally classified as clay loam.

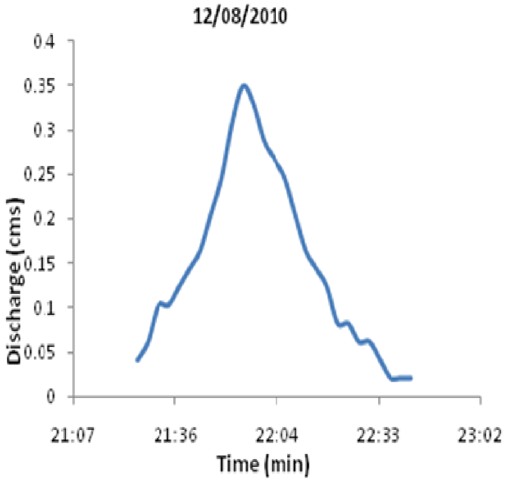
Runoff Hydrograph

Hydrograph analysis is often combined with rainfall analysis to investigate how a catchment responds to a particular rainfall event. Here the dominant factors are catchment characteristics which affect runoff flow to the outlet and rainfall amount there by affecting the amount of discharge at the outlet.

The hydrograph describes flow as a function of time usually as a time series of flow. It was generated based on the rainfall events and frequently occurs in the development of a rainfall runoff relationship for a catchment. It increased in magnitude shortly after the start of the rainfall event and reached a peak after the maximum rainfall intensity has occurred as shown in the figure below (Figure below). When the discharge reached its peak, it again started to gradually decline at the falling limb. For the same rainfall, sub catchment having small area coverage reaches its peak quickly. This is due to the fact that time of concentration for such sub catchment is small and with in short period of time streams start to contribute runoff discharge to the stream out let.







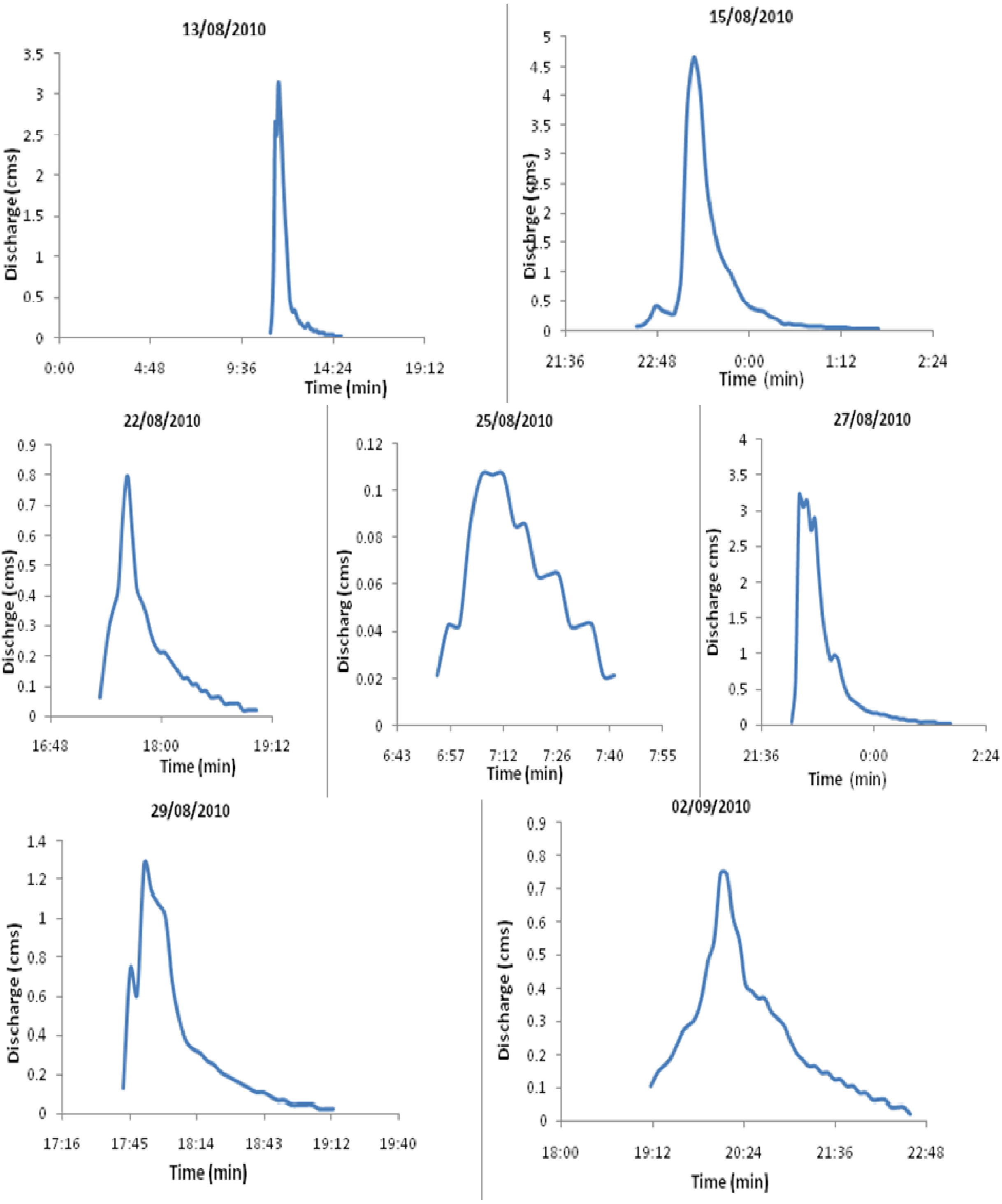


Figure 5. Runoff hydrograph from gauging station

All runoff hydrographs were characterized with trend reaching peak after the rising limb and started decreasing at the recession limb. Most of the hydrographs have one peak but rainfall variability during the storm also produce more than one peak because once rain has stopped on the point for the first falling limb, immediately the rainfall has again started and produced another peak on the same hydrograph.

Runoff/ discharge monitoring

Runoff was monitored at each gauging station in which runoff depth was recorded for each rainfall event. The depth was converted to peak discharge from runoff rating curve and hence runoff volume was determined (Table 9). The continuous flow depth series could be converted to continuous runoff discharge series by means of rating curves (Descheemaeker et al., 2008). The trends of rainfall and runoff depth were correspondingly observed.

Table 4. Average runoff discharge and runoff coefficient at Maykaebo

Date	Q m3/sec	Volume(m3)	Q (mm)	RF (mm)	RC %
11/8/2010	0.41	1454.5	2.28	10.21	22.3
12/8/2010	0.35	714.02	1.12	14.88	7.51
17/08/2010	0.06	125.5	0.2	6.21	3.17
22/08/2010	1.61	3897.05	6.1	28.93	21.09
25/08/2010	0.23	586.71	0.92	9.5	9.67
2/9/2010	0.74	3091.32	4.84	18.86	25.65

Where, Q (m^3/sec)= Discharge (m^3/sec), Q (mm) = runoff depth, RC% = Runoff coefficient and RF= Rainfall (mm)

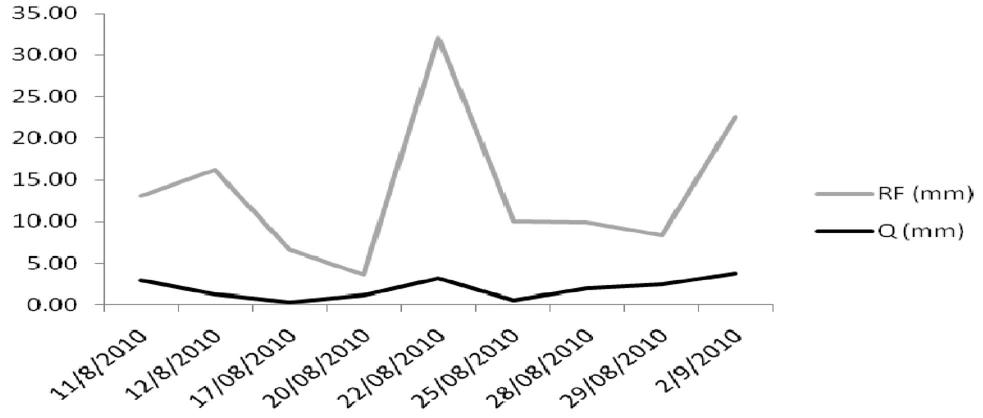


Figure 6. Rainfall-runoff trend at Maykaebo sub catchment

Table 5. Average runoff/ discharge and runoff coefficient at Abayshintro

Date	Q (m^3/sec)	Volume(m3)	Q (mm)	RF (mm)	RC %
9/08/2010	1.91	2884.40	5.55	52.94	8.8
9/08/2010	3.06	9496.80	18.27	52.94	28.9
11/08/2010	0.49	2072.80	3.99	10.21	28.5
12/08/2010	0.30	607.01	1.17	14.88	7.9
13/08/2010	3.14	6504.50	12.51	19.77	48.3
15/08/2010	4.65	6966.41	13.40	25.18	49.1
22/08/2010	0.80	1210.40	2.33	28.93	8.8
25/08/2010	0.11	177.12	0.34	9.50	2.5
27/08/2010	3.23	8354.67	16.07	21.40	75.1

Where, Q m^3/sec= Discharge (m^3/sec), Q (mm) = runoff depth, RC= Runoff coefficient and RF= Rainfall (mm/hr)

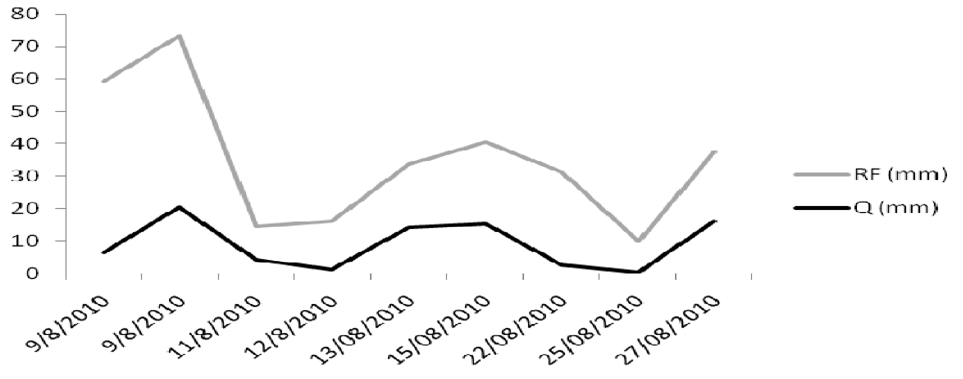


Figure 7. Rainfall runoff trend in the study area

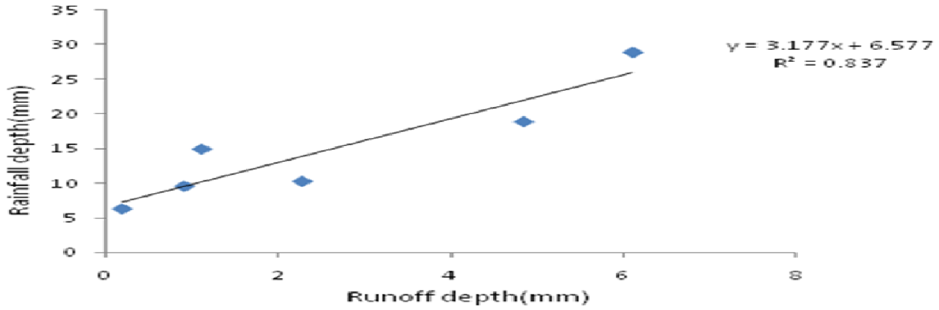


Figure 8. Rainfall runoff relationship in Maykaebo sub catchment

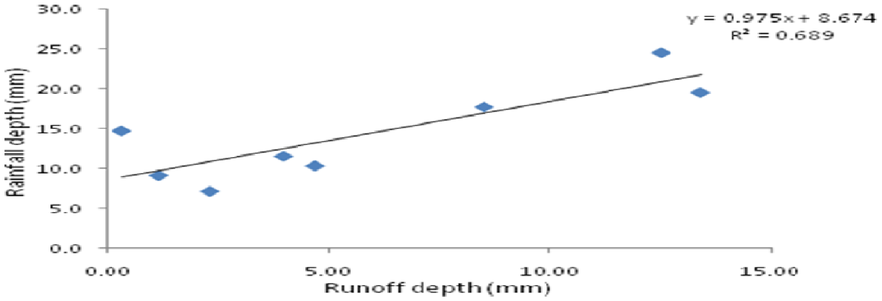


Figure 9. Rainfall runoff relationship in Abayshintro sub catchment

Sub catchment	Equation	n	R2
Maykaebo	Y = 3.177 + 6.577	6	0.84
Abayshintro	Y = 0.975 + 8.674	8	0.69

Table 6: Rainfall runoff relationship and coefficient of determination

For the rainfall runoff trend, in all sub catchment runoff is produced at the outlet in response to rainfall event but differing in magnitude due to the catchment characterstics.. From the rainfall runoff relationship (Figure 8 and 9) the R^2 is relatively good in the sub catchments.

A rating table or curve is used to interpolate runoff discharge and produce relationship between stage and discharge. Daily runoff depths and runoff coefficients (ratio of runoff depth to rainfall depth) were then calculated (Descheemaeker et al., 2006) (Table 9).

Table 7. Peak runoff/ discharge at each sub catchments

Date	A Q (m3/sec)	B Q (m3/sec)	C Q (m3/sec)	D Q (m3/sec)	Average	St.dev	CV %
9/8/2010	1.01	3.84	0.62	1.91	1.84	1.43	77.72
9/8/2010	0.39	2.91	1.04	3.06	1.85	1.34	72.32
11/8/2010	0.41	1.23	0.19	0.49	0.58	0.45	78.17
12/8/2010	0.35	0.9	0.19	0.3	0.44	0.32	73.15
12/8/2010	0.41	0.83	0.2	0.43	0.47	0.26	56.7
13/8/2010	1.14	2.62	0.82	3.14	1.93	1.12	58.2
15/8/2010	0.54	6.09	1.49	4.65	3.19	2.61	81.72
17/08/2010	0.06	0.56	*	*	0.31	0.35	113.57
20/8/2010	0.16	*	0.17	*	0.17	0.01	4.05
22/08/2010	1.61	0.83	0.3	1.11	0.96	0.55	56.75
22/8/2010	1.61	2.02	0.42	0.8	1.21	0.73	60.45
25/08/2010	0.23	*	0.05	0.32	0.2	0.14	68.6
25/08/2010	*	*	0.15	0.11	0.13	0.03	22.06
27/8/2010	0.37	4.28	0.9	3.23	2.19	1.87	85
28/08/2010	1.35	1.8	0.17	0.98	1.07	0.69	64.07
29/08/2010	1.28	2.18	0.65	*	1.37	0.77	55.96
2/9/2010	0.74	1.87	0.15	0.92	0.92	0.71	77.48
Average	0.73	2.28	0.47	1.53	1.11	0.79	65.06
stdev	0.53	1.57	0.41	1.42			
CV %	72.06	68.84	87.84	92.96			

Where A= Maykaebo, B= Mengediweste, C= Nushteyshintro, D= Abayshintro and Q= Discharge (m^3/sec), *= missing data

From the table above, it is indicated that there is variation in discharge among the sub catchment. The governing factors for the variation in surface runoff are surface area, infiltration, catchment shape, topography and land management practices. It is also observed that more flow paths are appeared in Abayshintro sub catchment due to poorly maintained land management intervention (Terraces) total runoff volume is higher in the absence of conservation measures (Bruijnzeel, 2004), as compared to Maykaebo sub catchment. Maykaebo and Nushteyshintro sub catchmentds are relatively treated with soil and water conservation measures and comparatively reduced runoff generation (Nyssen J., 2010). The highest average runoff discharge is recorded from Mengediweste sub catchment due to higher average slope and area coverage. In case of Makaebo and Abayshintro sub catchment even though they have almost similar area coverage, the average discharge is different because of geology, soil texture and infiltration rate. In the former sub catchment it is dominated by basaltic type which is not active in producing flow path revealing that infiltration is relatively higher. While, the later sub catchment is dominated by limestone. It is also observed that more flow paths are appeared in Abayshintro sub catchment due to poorly maintained land management intervention (Terraces) total runoff volume is higher in the absence conservation measures (Bruijnzeel, 2004), as compared to Maykaebo sub catchment. Maykaebo and Nushteyshintro sub catchmentds are relatively treated with soil and water conservation measures and reducing runoff generation (Nyssen J., 2010).

Runoff modeling

A result of the study on runoff depth was simulated using the SCS Curve Number method. In the CN method, runoff is calculated based rainfall and a CN, which can be looked up in tables. Values differ according to land use, soil type and hydrological conditions (Descheemaeker, et al., 2008). Infiltration rate were measured and textural classification was made so as to identify the hydrologic soil group. A CN was assigned for each sub catchment by considering soil condition as one of the factor governing runoff and runoff depth is predicted.

Table 8. Comparison of measured and predicted runoff depth using SCS CN method in Adigela sub catchment

Date	Q (mm)	SCS CN	(Qm-Qp)^2	(Qm-Qave)^2
9/8/2011	5.55	8.22	7.14	2.34
9/8/2011	18.27	13.01	27.68	125.23
11/8/2010	3.99	0.37	13.06	9.56
12/8/2010	1.17	0.15	1.04	34.94
13/8/2011	12.51	9.75	7.66	29.53
15/8/2011	13.40	6.58	46.57	39.98
20/08/2010	4.71	1.94	7.69	5.61
22/8/2011	2.33	0.86	2.17	22.57
25/08/2010	0.34	0.26	0.01	45.40
29/08/2010	8.52	5.53	8.94	2.08

Where Qm= measured runoff depth in mm, Qp= predicted runoff depth in mm, Qave= average runoff depth in mm and Q= runoff depth in mm

The efficiency of the model used to predict runoff discharge as a function of runoff depth is evaluated using equations for Model efficiency (ME) and Relative Root Mean Square Error (Van Rompaey et al., 2001):

$$ME = 1 - \frac{\sum_{i=1}^{N}(\mathrm{Qmi} - Qpi)2}{\sum_{i=1}^{N}(\mathrm{Qmi} - Qmean)2} \text{--} 1$$

Where, ME is Model Efficiency, N is number of observation, Q_{mi} is the observed value, Q_{mean} is the mean of observed value and Q_{pi} is the predicted value.

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{Qmi}+\mathrm{Qpi})}^{2}}{\frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}\mathrm{Qmi}} \text{--} 2$$

Where, RRMSE is Relative Root Mean Square Error, Q_{mi} is observed value, Q_{pi} is predicted value and N is number of observation.

The perfect model has a Model Efficiency = 1 and a Relative Root Mean Square Error = 0. A good model has a RRMSE close to zero and a ME close to 1. The Model efficiency is a criterion that determines the efficiency of the model in comparison with average values. If the Model Efficiency is lower than 0, it is better not to apply the model but just use average values (Asselman, 2000).

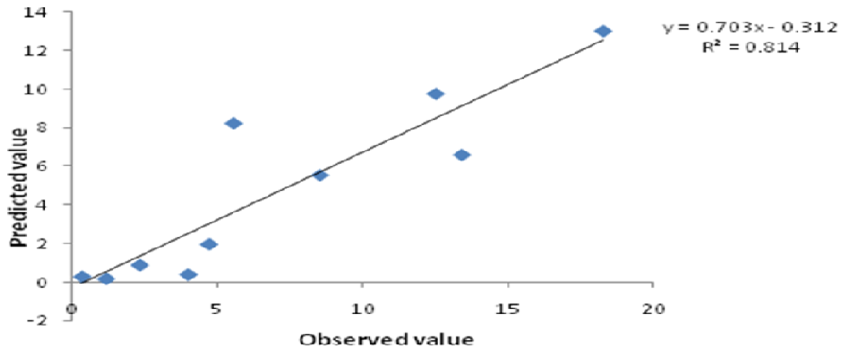


Figure 10. Relationship between predicted (SCS CN) and observed runoff depth value

According to the result (Table 11), the ME and RRMSE is found to be 0.62 and 0.32 with coefficient of determination (R^2= 0.81). Therefore, SCS curve number method can be applied to simulate runoff depth in the catchment.

Conclusion

The results of runoff hydrograph has shown that, runoff started to increase in the early of rainfall event until reaching its peak, then started again to fail down gradually to falling limb as a function of time.

In general there is surface runoff variation among the sub catchment. Results from Maykaebo, Mengediweste, Nustheyshintro and Abayshintro showed surface runoff variation. The major controlling factors for the variation in surface runoff are soil condition and infiltration capacity, area coverage and slope of the catchment, shape of the sub catchment and land management practice. The catchment is hydrologically connected and flow has produced discharge to each out let in response to rainfall event. Results from infiltration test have shown that there is infiltration rate variability among the sub catchments. Horton model has also performed well in predicting infiltration rate (R^2= 0.83-0.92) of the catchment. Accordingly, high infiltration rate is observed in Maykaebo sub catchment with low infiltration rate in Nushteyshintro and Abayshintro sub catchment. This has an implication on runoff producing potential and runoff discharge at the outlet of the gauging station.

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