Runoff estimation and the potential sites for water harvesting in central Butana rangeland, Sudan (2006 – 2007)

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ABSTRACT

Estimation of direct surface runoff in a watershed is necessary for planning, designing and environmental impact analysis of water resources management projects. The standard soil conservation service – curve number is a versatile and widely used procedure for runoff estimation. This model computes direct runoff through empirical equations that requires rainfall and a watershed coefficient data. The watershed coefficient, known as the runoff curve number (CN), represents the runoff potential of the land cover soil complex. Butana rangeland is located in eastern Sudan and considered as one of the best grazing areas in central Sudan. Due to rain variability and uneven distribution of rains, the area suffers from severe shortage of water which is reflected on the quantity and quality of biomass production and drinking water. The runoff potential of the central Butana rangeland was evaluated and assessed, during the rainy season of 2006 -2007, through curve number model for better management of this rangeland which faces severe water shortage problem during the dry season. This potential of runoff water can be harvested either in the soil profile to improve biomass production or can be stored in artificial ponds for supplementary irrigation and drinking water. Rainfall data, as input, was taken from six rain gauges installed in this area. Landform, drainage pattern, slope, vegetation and land use/land cover were precisely mapped by the mean of perpendicular vegetation vegetation index (PVI), calculated from Spotview satellite scene and field survey data, and digital elevation model data. Soil units were digitized and saved in GIS database and intersected with other watershed characteristics. The model was run and the result shows big variation of runoff depths, but the average potential runoff depth in the study area, which covers 3600 km^2, was found 52 mm yr^{-1}. Hence, the total runoff volume was estimated for the whole study area as 187.2 x 10^6 m^3 annually. The watershed delineation and drainage routes, derived from digital elevation data, show the appropriate sites to construct water harvesting structures.

INTRODUCTION

Butana area lies in the central clay plains of the Sudan. It is situated between the rivers of Rahad, Blue Nile, Nile and Atbara with approximate total area of 120 000 km^2. The area is located in the Sahel zone and determined by climatic and ecological transitions from the savannah in the south to the arid Sahara in the north (Akhtar, 1994). According to Adam (2008), the area is located in the arid zone and marked by annual rainfall from less than 50 mm in the north (Atbara) to 600 mm in the south (Gedarif) (Oliver, 1965). Generally, rainfall is characterized by very high variability, uneven distribution and long dry spells that affect crops and range vegetation at their critical growth and filling stages which leads immediately to a significant reduction in the total production and productivity of the area (Zengxin *et al*., 2011; Elfaig *et al*., 2013). There is a great potential of water harvesting as a methodology to overcome the problem of water shortage due to the long dry spells occurring from the high variability of rainfall in the arid regions of central Butana in Sudan.

Water harvesting is a technology based on the collection and concentration of surface runoff for cultivation before it reaches seasonal or perennial streams (Reij *et al.*, 1988). Surface runoff information is required for watershed management purpose. The *in situ* measurement of runoff is considered more accurate but cannot be operated anytime and anywhere as required. This conventional measurement is also expensive, time-consuming and difficult. Therefore, the accurate surface runoff modelling developed can serve this purpose with more convenient and less time consumption. A hydrological model is a mathematical simulation of the complex hydrological cycle (Athanassios *et al.*, 2006), and is a powerful technique in hydrological system investigation for both research hydrologists and practicing water resources engineers involved in the planning and development of integrated approaches for the management of water resources (Webler and Tuler, 1999).

Remote sensing is a major source of information required for the study of landscape, landuse and vegetation development (Kumar, 2001). The perpendicular vegetation index (PVI), proposed by Richardson and Wiegand (1977) is an efficient vegetation index for landuse discrimination in dry areas. Use of remote sensing (RS) and geographic information system (GIS) helps to spatially integrate all the parameters of the model (Gangodagamage and Agrarwal, 2001). Selection of a rainfall-runoff model is a compromise between model complexity and available input data. While more complex models should better represent the physical processes, the assumption that ththey lead to they lead to more reliable results has been questioned (Loague and Freeze, 1985 serve this purpose with more convenient and less time consumption. A hydrological model is a mathematical simulation of the complex hydrological cycle (Athanassios *et al*,2006) and is a powerful technique in hydrological system investigation for both research hydrologists and practicing water resources engineers involved in the planning and development of integrated approaches for the management of water resources (Webler and Tuler, 1999).

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The objective of this study was to simulate the surface runoff volume of central Butana watersheds using grid-based curve number (CN) method for better planning of water harvesting projects and to determine potential sites of water harvesting. In this method, watershed characteristics are considered to be spatial heterogeneous.

MATERIALS AND METHODS

Location

This study covers the central area of Butana in the Sudan, which administratively belongs to Gezira State and located between latitudes 14° 32` and 15° 17` N and longitudes 32° 21` and 34° 18` E with a total area of 3600 km^2 as shown in figure 1.

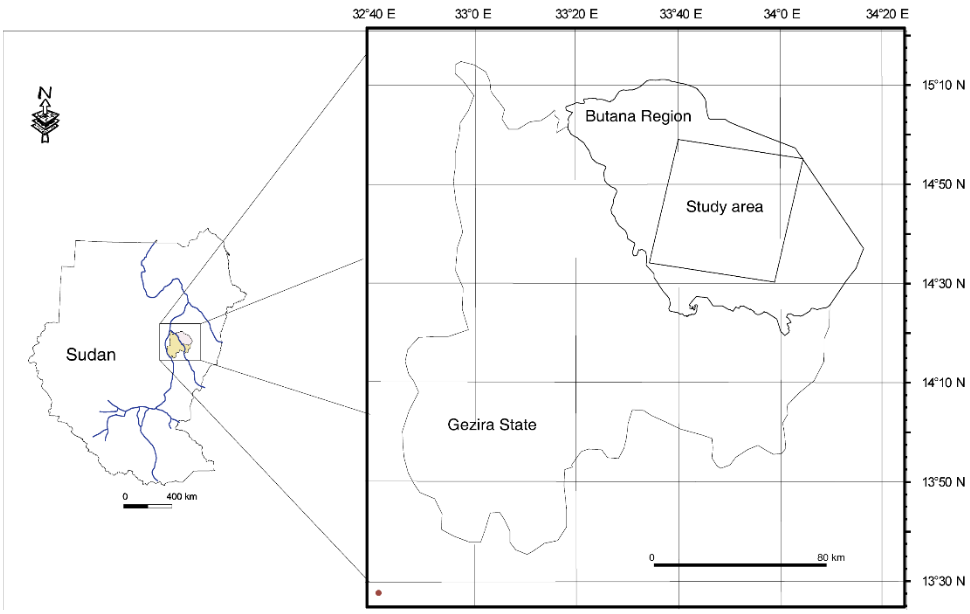

Figure 1. Location of Butana area

Soil map and hydrological soil group (HSG)

The soil map of central Butana rangeland was acquired from the Agricultural Research Corporation (ARC) of the Sudan, and digitized in GIS and the hydrological soil group (HSG) was determined according to soil characteristics. Soil conservation service has classified all soils into four hydrologic groups which have been given symbols of A, B, C and D (Dingman, 1994). The classification was based on the infiltration rate which was obtained for a bare soil after prolonged wetting. The characteristics of these four groups are summarized in Table 1.

Landuse and vegetation map

Remote sensing data (SpotView), dated 5/10/2006, coupled with ground vegetation survey was used to determine the different classes of land use and land cover in central Butana. Spectral reflectance of different landuse and vegetation cover in 18 field survey points, determined according to previous survey (Elfaki *et al*., 2010), covered by the satellite image was extracted from the image and used to classify vegetation units by means of PVI.

Runoff estimation

The standard soil conservation service - curve number model (SCS-CN) (USDA-SCS, 1972) based on the following relationship between rainfall depth, P, in mm, and runoff depth, Q, in mm as shown in equation (1), was used to determine runoff depths.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{........ (1)}$$

$$(Q = 0, IF, P \angle 0.2S)$$

The potential maximum retention, S, in mm, represents the upper limit of the amount of water that can be abstracted by the watershed through surface storage, infiltration, and other hydrologic abstractions. For convenience, S is expressed in terms of a curve number (CN) as shown in equation (2).

$$S = \frac{25400}{CN} - 254 \quad \text{........ (2)}$$

Curve number is a dimensionless watershed parameter ranging from 0 to 100 as shown in Table 2. A CN of 100 represents a limiting condition of a perfectly impermeable watershed with zero retention and thus all the rainfall becoming runoff; on the other hand CN of zero conceptually represents the other extreme, with the watershed abstracting all rainfall with no runoff regardless of the amount rainfall

Table 1: Hydrologic soil groups.

Soil Group	Characteristics
A	Low overland flow potential, High minimum infiltration capacity even when thoroughly wetted (> 0.76 cm/h), Deep, well to excessively drained sands and gravel.
B	Moderate minimum infiltration capacity when thoroughly wetted (0.13-0.76 cm/h), Moderately deep to deep, Moderately to well drained, Moderately fine to moderately coarse grained (e.g. sandy loam).
C	Low minimum infiltration capacity when thoroughly wetted (0.13-0.38 cm/h), Moderately fine to fine grained soils or soils with an impeding layer (fragipan).
D	High overland flow potential, Very low minimum infiltration capacity when thoroughly wetted (< 0.13cm/h), Clay soils with high swelling potential, Soils with permanent high water table, Soils with a clay layer near the surface, Shallow soils over impervious bedrock.

Source: Dingman, 1994.

Table 2: Runoff curve numbers.

Land use, crop, and management	Hydrologic Soil Group			
	A	B	C	D
Row crops, poor management	72	81	88	91
Row crops, conservation management	65	75	82	86
Small grains, poor management	65	76	84	88
Small grains	61	73	81	84
Meadow	55	69	78	83
Pasture, permanent, moderate grazing	39	61	74	80
Woods, permanent, mature, no grazing	25	55	70	77
Roads, hard surfaces and roof areas	74	84	90	92

Source: (USDA-SCS, 1972).

RESULTS AND DISCUSSION

Landuse and vegetation pattern

A visual interpretation of PVI map was done to differentiate between different landuse types and vegetation units. Different values and classes of PVI represent different land use patterns. The lowest value of PVI was found in water bodies (*haffirs*), which cover approximately 0.01% of the total area and determined precisely by checking all the pixels cover all around *haffirs*. The next class to water is bare soil around water points and in the high pressure grazing areas. The third class is rangeland vegetation from which the extreme low value of PVI represents the degraded and poor condition of rangeland around water points and most of the high land and the high value is for good condition rangeland in water courses and adjacent to rainfed agriculture sector. The last PVI class represents the rainfed agriculture and reserved forests.

The wide range of this class started from sparse sorghum fields to well mechanized and water managed fields. The reserved forest, which occupied the south western part of the study area, showed the same value of rainfed agriculture PVI and precise mapping of these forests was done by visual interpretation.

Figure 2 explains three main classes of land use in central Butana. Crop land, shown in green colour, comprises the large portion of the study area with the total area of 1695 km² (47.8%). The main crop grown in this area is sorghum, which constitutes the main source of food for all people living in Butana. Beside that, the crop residue is kept as fodder for animals in the summer season. The second landuse type is rangeland which covers approximately 44.7% of the total area with a surface area of 1583 km². The last landuse type is forest, shown in brown and located in the south western side of the study area and covers an area of 264 km² (7.5%). The forests are dominant on red sandy clay soil (goz) and the dominant trees are *Seyal* (*Acacia tortilis* L.), while sparse trees of *Kitir* (*Acacia mellifera* L.) are found on clay soils.

Hydrological soil group (HSG) and curve number (CN)

Hydrological soil groups (HSG) of central Butana were determined on the basis of information from the basic soil map of Butana. The soil map was digitized in GIS and HSG was determined according to soil characteristics and Table 1. Four groups of HSG are found in Butana area, namely, A, B, C and D (Ramakrishnan *et al.*, 2008).The results of HSG of the central Butana rangeland indicated that the HSG (C) occupied almost 60% of total area followed by HSG (D), which covers 30% and HSG (B) and HSG (A) are 9% and 1%, respectively. Information on land use and pattern of their spatial distribution is one of the criteria used for selecting a curve number (CN) (Ramakrishnan *et al.*, 2008). As the SCS-CN method is very sensitive to CN value, accurate determination of this parameter is very important (Ramakrishnan *et al.*, 2008). In each watershed, the combination or intersect between HSG and land use was assigned a special CN value, ranging from 0 to 100, extracted from Table 2. The maximum value of CN was found to be 88, while the minimum was 25 and the average value was 75. The result of the CN showed that 31.5 % of the CN values in the study area are found within the range of 80 to 88, 52.6% in the range of 70 to 76, and only 0.1% are between 60 to 69 and the rest of the area is less than 60. Forty percent of the area is dominated by CN value of 74, which represents in most cases the rangeland area around and in between the rainfed agriculture, while 22.4% of the area was covered by CN value 84, which represents the high potential runoff area used in rainfed agriculture. The rest values of CN are less contributing and they are less than 10% of all values.

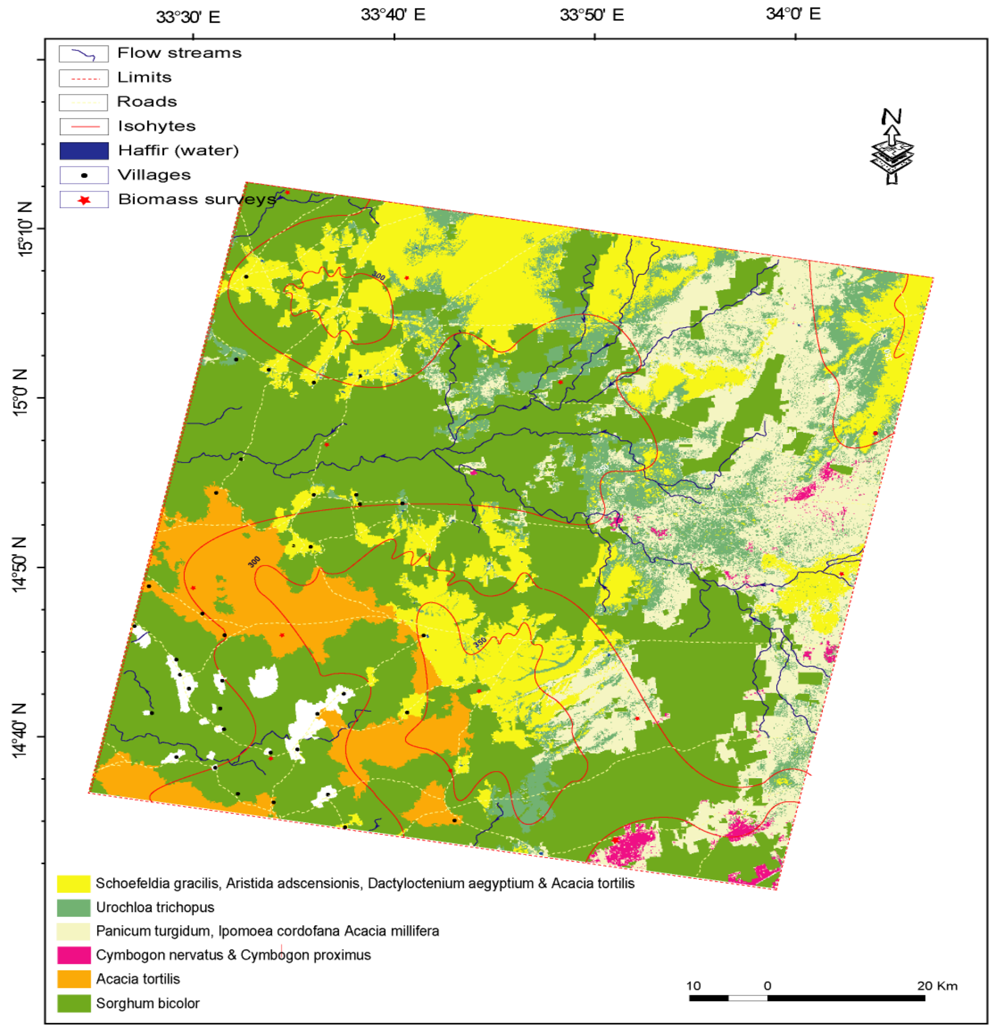

Figure 2. Land cover and landuse map of central Butana

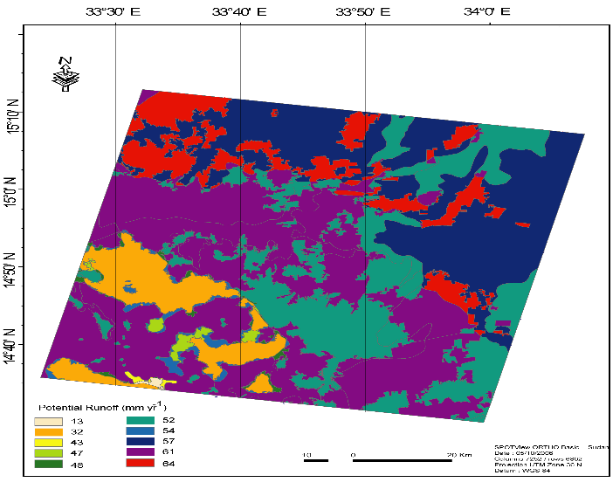

Figure 3. Hydrological oil group (HSG) of central Butana rangeland

Annual runoff potential

The spatial distribution of annual runoff depths was displayed in Figure 4 which showed a big variation from the minimum annual potential runoff of 13 mm/yr in the forest to the maximum amount of 64 mm/yr in some areas usually occupied by rainfed agricultural activities.

According to Blokhuis (1993), who noted that the reddish sandy clay soils (*goz*) showed an open growth of trees with much different types of Acacia species mainly *seyal (Acacia tortilis* L*)* and sparse shrubs and grass covered surface, the lowest annual runoff potential was observed in the forest area which dominates the reddish sandy clay soils and produced the minimum potential of runoff (13 to 32 mm/yr) as shown in Figure (4). This was due to the fact that the sandy soil shows high infiltration rate values and also the dense canopy of trees increases the interception and water losses through evaporation. The rainfed agriculture areas in the central part and the open rangeland in the centre, north and east, dominated by clay soils, produced high to moderate runoff potential (61 to 64 mm/yr).

On the basis of runoff coefficient, which is the ratio between the rainfall and runoff (Ramakrishnan et al., 2008), the results showed these runoff coefficient classes and grouped them into three broad classes such as high (>25%), moderate (20% to 25%) and low (<20%). It is evident from these figures that only 16% of the study area falls under the high runoff potential class. The moderate and low runoff coefficient classes occupy 57% and 27% of the total area, respectively.

The average potential runoff depth in the study area, which covers 3600 km^2, is 52 mm. Hence, the total runoff volume was estimated for the whole study area as 187.2 x 10^6 m^3 annually. This water is sufficient to support 10 million animals and humans for nine months at a consumption rate of 30 litres per individual per day and a loss of half the quantity by evaporation and deep percolation. If this water is captured, it is sufficient to cause dramatic improvements in the livelihood of Butana people and the herder community.

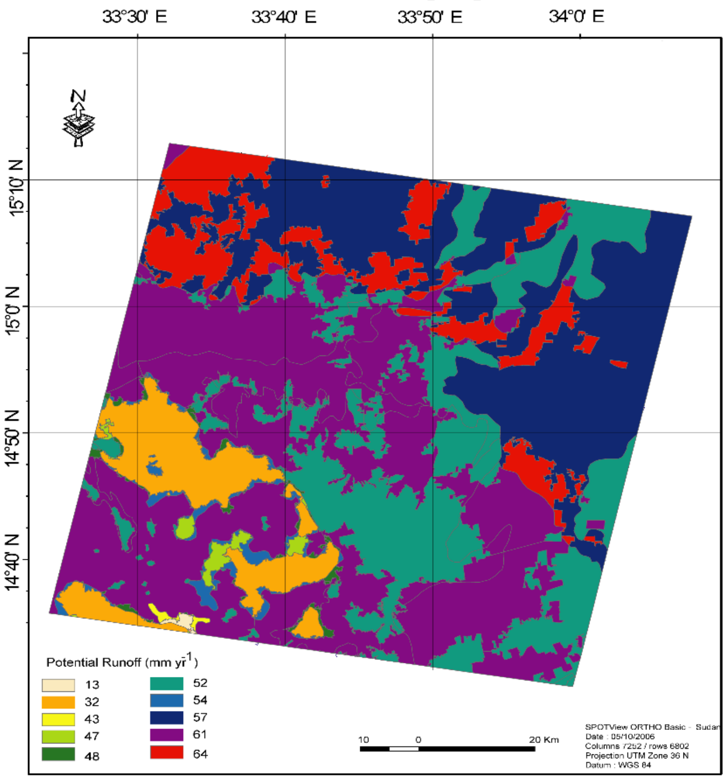

Figure 4: Runoff potential of central Butana rangeland

CONCLUSIONS

These results give positive indications to perfect and beneficial application of water harvesting techniques to maximize the use of scarce water resources. The high and moderate runoff coefficient areas were almost 73% of the total area and water harvesting application in these areas can produce appreciable amounts of stored water that can be used in either short term measures of drought mitigation for drinking water or improving pasture productivity or in long term measures in planning and constructing small dams and reservoirs for supplementary irrigation.

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تقدير الجريان السطحي لحصاد المياه في مراعي وسط البطانة، السودان

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الخلاصة

يعتبر نقص المياه من أكبر المهددات لنظم الحياة في المناطق الجافة وشبه الجافة من العالم والتي تعتمد علي الامطار كمورد للمياه ولذلك فإن تقدير الجريان السطحي في مناطق سهول الأمطار ذو أهمية قصوي من أجل تخطيط وتصميم ودراسة الأثر البيئي لمشاريع إدارة المياه. صممت الشعبة الأمريكية للمحافظة علي التربه نموذجاً رياضياً ،يعد الأسهل والأوسع إنتشاراً ، لتقدير الجريان السطحي. هذا النموذج يعمل علي حساب وتقدير عمق الجريان السطحي من خلال معادلات تجريبيه تتطلب فقط معلومات عن الأمطار وخصائص سهول الأمطار والتي تشمل نوعية التربة والغطاء النباتي ويتم التعبير عن هذه الخصائص بما يعرف برقم المنحني (curve number) والذي يمثل مقدرة السهل المطري علي إنتاج جريان سطحي. مراعي البطانة تقع في شرق السودان وتعتبر واحدة من المراعي المهمة في السودان ولكن نسبة لتباين الامطار والتوزيع المكاني غير المتكافئ فإن المنطقة تتعرض لنقص كبير في المياه ينعكس مباشرة علي نوعية وكمية الكتلة الحية التي تنتجها تلك المراعي وكذلك علي مياه الشرب. تم تقييم الجريان السطحي لمراعي منطقة وسط البطانة بإستخدام هذا النموذج من أجل الإدارة المثلي والتغلب علي نقص المياه في فترات الجفاف. كمية المياه الناتجه من الجريان السطحي يمكن حصادها وتخزينها في قطاع التربة من أجل زيادة إنتاج الكتلة الحية أو يمكن تخزينها في حفائر او سدود والإستفاده منها في الري التكميلي أو الشرب. تم أخذ معلومات الأمطار من ست محطات إرصاد حول المنطقة كما تم تخريط منحنيات الصرف وميولها والغطاء النباتي باستخدام صور الأقمار الصناعية spotview وذلك بواسطة معامل الغطاء النباتي العمودي perpendicular vegetation index (PVI) . خريطة التربة تم مسحها وحفظها كبيانات في برنامج GIS . بعد توفر كل المطلوبات تم تفعيل النموذج وأظهرت النتائج تباين كبير في أعماق الجريان السطحي ووجد أن متوسط عمق الجريان في كل منطقة الدراسة والتي تبلغ مساحتها 3600 كلم ^{2} حوالي 52 ملم / عام ومنها تم تقدير حجم الجريان السطحي 10^6* 187.2 متر ^{3} سنويا كما أظهرت خرط الصرف السطحي المناطق المناسبة لحصاد هذه المياه.