American Journal of Water Science and Engineering
2023; 9(3): 77-85
http://www.sciencepublishinggroup.com/j/ajwse
doi: 10.11648/j.ajwse.20230903.14
ISSN: 2575-1867 (Print); ISSN: 2575-1875 (Online)

Validation of Ex-Situ Runoff Harvesting in Semi-Arid Areas Using Grid-Based NRCS – CN

Kennedy Ochieng Okuku*, Japheth Ogalo Onyando, Nancy Waithira Matheri, Samuel Muhoro Kinyanjui

Faculty of Engineering and Technology, Egerton University, Nakuru, Kenya

Email address:

okukukennedy@gmail.com (Kennedy Ochieng Okuku), jonyando@gmail.com (Japheth Ogalo Onyando), nancy.matheri@egerton.ac.ke (Nancy Waithira Matheri), samuelmuhoro78@gmail.com (Samuel Muhoro Kinyanjui)

*Corresponding author

To cite this article:

Kennedy Ochieng Okuku, Japheth Ogalo Onyando, Nancy Waithira Matheri, Samuel Muhoro Kinyanjui. Validation of Ex-Situ Runoff Harvesting in Semi-Arid Areas Using Grid-Based NRCS - CN. *American Journal of Water Science and Engineering*. Vol. 9, No. 3, 2023, pp. 77-85. doi: 10.11648/j.ajwse.20230903.14

Received: August 7, 2023; **Accepted**: August 22, 2023; **Published**: August 31, 2023

Abstract: Arid and Semi-Arid agroclimatic zone covers about 80% of Kenya's land mass and supports more than 50% of the livestock and 35% of human population. Subsistence rainfed farming is key in these areas as a source of livelihood and for food security. Cases of crop failure, under rain-fed systems, due to extra and intra season drought are rampant and currently amplified by climate change. This calls for adaptive management, water smart agricultural utilization systems, in-situ and ex situ runoff harvesting for crop production. This study aimed at validating ex-situ runoff harvesting, and the use of grid based NRCS-CN integrated with GIS tools in siting water harvesting structures and quantifying the runoff in a semi-arid zone. A multi-criteria analyses was applied to the study catchment by overlaying slope, proximity to irrigable land, soil characteristics, land use and drainage pattern. A grid-based NRCS-CN model was used to evaluate the spatial distribution of event-based rainfall excess and expected runoff volume at the selected site. The estimated volume was compared to the recorded storage volume at a water pan that was installed at selected site. Based on the multi-criteria analyses a suitable site was selected and a water pan installed with a collection ditch to direct flow to the pan. The estimated spatial rainfall excess varied between 2 mm and 7 mm for a 19.6 mm event. These reflects the potential of runoff harvesting in the area. The site selection was ground validated as runoff followed the expected pattern through the collection ditch into the water pan. The estimated event-based runoff using CN method was representative as these was reflected in recorded volume of run off harvested by the water pan. The grid based NRCS-CN integrated GIS model is proved as an effective tool for siting runoff harvesting structures and estimating the expected runoff volume.

Keywords: Subsistence Rainfed Farming, Adaptive Management, Ex Situ Runoff Harvesting, Grid-Based NRCS-CN Model

1. Introduction

In East Africa, agriculture is a key economic activity supporting over 67% of the population [4]. In Kenya, the sector contributes about 24 % of 101 billion USD gross domestic production (GDP) [10]. However, about 80% of Kenya's land mass falls under the Arid and Semi-Arid (ASAL) agroclimatic zone, supporting more than 50% of the livestock and 35% of human population [14]. Subsistence rainfed agriculture is common in these areas, thus, cases of crop failure due to drought are rampant. Climate change has amplified the challenge of food security in these areas where agricultural production has remained rain-fed. Currently, adaptive management of agricultural system in ASALs has become a key issue under climate change [15]. Surface runoff must be accurately estimated in order to plan irrigation systems, ground water development strategies, soil erosion control structures, waterways, water harvesting structures, and water storage structures [2].

Most semi-arid zones in Kenya receive erratic rainfall with seasonal totals of up to 700 mm. This amount would ordinarily be enough to sustain short season crop production, however, poor distribution, high evaporation rates and occurrence of intra-season and off-season dry spells leads to crop failure. This project accesses the potential of successful farming through a combination of runoff harvesting, runoff storage, irrigation and soil moisture conservation techniques in Baringo. Baringo county is among the semi-arid regions of Kenya with fertile soils, but crop production is mainly limited by poor rainfall distribution as up to 50% of rainfall received may be lost through runoff and evaporation.

In such areas where crop failure is caused by poor rainfall distribution rather than lack of rain itself, climate and water smart agriculture techniques can improve production. Thus, increasing water conservation and harvesting techniques are critical to ensure high agricultural water productivity in semi-arid zones and thus countrywide. Runoff water harvesting is the capturing and storing seasonal rainfall excess and directing it to agricultural uses or domestic purposes. For agriculture uses, rainfall excess can be captured and stored within the crop field around the root zone, this is termed as in-situ water harvesting. Alternative runoff can be captured and stored out of the crop field, termed as ex-situ water harvesting. The main method of ex-situ water harvesting is by use of water pans/ ponds. A proper siting and design of a water pan system for semi-arid areas is key to provide enough water for supplemental irrigation.

Conventional geographical surveys employed to site water pans for harvesting rainfall excess are bulky, tedious and costly. A combination of geographic information system, field survey and remote sensing technique gives large coverage in less time and cost. In semi-arid areas, run off is the critical parameter to predict potential sites for harvesting the rainfall excess. The runoff parameter of the catchment has been studied widely [2, 13]. The properties of soil, land-use-land-cover and antecedent moisture of the area are the main factors that determines the amount of rainfall excess for a given event. The rainfall excess flows to the pourpoint as influence by the geomorphologic characteristics of the catchment. To study and estimate rainfall excess several rainfall-runoff models have been used; Rational formula, Cypress-Creek Formula, and Soil Natural Resources Conservation Service Curve Number (NRCS-CN) [12], among others.

The USDA-Soil Conservation Service (SCS, 1972) developed NRCS-CN method formerly known as Soil Conservation Service Curve Number (SCS-CN). NRCS-CN method is widely used to estimate runoff as it considers antecedent soil moisture condition and combine all factors into one variable, Curve Number (CN) [5, 12]. Its simplicity and high accuracy have seen it largely integrated within advance tools and models.

A grid based NRCS-CN can be simulated on GIS interface as thematic maps corresponding to input parameters can be generated. Field and remote sensing data comes in handy in generating these thematic maps namely; rainfall event map, soil map, land use/cover map and elevation map. Therefore, this offers a viable method of siting water harvesting structures and estimating the expected runoff. The effectiveness of the runoff harvesting systems including diversion and collection ditches and structures depends on accurate identification of suitable sites and structure technical design [1, 3]. This study uses grid based NRCS-CN on GIS interface to site ex situ runoff harvesting pans and quantify the runoff collected and stored in a semi-arid climate.

In hydrology, water balance is a model representing a water flow system showing the relationship between inflows and outflows. In general water balance model can be simplified as (Equation 1);

$$P = R + E + \Delta S \quad (1)$$

Where; P = precipitation
E = evaporation
R = stream flow
Δs= change in storage

The model applies the principle of conservation of mass in a closed system, that is, water enters the system as precipitation, is stored within the system or released through evaporation and runoff. Water balance model allows for evaluation of efficiency of water harvesting structures such as water pans. water storage design aims at storing the maximum available runoff at lowest cost with minimal losses.

2. Materials and Methods

2.1. Study Area

The study was carried out as part of a series of research under “Validating Climate Smart Water Harvesting Technologies to Increase Food and Nutrition Security in Semi-Arid Kenya- Baringo County” project. The project had sites within Baringo county in Kenya as shown in Figure 1. However, for this study all of catchment modelling and runoff estimation were done at site 2 located at 00^0 26.911’ N, 35^0 56.207’ E and at 1162 m above mean sea level (a.m.s.l.). At site 2, a pyramid frustrum shaped lined water pan has been installed with a collection ditch. The collection ditch directs the water from a natural drainage network to the pan. the identification of suitable water pan site, estimation runoff and design of the water pan plus the collection ditch were informed by the prior research presented in this paper. Catchment area draining into the water pan serves as the study catchment in this present work.

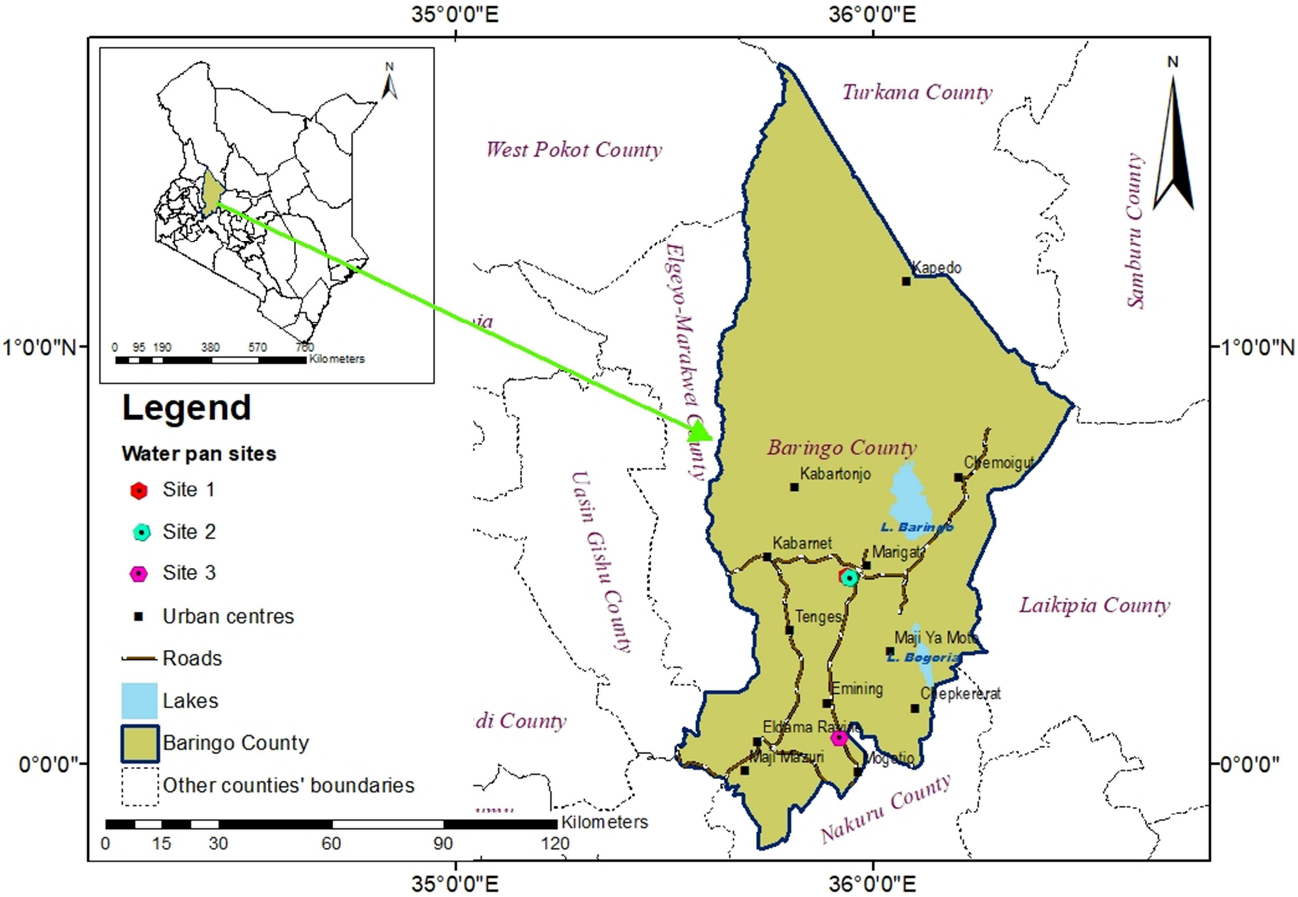


Figure 1. *A map showing the location of study sites within Baringo County.*

2.2. Data Acquisition

The data required for the runoff estimation and siting of water pan are; Remote Sensing data (Digital Elevation Model, Sentinel Imagery and Soil map) and in situ rainfall depths. Additional data required to evaluate performance of the pans were evaporation depth and water level changes in the pans. The DEM and sentinel 2 imagery for the study are were downloaded from USGS, Earth explorer website. Rain gauges and water level gauge were installed at all the three sites and data recorded daily over a period of three months (May – July, 2022).

2.3. Rainfall Excess Evaluation

On ArcMap environment, DEM was pre-processed to fill in the sinks and a drainage network of the study are was derived using the spatial analyst functionality. A slope map was then derived from the DEM as a reflection of the topography of the study area. The sentinel 2 image for 15th June 2022 was downloaded and classified into land use land cover map supervised using ground data. A soil map for the study area was made by editing downloaded KENSOTER dataset using ground truthing data (infiltration, soil colour and textural classification). Based on the slope, drainage pattern, soil properties and proximity to irrigable area the potential water pan site was picked [9]. The selected site was off the drainage route; thus, an artificial diversion ditch was required to direct flow to the site. The modification was made on the DEM to reflect the new drainage pattern. Using the modified drainage network and DEM, and selected site a catchment was delineated and size computed.

Curve number was computed for AMC-II by combining the soil characteristics (soil map) and the land use/cover characteristics using the map algebra functionality of the GIS environment. The NRCS-CN is founded on the continuity principle and a hypothesis [6] as follows (Equation 2 – 6);

$$P = Ia + F + Pe \quad (2)$$

Where;
P= depth of precipitation (mm)
Ia = initial abstraction depth (mm)
F = cumulative retention depth (mm) excluding Ia
Pe = rainfall excess (direct runoff) (mm).

The hypothesis of the method is that the ratios of rainfall excess (Pe) to maximum potential direct runoff (P-Ia) and cumulative retention depth (F) to maximum possible retention (S) are equal.

$$\frac{Pe}{P-Ia} = \frac{F}{S} \quad (3)$$

Maximum retention, S is a fraction of the initial abstraction, Ia (ƛ = 0.2 in most application).

$$Ia = \lambda S \quad (4)$$

Combining equation 1, 2 and 3 above, rainfall excess is given as;

$$Pe = \frac{(P-I_a)^2}{P+S-I_a} \quad (5)$$

The maximum retention S (in mm) is a factor of the catchment characteristics and its computed as follows;

$$S = \left(\frac{25400}{CN}\right) - 254 \quad (6)$$

Where; CN = curve number, which is a function of soil type, land cover and varies with antecedent soil moisture conditions (AMC) and its values range from 0 to 100.

A grid-based CN-II map was created by crossing hydrological soil group map and LULC map. The CN value assigned to various combination of soil hydrological group and LULC for AMC-II were as provided in literature [6]. The CN-II was then adjusted for slope [8] using the following Equation 7;

$$CN_{2\varphi} = CN_2 \frac{322.79+15.63(\varphi)}{\varphi+323.52} \quad (7)$$

Where; $CN_{2\varphi}$= Curve number for AMC-II adjusted for slope.

φ = slope in m/m.

To make adjustment for AMC-I or AMC-III given the five-day antecedent rainfall depth the following Equations 8 and 9 [6] were used;

$$CN_1 = \frac{4.2\, CN_{2\varphi}}{10-0.058\, CN_{2\varphi}} \quad (8)$$

$$CN_3 = \frac{23\, CN_{2\varphi}}{10-0.0013\, CN_{2\varphi}} \quad (9)$$

Where; CN_1 = curve number for AMC-I

CN_3 = curve number for AMC-III

The selected rainfall events were evaluated for AMC condition by adding the depth of rainfall for five preceding days and condition assigned according to Chow, V. T. et al. the events were then rasterized and resampled to equal resolution as the CN maps [6].

A grid-based GIS CN rainfall excess assessment tool for the water pan's catchment was developed, which computed the rainfall excess at pixel level and sum for the entire catchment as indicated below (Equation 10 & 11).

$$Pe = A_i \times \sum_{i=1}^{n} Pe_i \quad (10)$$

$$Pe_i = \begin{cases} \frac{(P_i-0.2\, S_i)^2}{P_i+0.8\, S_i}; if\ P_i > 0.2\, S_i \\ , \\ 0; if\ P_i \leq 0.2\, S_i \end{cases} \quad (11)$$

and,

$$S_i = \left(\frac{25400}{CN_i}\right) - 254 \quad (12)$$

Where; A_i = pixel spatial resolution

i = pixel index

n= total number of pixels

The change in volume of water harvested was compared with runoff volume of water expected to have been received at the site based on CN estimation for each rainfall event.

2.4. Comparison of Estimated Runoff Values to Recorded Storage

A lined water pan was installed at the selected suitable site and its water level changes monitored before and after a rainfall event. The dimensions were measured in the field after installation and the storage capacities and open surface areas computed. The changes in storage volume were monitored daily by recording water level daily. The rises in water level were attributed to inflows; runoff from an event and direct rainfall on the open surface, and drops attributed to outflows; seepage and evaporation. Water levels and rain gauge amounts were monitored daily and results used for comparison with the design values as estimated by NRCS-CN.

In the analyses water levels were converted in to storage volume and open surface area, based on depth–volume and depth–surface area geometric relationships. The open surface area directly affects the evaporation, while seepage varies with changes on wetted area and it is heavily determined by soil porosity and textural class. No computed seepage losses were considered on the assumption that they were equal to zero as the pan was lined.

3. Results and Discussion

The study area was characterized with three notable land use land cover classes namely; Dense shrubs, bare rock surface with sparse shrubs and agricultural use (mainly grassland for pasture). Rocky surface is the dominant land cover taking about 56.08 % of the total catchment area, 38. 8 was covered by light pasture grassland with small plots under cultivation, and 4.4 % was under relatively dense shrubs mainly the Prosopis *Juliflora*.

The geomorphology was characterized with a rocky heavy clay soil, flat plains (slope > 3 %) at the foot of steep slopy hill (5 < slope = 24 %) and well-defined natural drainage channels. The soil classifications across the spatial scale are represented in Figure 3 below. A potential water harvesting site was identified using a multi-criteria decision considering the proximity to farmable land, soil characteristics, ease of construction, drainage network, slope suitability and expected runoff (Figure 3). The grassland cover overlaid with deep clay soil which was considered easy to construct the water pan. In addition, the grassland cover overlaid with a relative flat slope (> 3%) and thus considered as suitable for farming with harvested water. A flat topography and stable soil were also considered in picking the site. The identified site was off the natural drainage network and thus expected minimal runoff. However, by including a collection/ diversion ditch the catchment area was increased with a corresponding increase in the amount of expected runoff. The inclusion of a diversion ditch of approximate average depth of 0.6 m and total length 165 m increased the catchment area from 0.012 km^2 to 0.911 km^2. GIS tool and remote sensing proved to be very useful in making and visualizing such a design and siting the water pan. Kadam, A. K. et al. used GIS with secondary data in identifying suitable rainwater harvesting sites in remote areas and it proved to an effective especially where data is limited [9]. Shown in Figure 3 is the drainage network modified to direct all runoff to the selected site. A study water pan and collection ditch were constructed at the identified site on the field. The site selection was validated as runoff flow pattern followed the expected pattern and the collection ditch diverted the flow successfully to the water pan.

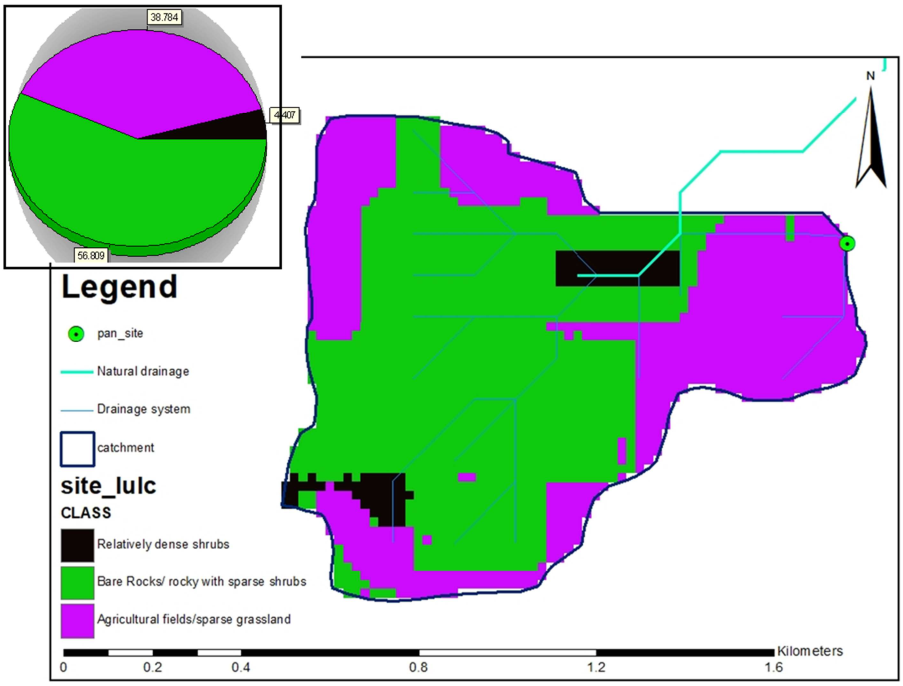


Figure 2. *A supervised classification map of land use land cover.*

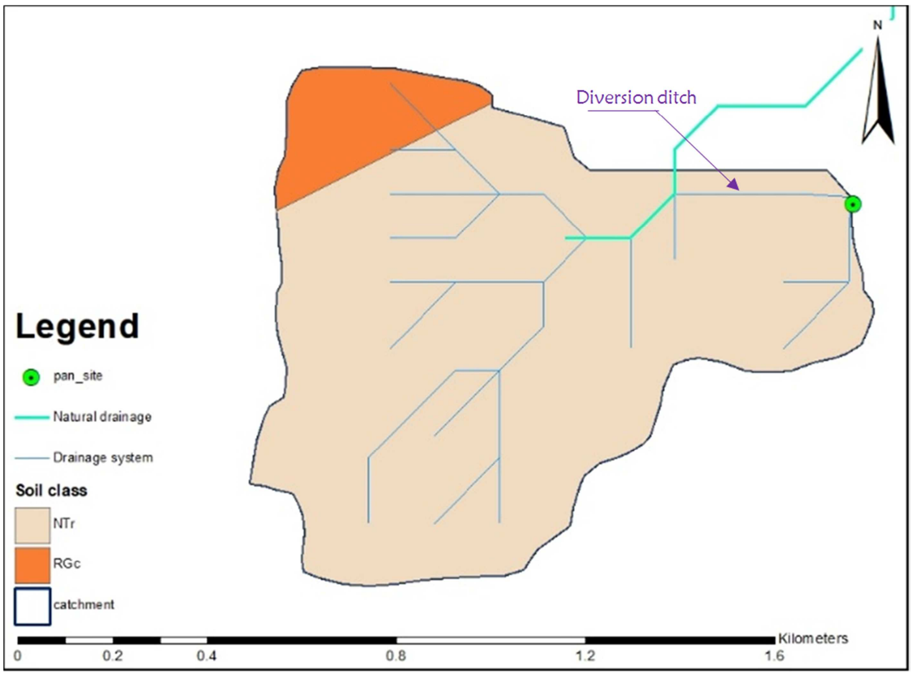


Figure 3. *A soil map of the study catchment showing natural drainage and modified drainage network directing flow into the selected site.*

Crossing soil characteristics (soil hydrologic group) map and land use land cover map, a grid-based CN- II map was created for the study catchment. Slope in the study catchment had high variations between 0 % and 24 %, and given that it is a key factor affecting runoff and is not considered in the original CN, a correction factor was applied [8]. The slope-adjusted CN-II for the catchment varied between 69 (on dense shrubs, steep slope and soil hydrological group C) and

93 (on rocky surface with very sparse shrubs and steep slopes) (Figure 4). The curve number map was considered to reflect high rainfall excess potential as compared to infiltration given the general high values CN-II. The CN-II map was further adjusted for antecedent soil moisture conditions, that CN-I and CN-III (Figure 5).

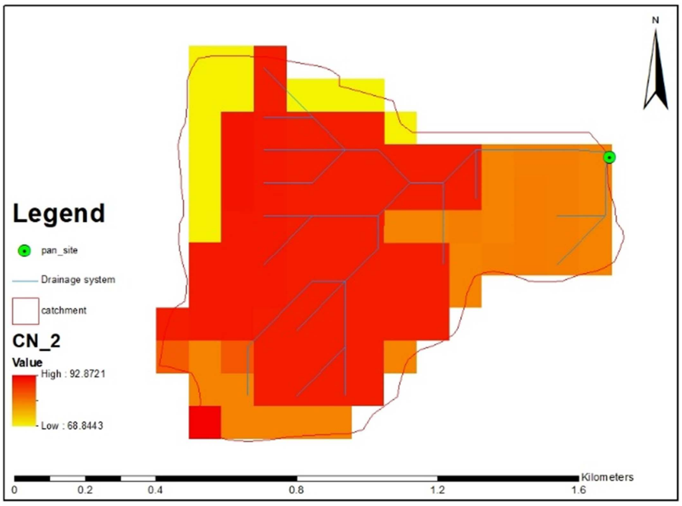


Figure 4. *A grid-based map of slope adjusted Curve Number, CN-II.*

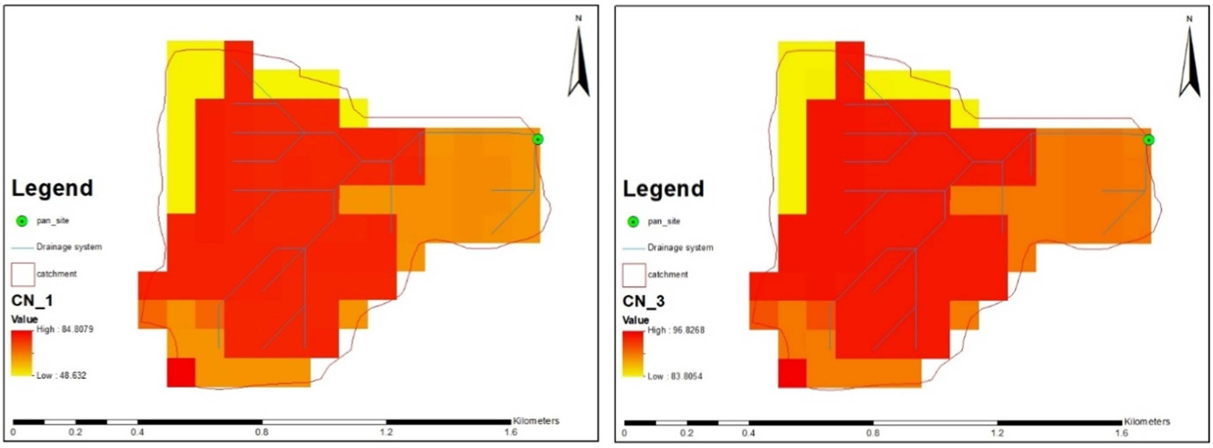


Figure 5. *Grid maps for adjusted curve number for antecedent soil moisture condition CN-I and CN-II.*

A time period when rainfall events equal or exceeds 0.5 ET_0 it is termed as onset of rainfall [7]. During the study period, May-July of 2022, approximately 13 rainfall events were captured by the installed rain gauge (Figure 6). The event varied from light rainfall (< 2 mm) to heavy storm of up to 19. 6 mm marking the onset of long rains in the study catchment. The catchment experiences a relatively high daily reference evapotranspiration ranging between 3.3 mm and 6.0 mm (Figure 6).

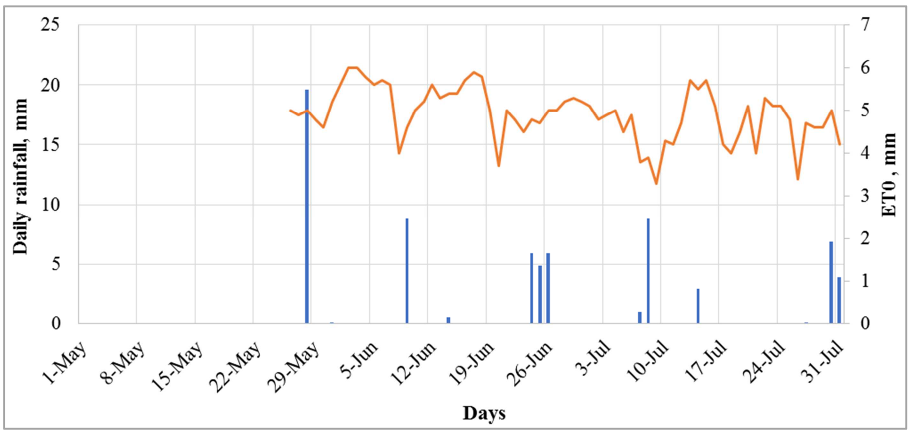


Figure 6. *A graph showing rainfall events depth and pattern, and the ET_o for the study period.*

CN simulation was done on selected six events; 28th May, 9th June, 24th June, 25th June, 7th July and 30th July with rainfall depth (mm) of 19.9, 8.8, 5.9, 4.9, 1.0 and 6.9, respectively. Taking account of the antecedent soil moisture condition for each event, CN-I was applicable to all the events. It was observed for semi-arid condition CN-I is mainly applicable as compared to CN-II and CN-III as all preceding 5-day cumulative depth didn't exceed the threshold of 12.5 mm. Figure 7 illustrates a matrix of maps showing the outcomes of the spatial allocation of event-based rainfall excess depth in millimetres. Table 1 shows detailed information on the potential of the study catchment to yield direct runoff after a rainfall event. A rainfall event of 19.9 mm will result to a potential rainfall excess of 2.941 mm per unit area, this translates into 2679.715 m^3 of expected direct runoff from the study catchment. It was further noted a rainfall event of less than 5 mm resulted to no significant direct runoff. By plotting a Curve Number plot of rainfall excess against rainfall depth for the study catchment, interpolating can be done for design of storage pan. For instance, the study catchment (~0.911 km^2) will take one rainfall event of 14 mm to generate a mean of 1.2 mm rainfall excess which results to slightly above 1000 m^3 direct runoff at the site (Figure 8). This reflects the potential of runoff harvesting in most Kenya's semi-arid, in this case Marigat area in Baringo county. Harvested runoff can be used for both supplemental irrigation and domestic uses [11].

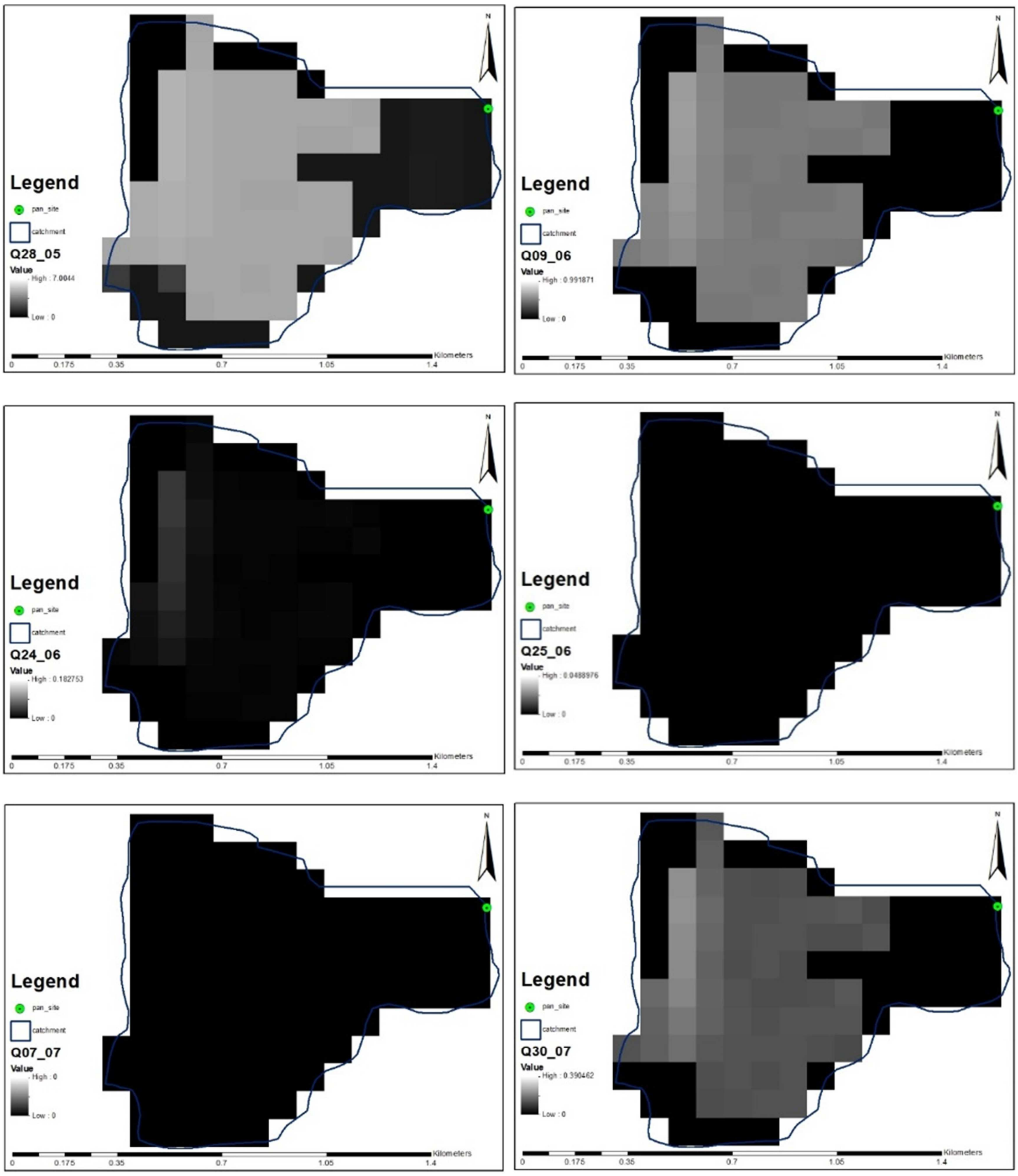


Figure 7*. A matrix of maps of spatial distribution of event-based rainfall excess.*

Table 1. Event based potential direct runoff computed for Marigat area in Baringo county for the period May-July 2022.

Rainfall event (Year 2022)	Depth, mm	Average rainfall excess per pixel, mm	Total rainfall excess, m^3
28th May	19.6	2.941	2679.715
9th June	8.8	0.194	177.196
24th June	5.9	0.003	2.817
25th June	4.9	0.001	0.419
7th July	1.0	0.000	0.000
30th July	6.9	0.033	30.001

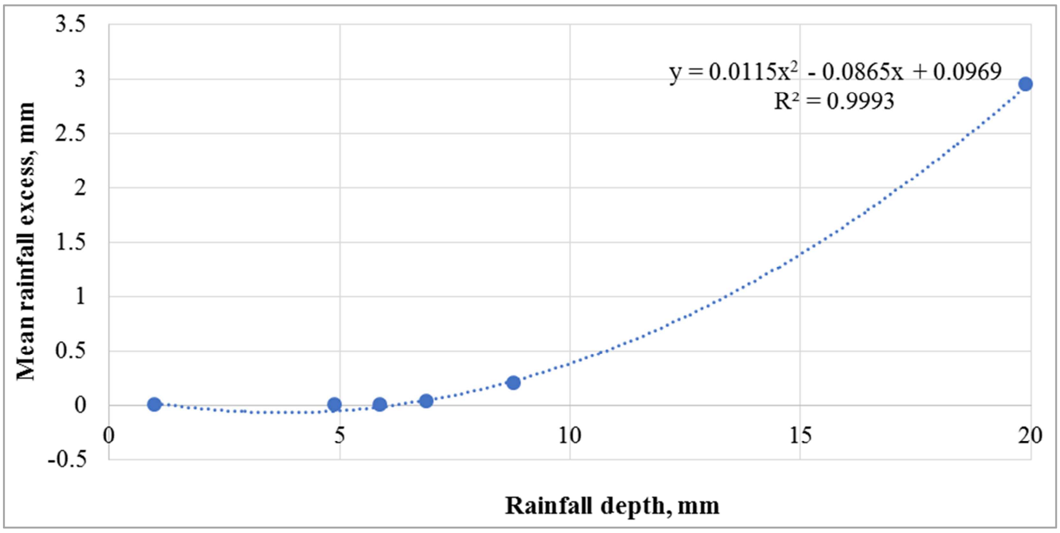


Figure 8. A Curve Number plot for the study catchment.

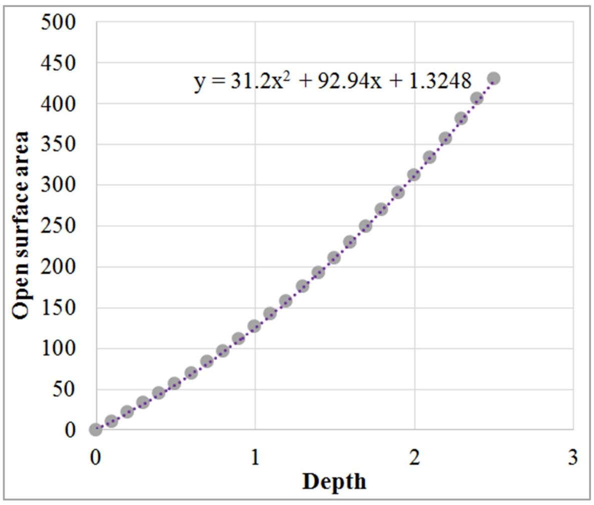
A lined storage pan with a pyramid frustum shape was installed at the site to collect the runoff. The depth-volume, and depth- open surface area relationships of the pan are given by the quadratic Equations 13 and 14, respectively (Figure 9).

$$y = 31.2x^2 + 92.94x + 1.3248 \quad (13)$$

$$y = 5.76x^2 + 48x + 100 \quad (14)$$

The pan water level changes were monitored after a rainfall events and compared with the expected runoff from the CN method. For all the monitored storms/events only two instances out of the 13 events had measurable response in water pan levels. where the magnitude of change was not measurable (< 10 mm) in field they were recorded as zero change. The two events that recorded a positive change are;

1) On 28th May, 2022 (19.6 mm rain) where the water pan level changed from zero (empty) to an overflow (>2.5m) and thus runoff volume could not be estimated.
2) On 9th June, 2022 (8.8 mm) the water level in the pan changed from 1.37 m to 2.18 m corresponding to 192.3 m^3 to 356.6 m^3 storage volume. Therefore, a change in volume of 164.3 m^3 was recorded within 24 hr after the event.



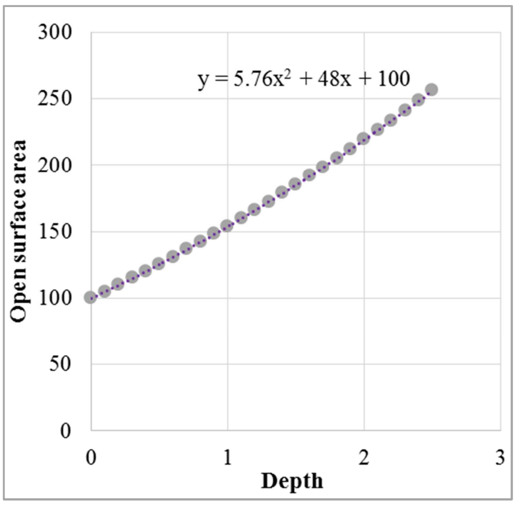


Figure 9. The Depth-Volume and Depth-Open surface area relationship of the water pan.

The field observations on runoff at the site agrees with the estimated volume from the CN. From the CN method for 19.6 mm depth of rainfall a volume runoff of 2679.7 m^3 was expected which is way greater than the total storage capacity of the install water pan (~ 430 m^3). This is reflected on the field by the overflow of the water pan after the event. For 8.8 mm event the CN method estimated runoff at 177.2 m^3 and the computed value from field measurement was 164.3 m^3. That gave a difference of 12.9 m^3, which this study attributes to seepage losses at the unlined silt trap at the inlet of the pan, the detention storage of the silt trap and losses due to evaporation. All listed suspected losses were not quantified in the scope of these paper.

4. Conclusion

The GIS integrated grid based NRCS-CN model is explored as a suitable method for siting direct runoff harvesting structures and estimating the expected runoff volume. Tool is proved effective in terms of accuracy, cost and time. Furthermore, with plenty of remote sensing data available and accessible online grid-based CN method can be used in areas with limited recorded data such as most semi-arid areas of Kenya. In most areas of Baringo county where soils are predominantly clayey and bare rocks, the rainfall excess goes as high as 36% of the total rainfall depth. For instance, a 19.6 mm rainfall event resulted 0.5 – 7.0 mm of rainfall excess on a spatial scale. Given such high intensity rainfall events and with moderate to high rainfall event depth, the region has a high potential of runoff harvesting. This will go a long way in addressing the issue of drought and crop failure due to poor distribution of rainfall in the region. Harvested water can be used for supplemental irrigation and in conjunction with other water smart techniques to address the issues of food security. The use of GIS and remote sensing on such models such as the NRCS-CN can aid in effective planning, siting and design of water pans and diversion ditches from small scale to large spatial scale.

Acknowledgements

The authors are acknowledging the Centre for Integrated Water and Basin Management (CIWAB, Egerton University) for the support extended to completion of this work under the Kenya Climate and Water Smart Agriculture Project (KCSAP). This work is part of research under “Validating Climate Smart Water Harvesting Technologies to Increase Food and Nutrition Security in Semi-Arid Kenya- Baringo County” project.

References

[1] Al-Adamat, R., AlAyyash, S., Al-Amoush, H., Al-Meshan, O., Rawajfih, Z., Shdeifat, A., & Al-Farajat, M. (2012). The combination of indigenous knowledge and geo-informatics for water harvesting siting in the Jordanian Badia.

[2] Al-Ghobari, H., Dewidar, A., & Alataway, A. (2020). Estimation of surface water runoff for a semi-arid area using RS and GIS-based SCS-CN method. Water, 12 (7), 1924.

[3] Ammar, A., Riksen, M., Ouessar, M., & Ritsema, C. (2016). Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: A review. International Soil and Water Conservation Research, 4 (2), 108-120.

[4] Binyam, A. Y., & Desale, K. A. (2015). Rainwater harvesting: An option for dry land agriculture in arid and semi-arid Ethiopia. International Journal of Water Resources and Environmental Engineering, 7 (2), 17-28.

[5] Bo, X. I. A. O., Qing-Hai, W. A. N. G., Jun, F. A. N., Feng-Peng, H. A. N., & Quan-Hou, D. A. I. (2011). Application of the SCS-CN model to runoff estimation in a small watershed with high spatial heterogeneity. Pedosphere, 21 (6), 738-749.

[6] Chow, V. T., Maidment, D. R. and Mays, L. W. (1988). Applied hydrology. McGraw-Hill, Inc. New York, USA.

[7] Dastane, N. G. (1978). Effective rainfall in irrigated agriculture. Bulletins FAO d'Irrigation et de Drainage (FAO)-Estudios FAO. Riego y Avenamiento (FAO).

[8] Huang, M., Gallichand, J., Wang, Z., & Goulet, M. (2006). A modification to the Soil Conservation Service curve number method for steep slopes in the Loess Plateau of China. Hydrological Processes: An International Journal, 20 (3), 579-589.

[9] Kadam, A. K., Kale, S. S., Pande, N. N., Pawar, N. J., & Sankhua, R. N. (2012). Identifying potential rainwater harvesting sites of a semi-arid, basaltic region of Western India, using SCS-CN method. Water resources management, 26 (9), 2537-2554.

[10] Kenya Institute for Public Policy Research and Analysis (KIPPRA) (2014). Achieving Food and Nutrition Security in Kenya: The Role of Irrigation (Nairobi, Kenya: KIPPRA); available at: http://www.kippra.org/News-and-Highlights/achieving-food-and-nutrition-security inkenya-the-role-of-irrigation.html.

[11] Ngigi, S. N., Savenije, H. H., Thome, J. N., Rockström, J., & de Vries, F. P. (2005). Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in Laikipia district, Kenya. Agricultural Water Management, 73 (1), 21-41.

[12] Paul, J. C., Panigrahi, B., Behera, B. P., & Patnaik, P. K. (2014). Design of surface drainage system for managing water congestion in Mahanadi delta: A case study. Journal of Agricultural Engineering, 51 (1), 44-50.

[13] Rawat, K. S., & Singh, S. K. (2017). Estimation of surface runoff from semi-arid ungauged agricultural watershed using SCS-CN method and earth observation data sets. Water conservation science and engineering, 1 (4), 233-247.

[14] Ulrich, A., Speranza, C. I., Roden, P., Kiteme, B., Wiesmann, U., & Nüsser, M. (2012). Small-scale farming in semi-arid areas: Livelihood dynamics between 1997 and 2010 in Laikipia, Kenya. Journal of Rural Studies, 28 (3), 241-251.

[15] Wang, J.-Y., et al., Exploring micro-field water-harvesting farming system in dryland wheat (*Triticum aestivum* L.): An innovative management for semiarid Kenya. Field Crops Res. (2016), http://dx.doi.org/10.1016/j.fcr.2016.07.001