DISAFTER SCIENCE AND ENGINEERING

XXXX, Volume 8, Number: 2
Page: 18 - 24
Received: 22 October 2022
Accepted: 26 December 20222

Modelling the Effect of Drought on Soil-moisture Availability Deficit for Sandy-loam Soils in Semi-arid Kano, Nigeria

Nura Jafar Shanono[1]

[1]Department of Agricultural and Environmental Engineering, Bayero University Kano, Nigeria; njshanono.age@buk.edu.ng; https://orcid.org/0000-0002-1731-145X

Abstract

Soil-moisture availability (SMA) is unquestionably important in crop production. Despite the acknowledgement of this, such conditions of SMA cannot easily be maintained during rainfed farming, especially in arid and semi-arid regions characterized by erratic rainfall. However, studying the historic trend of SMA in rainfed farming for the predominantly sandy-loam soils of semi-arid Kano could explore the dynamics of SMA and its effect on Maize crop production. To achieve this, a model for estimating SMA-deficit was developed, applied and reported herein. The model couples the SMA balance model, storm duration computation, cumulative infiltration (Horton's equation), crop evapotranspiration computation model and the algorithm for the computation of SMA-deficit. The model was able to predict periods when SMA-deficit is expected to be high or low whenever it takes a couple of days with or without rainfall events. The area below the SMA-deficit curve gives the amount of water that the rainfall failed to provide to make the water in the soil available to the crop due to dry spells. This deficit needs to be replaced using either supplemental irrigation or by means of in situ rainwater harvesting techniques otherwise, the crop will reach the permanent wilting point. However, the amount of water to be supplemented should depend also on the type of crop grown, the crop's growth stage, and soil and climate characteristics. The model was able to predict the fact that Maize plating may be delayed till around third-week of June to prevent the risk of long dry spells as Maize has little tolerance to water stress conditions.

Keywords: Rainfed farming, Sandy-loam, Semi-arid Kano-Nigeria, Soil-moisture availability deficit

1. Introduction

Soil-moisture refers to the water held in soil pores, which serves as a source of water for plant use. Optimum soil-moisture is undeniably important for crop growth and yield as it serves for the maintenance of turgidity necessary for cell enlargement. Despite the acknowledgement of the importance of soil-moisture to crop production, the optimum range of soil-moisture cannot be maintained during rainfed farming, especially in semi-arid regions such as Kano Nigeria which is characterized by erratic rainfall. However, studying the historic trend of soil-moisture in rainfed farming for the predominantly sandy-loam soils of semi-arid Kano, Nigeria could explore the trend of soil-moisture dynamics and its effect. For example, such a study can help in checking at which time (crop growth stage) soil-moisture is at or below the optimum (field capacity) level to take mitigation measures like estimating effective planting dates and deploying in situ soil-moisture conservation practices (Kamoni, 2005; Shanono et al., 2015; Zakari et al., 2017).

In semi-arid regions, soil hardening may reduce both water infiltration rate and biological activity. Rainfed farming constitutes 80% of the world's cropland and produces more than 60% of the world's cereal grains such as Maize, generating livelihoods in rural areas while producing food for cities. In temperate regions with relatively reliable rainfall and good soils, rainfed agriculture generates high yields whereas, supplemental irrigation practices in water-stressed areas boost crop yields (Barron *et al.*, 2013; Sabo 2021). Moreover, more than 80% of smallholder farmers in semi-arid regions of developing countries rely on rainfed farming for crop production (FAO, 2005). However, the crops are adversely affected by the temporal rainfall variability that is characterized by mid-season dry spells leading to a massive decrease in yield and hence, food insecurity (Barron *et al.*, 2013). According to Rockström *et al.,* (2003), a dry spell can be defined as a continuous period of no rainfall during a rainfall season lasting for 10 days or more. When

*Corresponding author: njshanono.age@buk.edu.ng dry spells occur, crops suffer water stress that results in yield reduction. The dry spell period varies from year to year in terms of both the length (period) as well as the number of dry spells within a rainfall season (Chibulu, 2007). Severe and long dry spells result in crops reaching permanent wilting points and eventually total crop failure. Mitigation against the negative effects of dry spells is possible where the severity is limited. In situ rainwater harvesting and mulching, practices are some of the approaches for mitigating long dry spells. In order to select and design the most appropriate mitigation technique, it is important to know how much water is required or should be made available by the technique. Thus, SMA-deficit during dry spells should be evaluated by studying the soil-moisture dynamics for the season. For sustainable crop production in semi-arid regions, the required soil-moisture for optimal crop productivity should be known and this can be estimated from daily or weekly rainfall data by analysing the dynamic change in soil-moisture content. These parameters not only provide information but also allow for the selection and adoption of soil-moisture conservation strategies for sustainable crop production and food security. Nonetheless, the determination of water balance and soil-moisture content is still challenging because the stored water quantities and their variation during the year need adequate climate and specific soil data, which is often unavailable in developing countries. Furthermore, the variations in soil-moisture content, especially in agricultural zones, are difficult to quantify due to uncontrolled water use, which also alters land-atmosphere interactions and local hydrological processes (Milliman, 2008).

Rainfed agriculture accounts for more than 95% of the land used for staple food production in Sub-Saharan Africa (Amrakh et al., 2020). In semi-arid regions, the erratic rainfall pattern is regarded as the most limiting factor to dryland crop production as this affects rainfed agricultural productivity significantly (Duckham and Masefield, 2008). Semi-arid areas like the north-western part of Nigeria, experience low rainfall which is highly variable and yet farmers still want to grow staple food crops. The major problem in this area is that the evaporative demand of the atmosphere is generally high, whereas the supply of water by natural precipitation is only occasional and highly irregular. For crops to survive during dry spells, the crops must rely upon the reserves of water contained in the soil pores, or upon the very limited reserves contained in its tissues (FAO, 2005). Questions about how efficient is the soil as a water reservoir for plants? How readily can plants draw water from the soil in varying circumstances and to what limit can soil-moisture continue to sustain plant growth in rainfed farming are some of the questions that continue to challenge the researchers in the area of soil-plant-water relations (Shanono et al., 2015). These are particularly acute and pressing in semi-arid and arid regions due to the erratic nature of rainfall. Therefore, the SMA-deficit during rainfed farming must be evaluated using historic rainfall data and other climatic and soil data to historically trace the effect of dry spells on sandy-loam soil moisture dynamics and crop yield. Sandy-loam soil was selected because it is the predominant type of soil in Kano State. It is, therefore, important to historically study the dynamics of moisture in sandy-loam soils during rainfed farming in semi-arid Kano, Nigeria.

2. Materials and Methods

2.1 Study Area

Kano is located between latitudes 10° 38′ N to 12° 38′N and longitudes 08° 02′ to 09°03′E on the high plains of northern Nigeria. The state is bounded to the north and north-east by Jigawa state, to the south and south-west by Kaduna state, to the north-west by Katsina state and the south-east by Bauchi State as shown in Fig. 1. Kano is found within the Sudan Savanna vegetation and is characterized by 2 distinct seasons (wet and dry seasons). The rainy season starts in June and ends in September with a mean annual rainfall of about 800-900 mm. The average duration of the hydrological growing season at Kano according to NIMET, 2008 is between 90-120 days. Temperatures are high throughout the year but highest in April (over 30°C). December is the coolest month with a mean temperature of 26°C (Shanono et al., 2012; Ibeje et al., 2012).

2.2 Determination of soil-moisture availability deficit

The methods employed in this study involve the development of a model for estimating SMA-deficit. The model was coded in a computer spreadsheet (excel) where input data was entered. The input data comprise the soil properties and climatic data. The climatic data including precipitation, evaporation, reference evapotranspiration, maximum and minimum temperatures for 30 years (1986 - 2015) was collected from the Nigerian Meteorological Agency (*NiMet*), Mallam Aminu Kano International Airport, Kano. The soil data including soil texture, infiltration, field capacity, and the permanent wilting point was obtained from both laboratory analysis and various studies that have been carried out on sandy loam soils of the semi-arid region of Kano State.

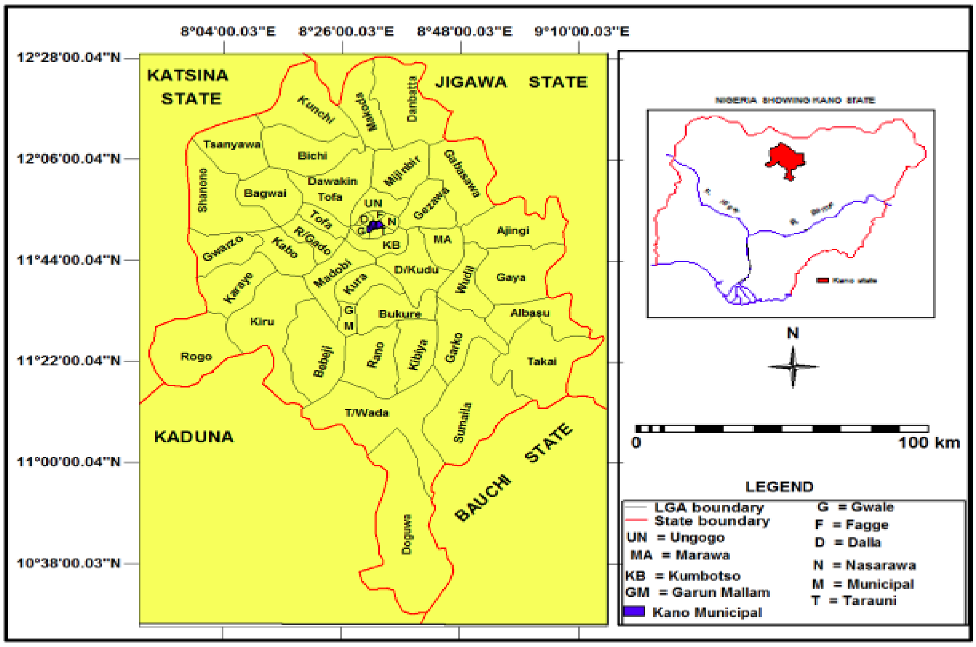

Figure 1: Map of Kano state (Ibeje et al., 2012)

Water availability for crop growth under rainfed farming is the soil-moisture within the root zone of the crops. In order to assess the SMA-deficit, only the soil water balance within the root zone profile will be considered. The inflow into this profile comprises infiltration (F), lateral soil-moisture flow (Q_i) and capillary rise (C_r). The outflow consists of lateral flow (Q_o), percolation to the groundwater (P_g) and evapotranspiration (ET). Therefore, the soil-moisture availability balance model can be as expressed in Equation 1 and schematically shown in Fig. 2.

$$\frac{dS}{dt} = F + C_r + Q_i - Q_o - P_g - ET \qquad (1)$$

Where; dS/dt is change in storage (soil-moisture) during the time t, F is infiltration, C_r is the capillary rise, P_g is the percolation to groundwater, ET is the evapotranspiration during the time, Q_i and Q_o are the lateral flow into and out of the soil profile during the time respectively.

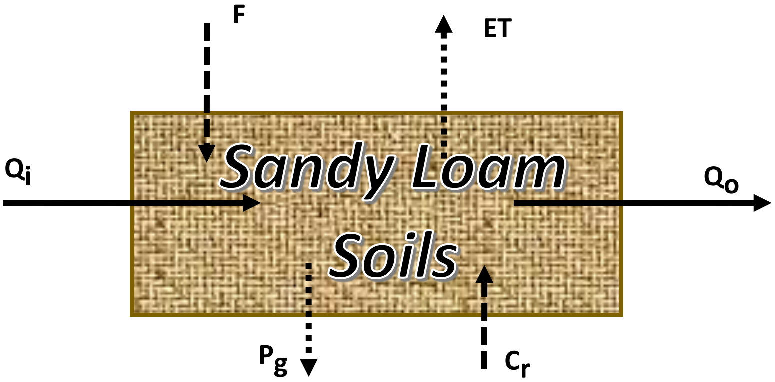

Figure 2: Soil-moisture availability balance model

The exchange of water between the root zone and the groundwater zone through percolation (P_g) and capillary rise (C_r) occurs when the moisture in the root zone exceeds field capacity or when the water table is close to the root zone. This is hardly the case in the larger proportion of semi-arid soil conditions as the limited water stored in the root zone can hardly find its way beyond the root zone (Jewitt, 2006). In addition, for porous soils like sandy-loam, the lateral flow into the soil profile (Q_i) and out (Q_o) can be considered the same (Chibulu and Mhizha, 2014). Thus, in such a situation, Equation1 can be reduced to Equation2.

$$\frac{dS}{dt} = F - ET \qquad (2)$$

Water availability deficit occurs when soil-moisture available (SMA) is less than field capacity (FC). Thus, the algorithm for the computation of soil-moisture availability deficit (SMA-deficit) can then be as expressed in Equation 3.

$$SMA_{deficit,t} = FC_t - SMA_{t-1} + F_t - ET_t \; ; \quad \text{If } SMA_{t-1} < FC_t \tag{3a}$$

$$SM_{deficit,t} = 0 \quad ; \quad \text{If } SMA_{,t-1} > FC_t \tag{3b}$$

Where: $SMA_{deficit,t}$ is the soil-moisture availability deficit during the time step t, SMA_{t-1} is the soil-moisture available during the time step t-1, and FC is field capacity.

The soil-moisture availability model requires input consisting of time series of climate and soil characteristic data including daily rainfall, infiltration capacity, recession constant and field capacity. The parameters that need to be determined during a time step are therefore infiltration and evapotranspiration. Infiltration was estimated in terms of daily precipitation using the Horton's equation. The rainfall duration was related to the amount of rainfall received using an empirical equation as modified from the Department of Meteorological Services formulae for storm duration as expressed in Equation 4.

$$T = \frac{2050 log(P)}{dt} \tag{4}$$

Where: T is the storm duration, P is the daily precipitation and dt is the time of day related to units of storm duration. The storm duration time can be taken as the infiltration time in Horton's equation. Thus, potential cumulative infiltration is then given as in Equation 5.

$$F = f_c T + \frac{f_0 - f_c}{k}(1 - e^{-kT}) \tag{5}$$

Where: F is cumulative infiltration for the day, f_c is the constant infiltration rate reached when steady-state conditions are reached, f_o is the initial infiltration rate, *k* is recession constant, and *T* is the equivalent storm duration for the daily precipitation

The average daily reference evapotranspiration (ET_0) was obtained using the FAO-Penman-Monteith method incorporated in CROPWAT (8.0) model as given in Equation 6 (FAO, 1977). The weather data for the calculation of ET_0 (daily maximum and minimum temperatures, relative humidity, wind speed at 2m height, and sunshine hours) was obtained from the Nigerian Meteorological Agency (*NiMet*), Mallam Aminu Kano International Airport, Kano.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_q)}{\Delta + \gamma(1 + 0.34U_2)} \tag{6}$$

Where: ET_0 = Reference evapotranspiration (mm/day); Rn = Net radiation at the crop surface (MJ/m^2/day); G = Soil heat flux density (MJ/m^2/day); T = Average temperature at 2m height (^{0}C); U2 = Wind speed measured at 2m height (kPa); Δ = slope vapor pressure curve (kPa/^{0}C); γ = psychometric constant (kPa/^{0}C); 900 = coefficient of the reference crop (KJ^{-1} KgK/day); (e_s – e_q) = vapor pressure deficit for measurements at 2m height (kPa); 0.34 = wind coefficient for the reference crop 0.408=value for γ^{-1} (i.e reciprocal of the latent heat flux required to vaporize one unit of water). The specific crop factor (Kc) of the selected popularly growing cereal crop (Maize) in the semi-arid Kano was found in FAO, (2013). The crop evapotranspiration (ETc) was estimated using Equation 7.

$$ET_c = K_c x ET_0 \tag{7}$$

3. Results and Discussions

The model was applied using 30-year climatic data (1986 to 2015) and the results presented here are for 1995, 2005 and 2015 which are considered to adequately represent the overall outcome of the model. Figure 3, 4 and 5 illustrate the soil-moisture availability deposit (SMA-depecit) obtained by the model for the year 1995, 2005 and 2015 respectively. The analysis is for the 125 days (1st June to 3rd October) which is the average rainy season in the semi-arid, Kano, Nigeria. This range of time was also considered the average period to grow Maize during rainfed farming on sandyloam soils in the same location as ascertained by Doorenbos and Pruitt (1977). For the computation of ETc for Maize crop on sandy-loam soils over the growing period of 125 days, the initial growth stage is 20 days (1st to 20th June with crop factor kc of 0.4), the development stage is 35 days (21st June to 25th July with a kc value of 0.8). The mid-season stage is 40 days (26th July to 3rd September with a kc value of 1.15) and the late season stage is 30 days (4th September to 3rd October with a kc value of 0.7).

From the results illustrated in the 3 figures below, the model was able to predict periods when SMA-deficit is expected to be high, moderate or low. Generally, the model predicted when SMA-deficit is high whenever it takes some couple of days without rainfall event and predicted when SMA-deficit is moderate or even zero whenever it rains heavily or it rains for 2 or more days continuously. In addition, the model can be said to accurately predict the SMA-deficit as the available data on SMA at field capacity (FC) for the sandy-loam soils is within the recommended range of 6.2cm/30cm (21%) to 7.5cm/30cm (25%) (Maduakor, 1991).

The area below the SMA-deficit curve gives the amount of water that rainfall failed to provide for the crop due to a dry spell (drought). Moreover, the same amount should be provided as either supplement irrigation or by means of rainwater harvesting technology. However, it is important to note that different amounts of water are required to mitigate against such drought impacts that occur also after different rainfall amounts. In addition, the type of crop grown, growth stage, soil and climate characteristics are also very important factors to be considered while estimating the amount of water to be supplemented. These factors must also be put into consideration when designing a rainwater harvesting technique to mitigate the effect of dry spells.

From the 3 graphs, there was a long period when the SMA-deficit is high in June (which is the beginning of raining season and the early stage of Maize crops) in 2015 than in 2005 and 1995. In June, there were about 17 days without rainfall event in 2015 which is far higher than in 2005 and 1995 with only 8 and 4 days without rainfall in June. This prediction can be said to provide the insight that Maize plating may be delayed till the last week of June to prevent the risk of a long dry spell as Maize has little tolerance to water stress conditions. This is particularly important if there is no alternative source of water (irrigation supply or in situ rainwater harvesting method). In addition, the initial crop growth stage for Maize in the semi-arid Kano, Nigeria is the first 20 days in June and during this stage, Maize crop is difficult to recover when soil-moisture reached the wilting point.

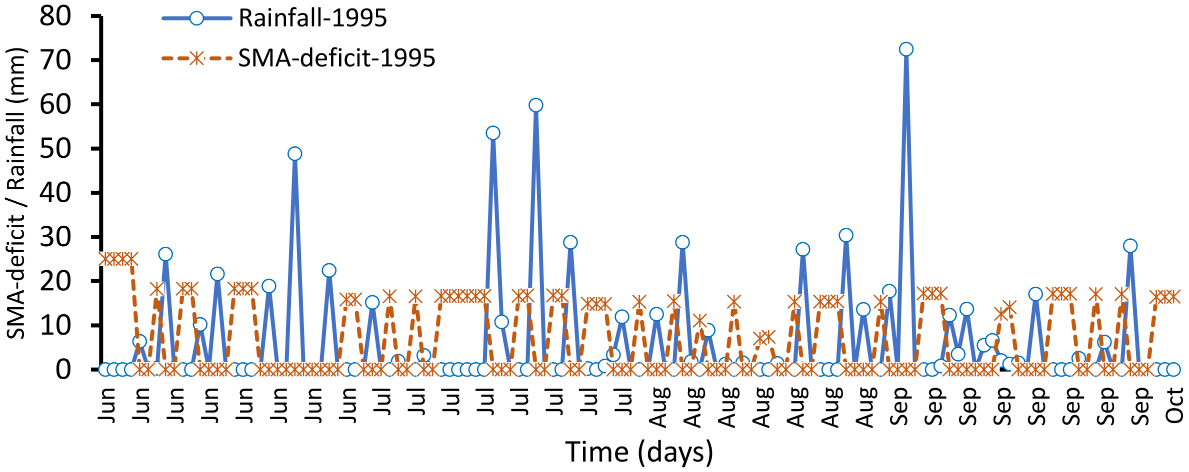

Figure 3: Variation of SMA-deficit during 1995 rainfed farming for sandy-loam soils when Maize crop is grown in semi-arid Kano, Nigeria

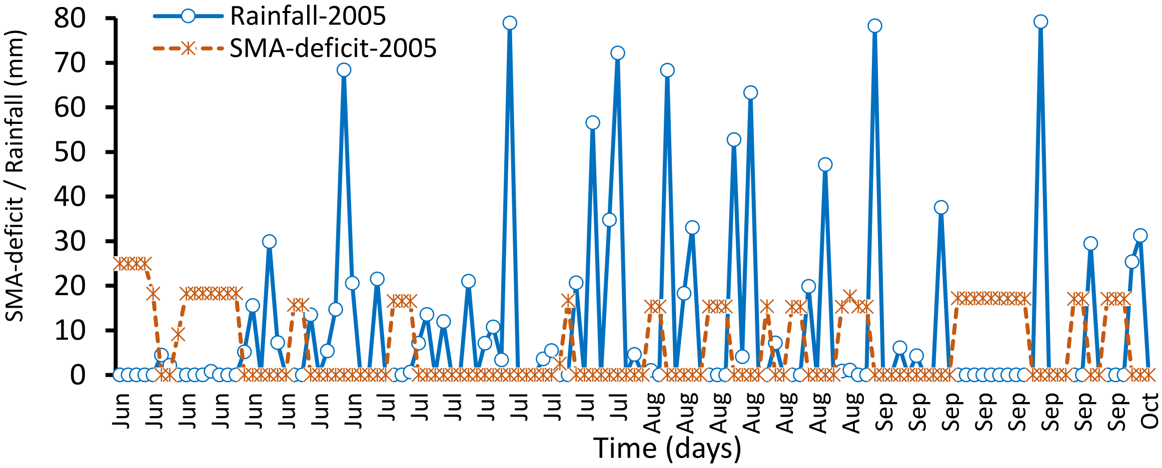

Figure 4: Variation of SMA-deficit during 2005 rainfed farming for sandy-loam soils when Maize crop is grown in semi-arid Kano, Nigeria

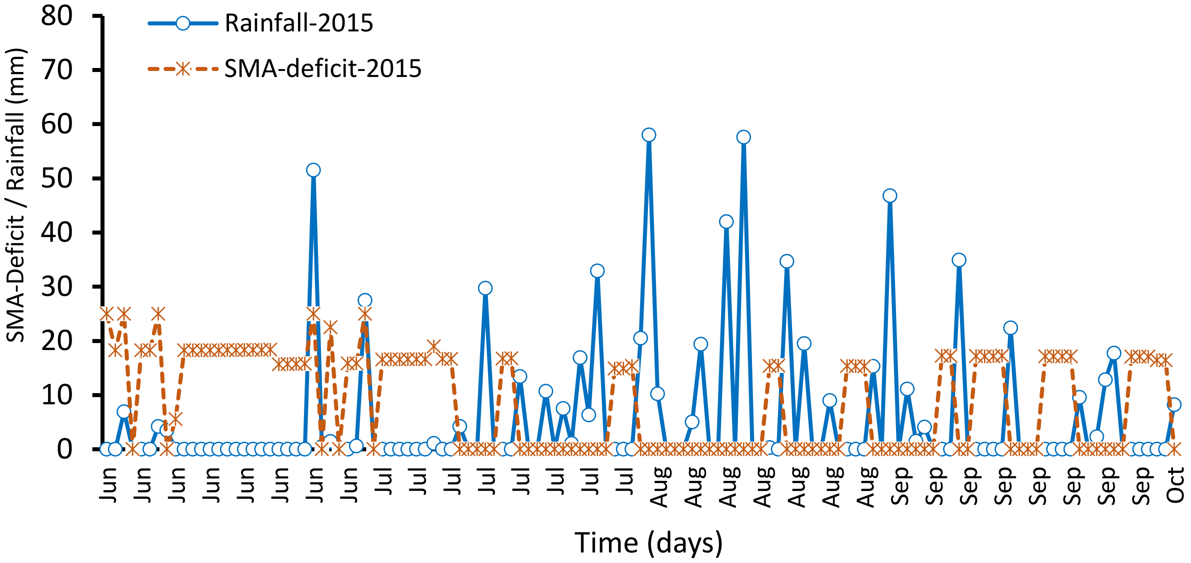

Figure 5: Variation of SMA-deficit during 2015 rainfed farming for sandy-loam soils when Maize crop is grown in semi-arid Kano, Nigeria

4. Conclusions

This study developed a model for estimating soil-moisture availability deficit (SMA-deficit). The model was able to predict periods when SMA-deficit is expected to be high or low whenever it takes some couple of days without rainfall event or whenever it rains. The area below the SMA-deficit curve gives the amount of water that rainfall failed to provide to make soil-moisture available to the crop due to dry spells which can be replenished using either supplemental irrigation or through in situ rainwater harvesting techniques. However, the amount of water to be supplemented should depend also on the type of crop grown, crop's growth stage, soil and climate characteristics. The model was also able to predict the fact that Maize plating may be delayed till the third week of June to prevent the risk of a long dry spell as Maize has little tolerance to water stress conditions.

Ethics Declaration

There are no ethical issues regarding the publication of this study.

Author's contributions

The author is responsible for the entire article.

References

Amrakh I. Mamedov, Atsushi Tsunekawa, Mitsuru Tsubo, Haruyuki Fujimaki, Imanverdi Ekberli, Cevdet Şeker, Hasan S. Öztürk, Artemi Cerdà and Guy J. Levy, (2020). Structure Stability of Cultivated Soils from Semi-Arid Region: Comparing the Effects of Land Use and Anionic Polyacrylamide Application. Agronomy 2020, 10, 2010; doi:10.3390/agronomy10122010. www.mdpi.com/journal/agronomy

Barron, J., Rockström, J., Gichuki, F., Hatibu, N., (2013). Dry spell analysis and maize yields for two semi-arid locations in east Africa. Agric. For. Meteorol. 117 (1–2), 23–37

Doorenbos, J. and Pruitt, W.O. (1977) Crop Water Requirements. FAO Irrigation and Drainage Paper 24, FAO, Rome, 144 p.

Duckham, A. N., And G.B. Masefield, (2008). Farming Systems Of The World. Chatto & Windus, London. Pp 542.

FAO, (2005). Food security in the context of economic and trade policy reforms: insights from country experiences. CCP 05/11. Rome.

Ibeje, A. O., Agunwamba, J. C., Okoro, B. C. (2012). Allocation Of Water Resources In Semi-Arid Region Of Northern Nigeria. African Journal Online. Faculty of Engineering, University of Nigeria, Nsukka, Nigeria.

Kamoni, P.T. (2005). Assessment of the land quality soil-moisture availability and its effects on potential production by using a quantitative land evaluation approach. MSc, Agricultural University, Wageningen, Wageningen.

Maduakor, H. O. (1991). Physical and hydraulic properties of soils of the Sudano-Sahelian regions of Nigeria. Soil Water Balance in the SudanoSahelian Zone (Proceedings of the Niamey Workshop, February 1991). IAHS

Publ. No. 199,1991. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1087.315&rep=rep1&type=pdf

Milliman, J.D.; Farnsworth, K.L.; Jones, P.D.; Xu, K.H.; Smith, L.C. (2008) Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951-2000. Glob. Planet. Chang. 62, 187–194

Mhizha, A. and B. Chibulu (2007), Effect of Rainfall Variability on Crop Yield Under Semi-Arid Conditions at Sub Catchment Level, MSc Thesis, University of Zimbabwe.

Rockström, J., Barron, J., and Fox, P. (2003). Water productivity in rainfed agriculture: Challenges and opportunities for smallholder farmers in drought-prone tropical agro-ecosystems

Sabo, A.A., M.S. Abubakar, M.D. Zakari, N.J. Shanono, A.N. Jibril, and U.K. Adamu (2021). Effect of organic materials on soil physio-chemical properties at Bayero University, Kano-Nigeria. Agricultural Engineering International: CIGR Journal, 23(3): 52-59. https://cigrjournal.org/index.php/Ejounral/article/view/6893/3669

Shanono, N.J., M.K. Othman, N.M. Nasidi and H. Isma'il (2012). Evaluation of Soil and Water Quality of Watari Irrigation Project in Semi-Arid Region, Kano, Nigeria. Proceedings of the 33rd National Conference and Annual General Meeting of the Nigerian Institute of Agricultural Engineers (NIAE) Bauchi. pp. 181 – 186.

Shanono, N.J., M.S. Adamu, N.M. Nasidi, M.D. Zakari, H. Isma'il and A.G. Halilu (2015). Evaluation of Soil Water Characteristics-Hydraulic Property Calculator (SWC- HPC) Model at Thomas Irrigation Project, Kano. 2nd International Interdisciplinary Conference, Chukwuemeka Odumegwu Ojukwu University, Nigeria, University of Eldoret Kenya and Kyambogo University Uganda. Held at Chukwuemeka Odumegwu Ojukwu University, Nigeria 2 – 5 September, 2015.

Shanono, N.J., N.M. Nasidi, M.S. Abubakar and M.D. Zakari (2015). Effect of Harrow Operations on Soil Physical Properties in Relation to Crop Production. *Journal of Engineering and Technology Vol. 10 (1).*https://www.bayerojet.com/wp-content/uploads/journal/published_paper/volume-10/ issue1/bjet6vC0pMuZ.pdf

Zakari, M.D., I. Audu, H.E. Igbadun, N.J. Shanono, M.M. Maina, N.M. Nasidi and A. Shitu (2017). Yield and Water-Use of Tomato under Deficit Irrigation and Mulch Practices at Kano River Irrigation Project. *Red Sea University Journal of Basic and Applied Science* Volume (2) Special Issue (1) http://repository.rsu.edu.sd/handle/123456789/2486