Investigation of sustainability of rain-fed agriculture through soil moisture modeling in the Pandamatenga Plains of Botswana

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Abstract

The agricultural economic sector of Botswana is limited mainly to range resources-based livestock and pockets of arable farming based on rainfall and limited irrigated agriculture at several places. In this study agricultural sustainability of rain-fed agriculture is investigated in Botswana by considering the Pandamatenga plains as a case study. Daily soil moisture regimes with respect to crop growth cycle were modelled using a water balance model based on 42 years of daily hydroclimatic inputs and corresponding simulated components of soil moisture, evaporation, surface runoff, and deep percolation. Using a sustainability criterion on crop water requirement and soil moisture availability during the cropping periods, it was found that rain-fed agriculture of maize, sunflower, and sorghum crops is sustainable. The relative sensitivity to drought of these crops was also found to conform to the Agromisa recommendations. In the pursuit to explore more IWRM opportunities, through the simulation of the corresponding direct runoff, we have also explored that more water harvesting opportunities exist in order to manage rainfall excesses effectively.

Keywords: Soil moisture modeling; Rainfed agriculture; Excess rainwater harvesting; Integrated water resources management; Botswana

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1. Introduction

Rain-fed agriculture based to a large extent on smallholder, subsistence agriculture is the source of livelihood of the majority of the population in sub-Saharan Africa (e.g., Malawi, 90%; Botswana, 76%; Kenya, 85%; and Zimbabwe, 70–80%, of the population) (Rockström, 2000). An estimated 38% of the population in sub-Saharan Africa (roughly 260 million people) live in drought-prone drylands (UNDP/UNSO, 1997). Only four of the SADC member states are self-sufficient in food production with the rest engaging in substantial food imports to meet domestic food deficits (SADC, 1995). Food production in the region is characterized by annual fluctuations due to rainfall variability.

Sustainability of rain-fed agriculture is a challenge most agriculturally-supportive areas strive for generation of food for their communities. The Pandamatenga Plains, located in Northern Botswana is one of such areas where rain fed agriculture is practiced. Studying the sustainability of rain-fed agriculture is an important research area for irrigation engineers and hydrologists especially in Africa, the outcome of which is useful for agricultural planners and decision makers. This study is devoted to developing a simple Soil Moisture Accounting Crop-Specific (SMACS) model and studying the sustainability of growing maize, sunflower, and sorghum in northern Botswana by employing a sustainability criteria based on crop water requirement and soil moisture availability during the cropping periods. The Pandamatenga plains, is a prominent agricultural area for the above crops.

The model used in this study, the Soil Moisture Accounting Crop-Specific (SMACS) model is a typical case of soil–vegetation–atmospheric transfer (SVAT) models. The hydrological concept and development of SVAT

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models is a wide area of immense research. The main issue is to identify the different formulations for runoff production, soil moisture and evaporation. Boone and Wetzel (1996) stated that one of the most important components of the SVAT scheme is the soil hydrology scheme, which is used to determine the partitioning of rainfall into infiltration, runoff, drainage, and storage within the soil. Large scale soil moisture data are available from soil–water retention parameters, hydrological model and remote sensing data at the SADC scale (e.g. Alemaw and Chaoka, 2003) as well as from remote sensing (ERS scatterometer) and soil data at a global scale (e.g. Wagner et al., 1999). The spatial and temporal scale of these data limits their applicability to study soil–plant relations at localized scale such as the Pandamatenga plains considered in this study.

Researches on plant response to sub-optimal levels of soil moisture have already been conducted for several decades. In his comprehensive work Hsiao (1973) examined and ranked plant physiological responses to water stress and the underlying mechanisms. Specific studies were conducted to assess, on a more practical level, the response of single crops to various water stress levels, for example soyabean (Sionit and Kramer, 1977), and sorghum (Gardner et al., 1981). The United Nations FAO has compiled the experience, practices, and guidelines on crop water requirement and crop evapotranspiration (Doorenbos and Pruitt, 1977; FAO, 1998; FAO, 1992).

In agricultural water management, a common straightforward definition of water harvesting is the one provided by Siegert (1994) as the collection of runoff for productive use. Runoff can be collected from roofs or ground surfaces (rainwater harvesting) as well as from seasonal streams (flood water harvesting) (Agromisa, 1997).

The most important decision criteria will be to determine the level of soil moisture and its reliability to sustain crop growth without excessively depleting the available soil moisture storage. The objective of the study covered in this paper is: (i) to simulate daily soil moisture on areas cropped with maize, sunflower, and sorghum in the Pandamatenga plains; (ii) to determine the proportion of available moisture content required to sustain crop growth during the entire crop cycle; and (iii) to investigate the potential of harvesting excess runoff formed on cropped areas.

2. The study area

The study area is the Pandamatenga Plains, located in Northern Botswana where rainfed agriculture is practiced (Fig. 1). The total area considered in this study consists of approximately 25,000 ha of land of which 15,840 ha is allocated for commercial farming. The annual average rainfall is 510 mm/yr with standard deviation of about 225 mm/yr. The soil type is predominately vertisols, where there are very low drainage slopes ranging between 0.05% and 0.4%. The land cover is originally acacia/baobab deciduous savanna. Farming in the area started prior to the 1950s.

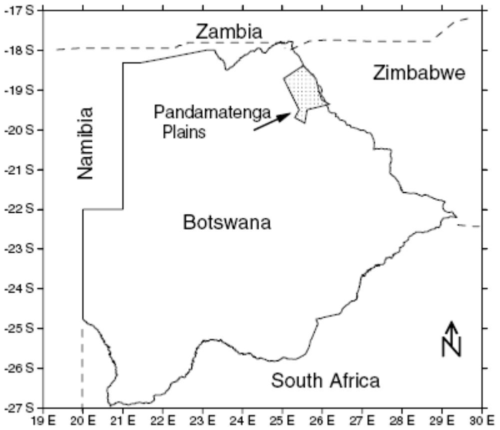

Fig. 1. The location map of the study area – Pandamatenga farm plains.

This investigation of the degree of sustainability of rain-fed agriculture in the Pandamatenga plains is an important as the outcome will be of great assistance to agricultural planners and decision makers. The Pandamatenga plains is one of the vast agricultural potential areas which is considered as a commercial farming magnet by the Government as well as private investors. Maize, sunflower, and sorghum which are predominant crops in the area have been considered to assess their agricultural sustainability.

3. Materials and methodology

The methodology employs a soil moisture accounting rainfall-runoff modeling approach and decision criteria that are based on results on: (1) simulated daily soil moisture, (2) the proportion of available moisture content that is required to sustain crop growth during the entire crop cycle, and (3) evaluated surface runoff available for potential excess water harvesting. An account of the approach followed in this study is presented below.

3.1. Simulation of soil moisture regime

In order to determine the variation of soil moisture and assess the availability of soil moisture to plants, daily soil moisture simulations were undertaken using a spreadsheet program called Soil Moisture Accounting Crop-Specific (SMACS) model developed for this study.

The SMACS model is based on a simple accounting of the daily moisture with the major terrestrial and atmospheric inputs of rainfall and potential evapotranspiration, along with the soil water retention properties and crop development factors. The approach followed is similar to the daily soil moisture accounting model of Williams et al. (1985) known as Simulator for Water Resources in Rural Basins (SWRRB) but with some modifications to some components to conform to input data availability. The SMACS model and its components are outlined below.

Soil moisture is modelled based on the continuity equation as follows:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P(t) - Q(t) - E_{\mathrm{a}}(t) - P_{\mathrm{r}}(t) \tag{1}$$

This can be reduced to a simple water balance equation as

$$S(t) = S(t-1) + P(t) - Q(t) - E_{\mathrm{a}}(t) - P_{\mathrm{r}}(t) \tag{2}$$

In which on a daily time scale, at day t, $S(t)$ is the soil moisture content (mm), $P(t)$ is the amount of precipitation (mm), $Q(t)$ is the amount of generated surface runoff (mm), $E_{\mathrm{a}}(t)$ is the actual evapotranspiration (mm), and $P_r(t)$ is the percolation (mm) beyond the root zone.

Surface runoff is estimated using modification of the USDA Soil Conservation Service (SCS) Curve Number (CN) technique (US SCS, 1985). The reference evapotranspiration (E_{o}) was determined using the Hargreaves equation (Hargreaves and Samani, 1985) which is a widely used empirical approach to compute potential evaporation and is usually referred to as temperature-based approach.

During a growing season the daily actual evapotranspiration, $E_{\mathrm{a}} = E_{\mathrm{o}} * K_{\mathrm{c}} * K_{\mathrm{s}}$, where K_{s} the soil coefficient (Doorenbos and Pruitt, 1977), and K_{c} is the crop coefficient at different growing stages of the crops considered in the study, estimated from the length of the growing period (LGP), as described by Doorenbos and Pruitt (1977), and Doorenbos and Kassam (1979). Percolation is estimated as that amount of water available when soil moisture exceeds the field capacity, and that satisfies the mass-balance equation, Eq. (2).

Crop type, soil characteristics, rainfall, and climate are integrated in the soil water balance model to simulate a soil moisture regime assuming a particular crop at a time. For a crop under consideration, the mass-balance equation, Eq. (2) was solved for the entire daily rainfall and temperature record period of 1961–2002. The analysis starts just before the beginning of the rainy season so that the initial soil moisture can reasonably be assumed to be at wilting point (S_{WP}). During the cropping season of each crop and for a given simulated day, when the soil moisture ranges between wilting point and field capacity, the model assumes a linear variation between the ratio of actual to reference crop evapotranspiration and the simulated soil moisture.

3.2. Assessment of soil–water–plant relationship

The purpose of the assessment of soil–water–plant relationships is primarily to estimate the mean frequency of water application or irrigation. This will in turn determines the level of soil moisture availability to cause stress to the crops. If the analysis was based only on dry-spell analysis of rainfall, the mean frequency of water application or irrigation determines the dry-spell duration longer than which it will cause damage to crop yield.

The crop water requirements of the selected crops for known soil–water retention and crop characteristics must be determined. The crop water requirement is the consumptive use of water by plants (E_{CROP}), which is the same as the actual evapotranspiration E_{a} described in Eq. (2) during the cropping season of each crop. The daily E_{CROP} is determined using the proposed daily soil moisture accounting model in which the crop reference evapotranspiration is an input along with daily rainfall, soil–water retention parameters, and crop growth factors.

The frequency of irrigation is estimated using the FAO (1992) formula as

$$I = \frac{pS_{\mathrm{a}}}{E_{\mathrm{CROP}}} D \tag{3}$$

In which p is the fraction of total available soil water which can be used by the crop without affecting its transpiration and/or growth; S_{a} is total available soil water or moisture ($S_{\mathrm{FC}} - S_{\mathrm{WP}}$) in mm/m; S_{FC} is available soil water or moisture at field capacity in mm/m; S_{WP} is the available soil water or moisture at permanent wilting point in mm/m; D is the depth of root zone of the crop (m); E_{CROP} is consumptive crop water requirement.

Not all the water that is held in the root zone between S_{WP} and S_{FC} is available to the crop. The depth of water that is readily available to the crop is pS_{a} and it is related to the depth of application by the following equation:

$$d = \frac{pS_{\mathrm{a}}}{f_{\mathrm{a}}} D \tag{4}$$

where f_{a} is the water application efficiency (fraction). The value of pS_{a} will vary with the level of evaporative demand. Since the evaporative demand varies with the growing stages of crops, pS_{a} will be different with different growing stages of crops.

3.3. Data used

Historical daily precipitation records for 42 years (1961–2002) at Pandamatenga, and daily/monthly maximum temperature and minimum temperature, and solar radiation data a close-by climate station at Kasane were obtained. The length of cropping period and crop coefficients used in the SMACS model for the various crop development stages is adopted from Doorenbos and Pruitt (1977). Soil water retention properties of the clay soil within the active root zone of the crops is used based on unit water retentions for given soil texture according to Saxton et al. (1986). The information on rooting depth, soil moisture characteristics length, and crop cycle coefficients is obtained from Doorenbos and Pruitt (1977).

4. Discussion of results

4.1. Soil moisture availability and sustainability of rain-fed agriculture

It was not possible to calibrate and judge the performance of SMSCS model objectively, for there were no measured soil moisture data. However, the closure of the water budget (Eq. 2) is one of main objectives followed in setting up the SMACS model. In this regard, the assumed initial soil moisture used in the model which was optimised until a minimum error in the simulated soil moisture was found between the beginning and end of the simulated hydrological year (starting with a wetter date/month in which S was close to 0.5 mm). The error as the difference between the initial and final simulated soil moisture within a given hydrological year was calculated for the period 1961–1990 and 1991–2002 as summarized for the three crops as shown in Table 1. With 1 mm increment or decrement of the initial soil moisture which starts with the value equal to S_{FC}, the minimum error was set as 0.5 mm between sequential differences in the average annual soil moisture changes (beginning to end of all simulated years) during the calibration period.

The optimisation covered all the first 30 years (1961–1990) record for the calibration of the model and the remaining 12 years (1991–2002) was used as model verification period. During the verification exercise, we used the optimized initial moisture which was set during calibration to observe the error induced in the closure of the hydrologic water budget. Initial soil moisture and average annual soil moisture change between the beginning and end of the simulation years used for the three crop types is also shown in Table 1. It can be noted from Table 1 that the soil moisture change between end and beginning of period of simulation is negative for the calibration period and positive for the verification period. The reason for the later case could be due to the low rainfall occurred towards the end (in 2001 and 2002) compared to the beginning (1991) of the verification period.

A number of factors apart from soil water could affect proper crop growth and its yield including nutrient availability and agricultural practice. The most important decision criteria adopted in this study is to determine the level of soil moisture and its reliability to sustain crop growth without excessively depleting the available soil moisture storage. Once the model is calibrated and based on Eq. (4), and considering water application efficiency of 100% with the assumption that there is no induced drainage and channeling, and that the rainwater is uniformly and well applied to the gentle slope and clays dominated plains of the Pandamatenga area, one can determine the extent of failure of soil moisture to sustain crop growth and yield.

Fig. 2 shows simulated daily soil moisture distribution throughout the growing season of maize along with the exceedance probabilities of given moisture conditions with respect to the readily available soil moisture regimes. Simulation results of the probability of failure of each crop during the respective cropping period are summarized in Tables 2 and 3. The probability of failure here refers to the proportion of days to the total number of days or the length of the growing period (LGP), within which the simulated soil moisture drops below the amount which is

Table 1
Initial soil moisture (mm) and average annual soil moisture change (mm) between the beginning and end of the simulation years used for the three crop types

Crop	Initial soil moisture, S_0	Average annual soil moisture change (beginning to end of year)	
		Calibration period 1961–1990	Verification period 1991–2002
Maize	431	−24.0	21.4
Sunflower	351	−22.7	20.0
Sorghum	540	−29.5	26.0

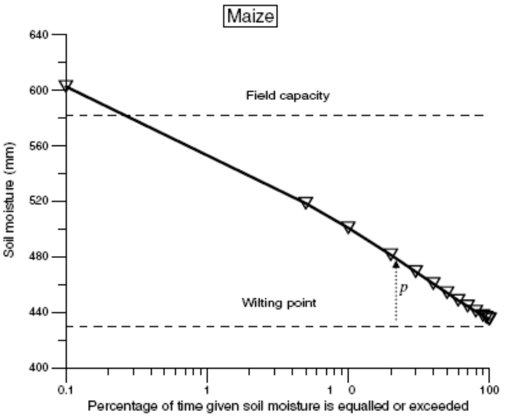

Fig. 2. Simulated soil moisture distributions for maize.

Table 2
Probability of failure in percentage of maize, sunflower, and sorghum for soil moisture at wilting point at $p = 0\%$ in proportion to the readily available soil moisture

CROP		1961–1970	1971–1980	1981–1990	1991–2002
Maize	Total days	1400	1400	1400	1680
	Failure no.	446	90	289	392
	Failure %	12.2%	2.7%	7.9%	9.0%
Sunflower	Total days	1300	1300	1300	1560
	Failure no.	391	189	259	471
	Failure %	10.7%	5.8%	7.1%	10.8%
Sorghum	Total days	1200	1200	1200	1440
	Failure no.	272	17	98	267
	Failure %	7.5%	0.5%	2.7%	6.1%

Table 3
Probability of failure (%) of maize, sunflower, and sorghum for different levels of soil moisture in proportion to the readily available soil moisture

Crop	Calibration period			Verification period
	1961–1970	1971–1980	1981–1990	1991–2002
Proportion of soil moisture, $p = 10\%$				
Maize	25.9	21.9	22.8	23.1
Sunflower	23.1	19.9	21.0	21.3
Sorghum	18.0	13.9	16.0	16.1
Proportion of soil moisture, $p = 30\%$				
Maize	34.9	31.9	34.0	31.7
Sunflower	30.7	27.7	30.2	27.8
Sorghum	28.4	23.6	27.3	25.1

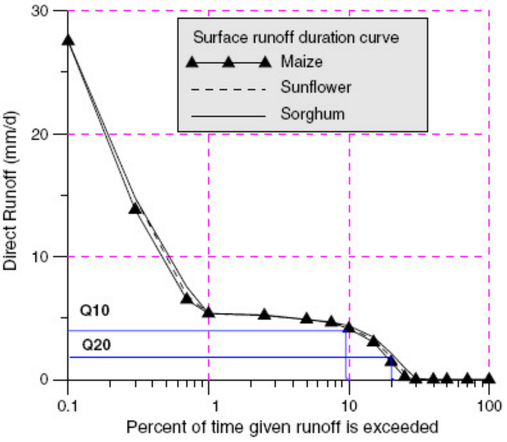

Fig. 3. Surface runoff duration curves showing the quantity of excess surface runoff that can be harvested in the Pandamatenga farms.

set at p times the readily available soil moisture content ($S_{FC} - S_{WP}$) as stated in Eq. (4). The readily available soil moisture content is a function of the soil–water parameters of field capacity and wilting point of the prevailing soil type.

Table 2 is the ideal condition where the plants are at critical stress limit where p is zero. From Table 3, it can be noted that without prejudice to the critical stress limit required for each crop, which depends also on nutrient and farming practice, it can be said that a modest moisture level say at $p = 30\%$, the probability of failure of maize is higher than that of sunflower and sorghum. The probability of failure on the average for the three crops, maize, sunflower and sorghum is 33.6%, 29.5%, and 26.4%, respectively, during model calibration period, and 31.7%, 27.8%, and 25.1% during the model verification period. These relative soil moisture levels indicate a relative sensitivity to drought of these crops, which conforms to the Agromisa recommendations where sorghum is least sensitive to drought than maize and sunflower. It is worthwhile to note that the aforementioned calibration period, 1961–1990 and verification period, 1991–2002 refer to the period under which the probabilities of failures are summarized and reported. The values of soil moisture thresholds set at p are not used in the calibration and verification process but are used here to evaluate the moisture stress limits against the simulated soil moisture values through counting of number of days whose soil moisture values drop below the soil moisture amount whose threshold value is set at p times the readily available soil moisture content as stated in Eq. (4). Counted number of days whose soil moisture drop below the threshold soil moisture through out the period of analysis during the cropping cycle of each crop was used to calculate the number failure days and probability of failures as summarized in Table 3.

4.2. Excess water harvesting opportunities

The high intensity rainfall storms during particular days cause immense surface runoff. Flooding of the Pandamatenga plains is common phenomena (MOA, 1990). Excess runoff computations made using the developed soil moisture accounting crop model, by applying the CN method that satisfies the mass-balance equation (Eq. (2)), though available at a daily time scale (result summarized as duration curves in Fig. 3), could be used to plan appropriate mechanism of water harvesting. The harvested runoff can involve different forms of surface runoff (sheet, rill, gully, and stream flow) and the storage is either done above ground, in different systems of tanks, reservoirs or dams, or below ground in the soil. Methods for harvesting runoff water can be distinguished using (i) source of the surface water (external or within-field catchments from sheet, rill, gully or stream flow) and (ii) the method of managing the water (maximising infiltration in the soil, storing water in tanks/dams, inundating crop fields with storm floods) (Rockström, 2000).

At a farm scale in the Pandamatenga plains which are nearly plain and dominated by flat slopes with clay soils, water harvesting of the excess runoff can be achieved through the provision of perimeter bunds around each sub-divided plots and cut-off drains as a means of runoff water management for regulation or disposal of excess runoff, delaying the flow, and/or preventing water logging and flooding during flashy storms. These systems will have a prominent role of prolonging soil moisture enrichment as the water is en route to downstream plots to affect water availability. These systems also create an opportunity to protect water logging as well as to control erosion. Erosion control is generally perceived as a soil conservation measure (e.g. Thomas, 1997).

The daily surface runoff duration curve showing the quantity of excess surface runoff that can be harvested in the Pandamatenga farms and its percentage of time exceedance simulated by the proposed SMACS model is shown in Fig. 3. The average surface runoff available that exceeds 10% of the number of the days in all the 42 years of simulation period is about 4.4 mm/day (Fig. 3). This depth of excess rainfall equals to a runoff of 12.7 m^3/s that can be collected from the entire Pandamatenga plains if all the three crops are planted each covering one-third of the Pandamatenga plains of 25,000 ha. In order to effectively harvest the rainfall excess a number of measures and factors should be considered. From engineering perspectives, design height of perimeter bunds, possible size of farm-level detention ponds as well as size and slope of cutoff drains should be based on capacity to accommodate flush floods and their timing. Such flush floods result from high frequency and short duration rainfall intensities. Therefore, it is worth minding that proper event based rainfall-runoff transforming models be used to derive design flood peaks and their timing in order to effectively harvest and manage the excess surface runoff.

5. Summary, conclusions and recommendations

The sustainability of rain-fed agriculture is explored in this study through assessment of effect of various degrees of soil moisture prevalence during the growing of maize, sunflower and sorghum. Opportunities for excess rainfall harvesting have also been explored by using a spreadsheet programme namely the Soil Moisture Accounting Crop-Specific (SMACS) model. This approach highlights one window of opportunity for more understanding of Integrated Water Resources Management (IWRM) in agricultural areas where soil moisture should be managed more effectively. The SMACS model has been applied with some degree of success to explore the study of rain-fed agriculture sustainability and IWRM opportunities through excess runoff harvesting in the Padamatenga plains of Botswana. The model can be further refined as more data becomes available.

The following are recommended opportunities to explore further the application of the model for real time applications: (1) In situ soil moisture and/or surface runoff measurement needs to be undertaken to improve the SMACS model; (2) also required is soil investigation and mapping and further field monitoring of crop specific water stress and yield; (3) further identification of potential water harvesting sites from field data and Digital Elevation Models (DEMs) exists; and (4) exploration of large scale water conservation structures to improve agriculture and increase frequency of cropping other than the single season currently practiced.

More opportunities to implement Integrated Water Resources Management (IWRM) exist using entry point strategies for contribution to livelihood improvement in rain-fed agriculture practicing areas of the region in general and in the Pandamatenga plains in particular. These IWRM entry point strategies that can be considered in cross-sectoral and multi-disciplinary dimensions can be through: (1) the introduction of conservation tillage to improve soil–water and land fertility; (2) the encouragement of financing of small, micro and medium scale agricultural enterprises which should explore opportunities to effectively use available rainwater and excess runoff; and (3) raising awareness at the political level so that politicians have the will to explore potential of economic diversification through rain-fed agriculture and excess water harvesting that would ultimately improve food security of a nation.

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