Assessment of Sustainable Agricultural Practice Using Distributed Crop Soil Moisture Balance Model (D_CSWB): A case Study of Pangani Basin in Tanzania

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Abstract: Due to increased climatic change and human activity in the last quarter of the past century, it is believed that the frequency of extreme metrological conditions are on the rise and is drawing attention of leaders and scientific communities all over the world. In developing countries, like countries in Africa, where farmers largely rely on rained agriculture, it has caused many crop failures and forced the society to live under draught and famine conditions. A case in point is the recent draught in Southern part of Africa. Grid-based daily soil moisture balance model coupled with dry spell analysis of the soil moisture condition of crops during the wet season were used to assess the sustainability of the practice of rainfed agriculture. Three main crops commonly grown in the basin were considered (maize, rice and beans). One crop is taken at a time and the soil moisture balancing was done for each grid resolution of 1km by 1km and analysed through the entire rainfall record. The analysis results shows that beans may generally be considered for rainfed agriculture without any supplementary irrigation in the basin. It has been learnt that beans can grow in low water availability areas and is considered as drought resistance crop. In the case of maize, rainfed agriculture may be possible in lowlands of Massai steppe and part of Kilimanjaro area. However, rice cultivation was found practically impossible as the probability of failure during the rainy season exceeds 80 % in most of part of the basin. It can generally be concluded that mixed agricultural practice may be a sustainable option to produce main food items like rice and maize in the basin. Similar study may be expanded to other basins in Tanzania and African countries at large to create increased awareness to decision makers and farmers themselves that rain fed agriculture alone are no more sustainable option of food production.

1. INTRODUCTION

Dry spell causes environmental stress that affects the soil, plants, animals and man. It is a recurrent hazard that occurs in different parts of the world at an unpredictable frequency such that it has become a global problem. It has always been a major roadblock to agricultural and industrial stability. In recent years parts of Tanzania have experienced recurring droughts. The most devastating were those of 1983-1984 and 1993-1994 (Amaglo, 1997). The historical breakdown indicates that the most affected areas in the past are central Tanganyika, Handeni, and parts of Arusha, Moshi, Bagamoyo, Shinyanga, Mwanza and Mara.

Rainfall in Tanzania is a crucial factor in the ability of farmers and pastoralists to produce the foodstuffs needed for the consumption. Rain-fed agriculture is the main stay of the economy; consequently severe droughts have disastrous impacts on the social economic development of the country. Several studies of drought patterns in East Africa and their potential impacts on the economy have been carried out by Nieuwolt (1978), Ogallo (1994), Mhita (1990), Nicholson and Nyenzi (1989). All these studies were based on meteorological drought analysis.

In this study, it is believed that from agricultural sustainability point of view, the moisture deficient or availability at the crop root zone is more pragmatic indicator of dry-spell than metrological or hydrological dry-spell conditions. Because the methodology, apart from metrological factors, can effectively account for the physical characteristics through parameter representation of the soil, crop type and the terrain in the soil moisture model.

In this regard, distributed soil moisture balance model **(D_SMBM)** was developed and applied to assess sustainability of rainfed agriculture in Pangani basin. Dry spell index (or probability of failure) was expressed as the ratio the number of soil moisture deficits through years of simulation and the total number of years of simulation. The soil moisture simulation was carried out on a daily basis.

2. DESCRIPTION OF THE STUDY AREA

Pangani River Basin is located in the northeastern part of Tanzania between 2°35'S to 6°6'S latitude and 3°E to 39°36'E longitude. The river has its sources at the slopes of Mountain Kilimanjaro and Mount Meru. Except a small part of the catchment, which lies in Kenya, the major part of the basin is located regions of Kilimanjaro, Arusha and Tanga, in Tanzania. The total area of the catchment is estimated to be 42,200km^2 (see Figure 1). The apparent movement of the Inter Tropical Convergence Zone (ITCZ) and the complex topography, together account for climatic variations in the Pangani river Basin. Highest rainfall, 1000-2000mm/year, occurs on the southeastern slopes of Mountain Kilimanjaro and Meru. In a southward direction, the rainfall reduces to 500-600mm/year in the semiarid area of central portion of the basin. The seasonal variation of average air temperature in the basin is minimal, ranges from 14°C to 25°C in the Kilimanjaro region, from 17°C to 29°C in the southern portion of the basin. Pangani map is given in figure 1.

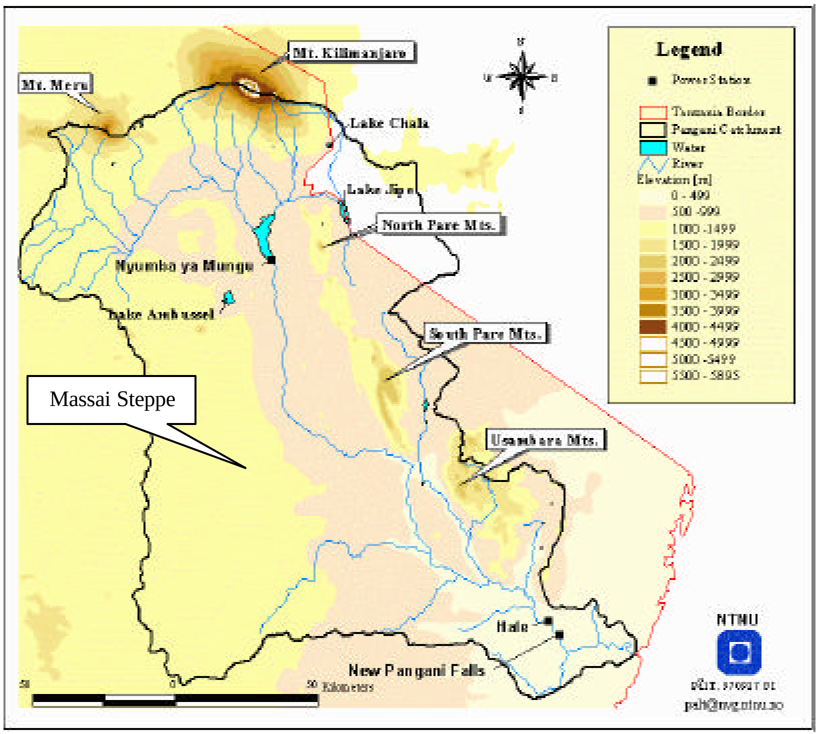

Figure 1. Map of Pangani basin

3. DATA

Data used in this study include daily rainfall data from 76 stations and climatic data from 9 stations for estimation of reference Evapotranspiration.

Digital Elevation Model (DEM) data of 1kmx1km accessed from USGS database was used to derive slope for each 1km by 1km grid. The slope parameter is used in the runoff generation component of the crop-soil water balance model (CROPSWB).

The digitised soil information for whole Tanzania obtained from FAO database (FAO, 1998) was used to derive average soil-water holding characteristics of each grid. Such characteristics include soil moisture content at wilting point (WP), at field capacity (FC) and Saturation (PO). The derivation of these parameters was based on Saxton et al., (1986) regression equations relating matrix potential (ϕ) as a function of proportion of soil texture (%clay, %sand and %silt) and water content (θ). Thus by substituting approximate matrix potential value of 1500kPa, 33kPa, the corresponding WP and FC of the soil can be estimated. Similar formula for a matrix potential of 0 (at saturation) is also given by the same authors and used to estimate PO (Moges, 2000). The soil texture attributes of the soil map were also used to derive the runoff parameter (CN) used in runoff generation (Equation 2).

Three crops – rice, maize and beans were used in the study. Local crop specific information of the crops is given in Table 1 below.

Table1. Local Crop Specific Information in Pangani basin

Crop	Planting Date	T.G.L (Days)	Development stages				Crop coefficients					Root depth (mm)
			Dev1	Dev2	Dev3	Dev4	Dev1	Dev2	Dev3	Dev4	p	
Maize	Mar-12	125	20	35	40	30	0.65	0.70	1.05	0.80	0.60	1000
Beans	Mar-12	95	15	25	35	20	0.65	0.91	1.05	0.65	0.45	500
Rice	Mar-12	102	20	20	32	30	1.10	1.10	1.10	0.95	0.20	500

Dev =development stage, p=fraction used to calculate readily available moisture (RAM)

4. METHODOLOGY

Determination of Rainfall onset

The analysis of onset, cessation and duration of rainfall involves, computation of seasonal dekadal rainfall values from the entire record, express it as a percentage of the total mean annual rainfall, plot the percentage cumulated seasonal dekadal rainfall values against the decade numbers. The onset of rainfall is then defined as the point of maximum positive curvature of the graph of the cumulative seasonal dekadal rainfall. Duration of rainfall is determined as the period from the onset of the rainfall to the cessation of rainfall. Figure 2 gives spatial distribution of the rainfall onsets in Pangani basin. These dates are assumed the starting date of plantation for this analysis.

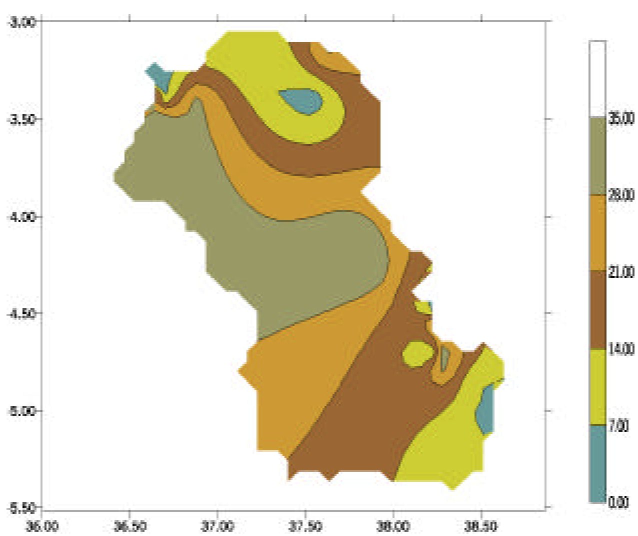

Figure 2: Spatial distribution of onset of rainfall [decades] in Pangani river basin

Distributed Crop Soil Moisture Balance Model (D_CSWB)

The crop soil moisture balance model (CROP_SWB) is a daily-based model with inputs of the major terrestrial and atmospheric inputs of rainfall and evaporation. The model simulates the soil moisture 1km by 1km grid resolution for non-water and non-rocky areas of the basin. The model and its components are outlined from equation (1) to (4).

$$SW_t = SW_{t-1} + R_t - Q_t - AET_t - P_t \quad (1)$$

Where: SW is the daily soil moisture content [mm] at time t, R is the daily amount of precipitation [mm] at time t. Q is the daily amount of runoff (mm). AET is the actual evapotranspiratiom (mm). *P* is the percolation beyond the root zone (mm). t is time step (day).

Surface runoff is estimated using modification of the Soil Conservation Service (SCS) Curve Number (CN) technique.

$$Q_t = \frac{(R_t - 0.2 * s_t)^2}{(R_t + 0.8 * s_t)} \qquad R > 0.2s \qquad (2)$$

$$Q = 0.0 \qquad R \le 0.2s$$

Where Q is the daily runoff, R is the daily rainfall, and s is a retention parameter, all in mm. The parameter s is related to curve numbers (CN) by the SCS equation (USDA, SCS 1972).

$$s = 254\left(\frac{100}{CN} - 1\right) \qquad (3)$$

Evapotranspiration was determined using FAO 1998 Penman-Monteith equation:

$$ET = \frac{0.408\Delta[R_n - G]}{\Delta + g\,(1 + 0.34u_2)} + \frac{g}{\Delta + g\,(1 + 0.34u_2)}\,\frac{900u_2(e_s - e_a)}{(T + 273)} \qquad (4)$$

Where the term R_n is the net radiation, G is the soil heat flux, $(e_s\text{-}e_a)$ represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.

Actual Evapotranspiration, $AET = ET * K_C$, where K_C is the crop coefficient at different growing stages of each crop.

In this section, crop type, soil type and rainfall regimes are integrated together through a soil water balance model to simulate a soil moisture regime assuming one a particular crop at a time. For the crop under consideration, soil moisture balance analysis was done for the entire rainfall record. The analysis starts just before the beginning of the rain season so that the initial soil moisture can reasonably be assumed at wilting point (WP).

Frequency Analysis of Dry-spell

The occurrence of a dry-spell of a critical duration over which crops wilt or start dying is primarily established. The critical duration (t) over which crops start wilting can be established using Equation (5) implemented to calculate the frequency of irrigation application (FAO, 1988). The assumption is that unless water is applied during the critical interval, estimated using the frequency formula (equation 5), the crop would be damaged irrecoverably and failure of crops in that year. The important parameter to estimate the critical duration (t) is then determining the readily available soil moisture (*RAM*) which crops cans uptake moisture without stress. This parameter varies from crop to crop and is represented by a fraction (p) times the difference of soil moisture content at field capacity and wilting point.

$$I = \frac{RAM * D}{ET_{CROP}} \qquad (5)$$

Where the term $RAM = p * (S_{fc} - S_{wp})$ and p is the fraction of total available soil water, which can be used by the crop without affecting its transpiration and/or growth. The term S_{FC} is the available soil water or moisture at field capacity in mm/m. S_W is the available soil water or moisture at permanent wilting point in mm/m. the term D is the depth of the root zone of a crop (m). ET_{CROP} is the consumptive crop water requirement.

Once the readily available soil moisture (*RAM*) and the critical duration are estimated, the *RAM* is compared with the simulated daily soil moisture values. If the available soil moisture to the plant is less than RAM for consecutive number of days equal or greater to the critical duration (t), then that crop would have experienced a critical moisture deficit and hence failure. Theoretically, more than one failure count may exist during the growing season, but from practical point of view, even if a crop fails more than once, it is assumed that that year is a drought year and counted as one failure. In such away, the numbers of failures are counted for the entire record years and divided by the total number of years to get the probability of failure.

5 RESULTS AND DISCUSSIONS

Based on the above procedure, the frequency analysis has been done for three crops. For interpretation of the results, the following general probability condition recommended by Belete (2000) for Ethiopian condition was adapted. If the probability of failure, p (t) is greater than 80%, rain-fed agriculture is practically impossible in the area. For probability of failure greater than or equal to 20% and less than or equal to 80%, rain-fed agriculture may have to be supplemented with irrigation. When the probability of failure is less than or equal to 20%, rain-fed agriculture may be possible without supplementary irrigation.

The grid probability values estimated for each crop have been geo-referenced and transferred into SURFER, GIS software. The probability maps for maize, beans and rice are shown in Figures 4 to 6. From the results it can be seen that rice has the highest probability of failure, followed by maize. Beans has the least probability of failure. It has been noted that rainfed rice cultivation is practically impossible in larger portion of the basin, as the essential conditions of growth, high rainfall and flat slope, were not fulfilled at the same time in most part of the basin. Probability of failure in the majority of the area is above 80%. However, some pocket area such as at the foot of Kilimanjaro Mountain and small portion of northeastern Pangani, near the Kenyan border seems suitable. One has to insure that the area is not reserved for wild life or national forest reserve.

Regarding maize crop, part of the basin north of the Nyumba ya Mungu reservoir and almost all of the north and south Pare area falls within the probability of failure between 20% and 80%. The vast majority of Massai steppe, part of the Usambara area and Kilimanjaro area falls with in the probability of failure less than 20%.

However, it is clearly shown in figure 5 that beans may generally be considered for rainfed agriculture without any supplementary irrigation. The vast majority of the basin except Usambara and small patches of Kilimanjaro exhibits probability of failure less than 20%.

The rainfall in Massai-steppe is low compared to places in the basin. The mean annual rainfall amount is less than 700 mm but almost all the area classified as Massai steppes is considered potentially suitable for rainfed agriculture of both beans and maize. Apart from being short season crop, it has been learnt that beans are high drought resistance crops that can be grown in low water availability area. The high water holding capacity (clay) and the flat slope of Massai steppe (less than 1%) may also contribute for sustainability of rainfed agriculture of these crops. Table 2 demonstrates the influence of each hydrological parameter on the probability of failure of crop.

Table 2. Typical probability of failure values for maize in selected grids of the basin

	Longitude	Latitude	Probability Of failure (p)	Slope (%)	Mar (mm)	Soil class	Grid code
Usambara South East of the basin	38.5531	-4.6703	0.14	10.45	1498.06	B	U1
	38.4712	-4.6794	0.04	5.12	1498.06	B	U2
	38.5895	-4.6885	0.10	10.38	1498.06	B	U3
Upstream of the NYM Reservoir - North	37.2151	-3.0505	0.30	13.03	1214.97	D	R1
	37.1787	-3.0687	0.16	8.83	1214.97	D	R2
	37.1878	-3.0687	0.17	9.08	1214.97	D	R3
Massai areas - south West	37.3334	-3.4418	0.18	0.23	674.806	D	M1
	37.3425	-3.4418	0.18	0.20	674.806	D	M2
	37.3516	-3.4418	0.18	0.16	674.806	D	M3

B=Silt loam and loam *D= clay to silt clay soil*

Examination of arbitrarily chosen grids from different parts of the basin demonstrates that the measure of sustainability should be evaluated from the combined effect of hydrology and physiographic conditions. As can be seen from the above Table 2, despite the variation of slope from 5 to 10 %, of grids U1, U2 and U3, the relative abundance of rainfall (about 1500 mm) is adequate enough for sustainable rainfed agriculture of maize. In the case of grid R2, in spite of the rainfall amount is as high as 1200m, rainfed agriculture couldn't be sustained. This can be attributed to the high slope condition of grid R2. The low rainfall amount shown for grids M1, M2, M3 (less than 700 mm) was not a deterrent for the rainfed agriculture. As seen in table 2, the probability of failure for these grids is less than 20%. It can be attested that the slope factor, which is less than 1 % and the high soil-water holding characteristics of the clay type soil of these grids is attributable to the likely sustainability of rainfed agriculture.

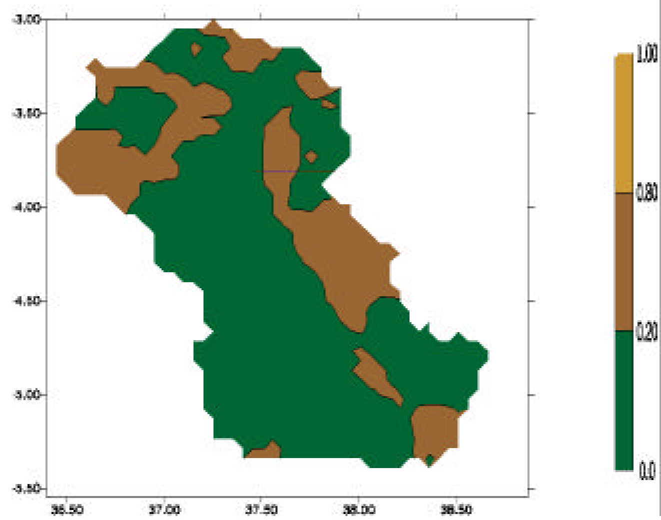

Figure 3: Probability of failure of maize

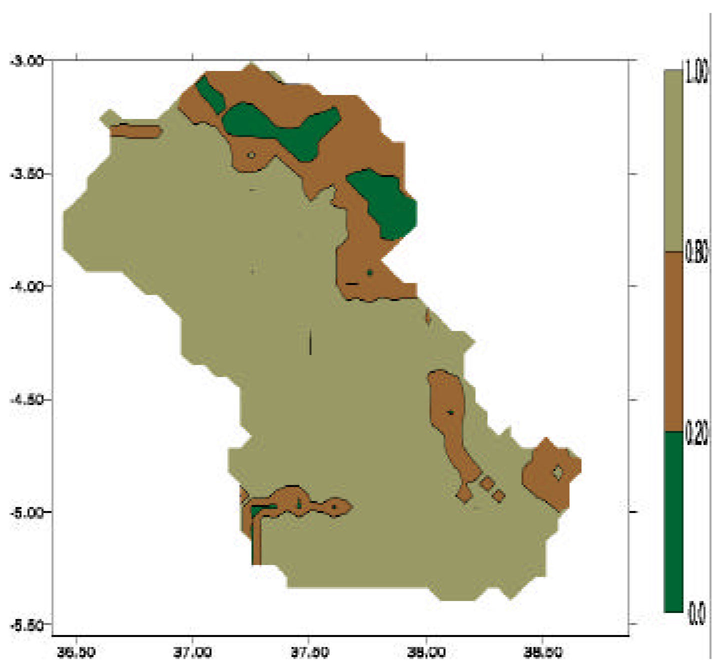

Figure 4: Probability of failure of rice

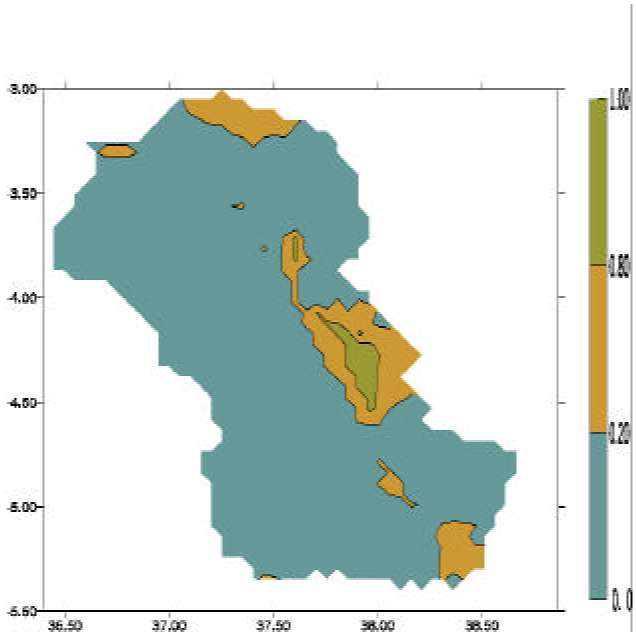

Figure 5: Probability of failure of beans

6. CONCLUSIONS AND RECOMMENDATION

Conclusion

1. Rice agriculture in the basin is virtually impossible without irrigation water supply (Figure 5.) as the probability of failure is predominantly between 80% and 100%.

2. Maize, rain-fed agriculture may be possible in areas such as the Massai-plateau, the Usambara area and patches of area near Moshi as the probability of failure in these areas are less than 20%.

3. Beans are the most suitable crop for rainfed agriculture in the entire basin. The probability of failure is predominantly less than 20% except at the peak area of the mount of Kilimanjaro and north and south Pare.

4. It can generally be concluded that mixed agriculture may be sustainable to produce main food items like rice and maize in the basin. Similar study may be expanded to other basins in Tanzania and African countries at large to create increased awareness to decision makers and farmers themselves that rain fed agriculture alone are no more sustainable option of food production.

Recommendation and Considerations

1. It is recommended that decision makers can use the probability of failure index to set irrigation development priorities in the basin.

2. In basins such as Pangani where there is high water use competitions and scarcity of water, *socio-economic* factor and *water productivity* will have to be considered in the model. In the next generation of the model, the authors are considering to link the socio-economic factor as total future food need in the basin vis-à-vis total food production. This will entail whether intensive irrigation has to be implemented to satisfy the food demand of the basin. Water productivity can be linked to the model through many parameters such as improving water efficiency, using less water consuming and high yield crops and implementing optimum soil water application strategies at the field.

3. This study was a large-scale study and was conducted with the assumption of the whole basin is available for agriculture. However, considerations are underway to further refine the study by incorporating the land use/cover map and variability of rainfall in the basin.

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