Using Pedotransfer Functions (PTFs) to Estimate Soil Water Retention Characteristics (SWRCs) in the Tropics for Sustainable Soil Water Management: Tanzania Case Study

Mdemu, M.V. and ***Mulengera, M.K.***

Department of Agricultural Engineering & Land Planning, Sokoine University of Agriculture, P.O. BOX 3003, Morogoro, Tanzania. E-mail: mulengera@yahoo.com

Abstract: Direct measurement of SWRCs, important for sustainable soil water management are expensive, time consuming, and labour intensive. To overcome these, PTFs have been developed mainly in the developed temperate countries. The PTFs developed using data from soils found in the temperate countries are directly inapplicable to soils found in the tropics. In this paper PTFs developed in Brazil are tested and new ones developed **and tested** using data collected from soils found in the study area. The Brazilian PTFs showed to be un-satisfactory for estimating SWRCs in the study area.The developed regression equations (PTFs) show to be good predictors of volumetric water contents at different matric potentials. The estimation of available water capacity using the PTFs was poor for both the Brazilian PTFs and the PTFs developed using data from the study area. This paper shows that when SWRCs are estimated accurately, crop consumptive water use and yield response can be reasonably estimated. This is useful in assessing the sustainability of soil water management and productivity.
Keywords: pedotransfer functions, temperate countries, water retention, available water capacity.

1 Introduction

Soil water retention capacity is a key soil parameter in soil and water management practices for sustainable and improved agricultural production. Soil water retention capacity is important for both modelling the hydrology of segments of the landscape and for evaluating field soil water regimes in relation to the potential of soil for various uses (Bouma, 1981). Direct measurements of soil water retention capacity are expensive, time consuming and labour intensive. This soil parameter alternatively have to be estimated using available soil data such as particle size distribution, organic matter content, bulk density and soil porosity (McKeague *et al*., 1982; Schaap *et al*., 1999; Young *et al*., 1999). The methods or equations used to estimate soil water retention capacity from available soil data are called pedo-transfer functions (PTFs) (Young *et al*., 1999).

The water retention is primarily dependent upon the texture or particle size distribution of the soil, the structure or arrangement of the particles and clods, bulk density, organic matter content, and other soil properties (Saxton *et al*., 1986; Vereecken *et al*., 1989).

The major work in the development of PTFs has been in the USA and Europe and therefore the soils used have been American or European (Young, *et al*., 1999). The physical, chemical, and biological properties of these soils are different from those of the soils found in the tropics (FAO, 1990). Variations in these soil properties which are the key parameters for PTFs, between the tropical and temperate soils cause direct inapplicability of the existing pedo-transfer functions to other areas such as Sub-Saharan Africa (Gowing and Young, 1996, Young *et al*., 1999).

The only available PTFs developed using data from soils found in the tropics that seem applicable under Tanzanian conditions for estimating SWRCs are those developed by Tomasella and Hodnett (1998) in Brazil. Thus, in this paper, these PTFs are adopted and tested using data from soils found in Morogoro, Tanzania and statistical regression analysis of the measured soil physical, chemical and biological properties vis-a-vis measured SWRCs are carried out to come up with locally accurate PTFs.

2 Materials and methods

2.1 Location of the study site

Field study was conducted at the central part of the Sokoine University of Agriculture (SUA) farm, Morogoro, Tanzania. This part covers approximately 420 ha, and is located at longitude 37° 39′ E and latitude 6° 50′ S. The climate at SUA farm is of sub-humid tropical type (Kaaya, 1989). The onset and distribution of the rainfall are irregular and unreliable. The study area is normally warm throughout the year with an average temperature of 24℃. The mean minimum and maximum temperatures are 18℃ and 30℃, respectively, (Kapele, 2000). The soils found in the study area originate from metasediment rocks made up of mainly pyroxene granulites containing plagioclase and quartz-rich veins (Kaaya, 1989). *Nitisols*, *Luvisols* and *Ferralsols* are the main soil types found in the study area.

A total of 14 profiles located on soils ranging from clays to sands were dug. A total of 51 bulk soil sample were collected, each (about1kg) from each horizon and 3 core samples were also collected from every horizon (Blake and Hartge 1986). The bulk samples were used for texture analysis and organic carbon content determination. Soil texture was determined using hydrometer method (Day, 1965). Organic carbon was determined by wet oxidation method of Walkley and Black (Nelson and Sommers, 1996). Particle density was assumed to be equal to 2.65 g/cm^3. Soil porosity was calculated from the determined bulk density and particle density (Landon, 1991). Two of the three core samples from each horizon were used to determine soil water retention characteristics (SWRCs). The SWRCs were determined using pressure membrane apparatus for suctions of 0.1, 1, 10, and 33 kPa. The same two samples used on the pressure membrane apparatus were transferred to the pressure plate apparatus for determining the SWRCs for suctions of 50, 100, and 1,500 kPa. Soil water retention at 33 and 1,500 kPa were taken to represent field capacity (FC) and permanent wilting point (PWP) water contents. The available water capacity (AWC) was determined as the difference between FC and PWP water contents. These samples used to determine the SWRCs together with the third sample from each horizon were used to determine bulk density after oven drying at 105℃ (Blake and Hartge 1986).

The PTFs developed by Tomasella and Hodnett (1998) for estimating SWRC were tested. This was done at matric potentials of 1, 10, 33, 100, 1,500 kPa, and for AWC. The testing was done using scatter plots and by determining mean differences (MD), root of mean squared differences (RMSD) and the correlation coefficients (R) between measured and estimated values. Microsoft Excel 97 and Microsta programs were used for testing the PTFs and for multiple regression analysis when developing new PTFs respectively.

The applicability of the developed PTFs was tested using data from runoff plots set up at the Agricultural Research Institute (ARI) Hombolo, by Water Harvesting Research Programme (WHRP), Department of Agricultural Engineering, SUA (Hatibu *et al,* 1995*)* and the soil survey report by De Pauw *et al.* (1983). The agricultural institute at Hombolo is located at 35 km north east of Dodoma capital city in the Central semi-arid regions of Tanzania. The data from the WHRP used to test the PTFs were rainfall storm volumes, soil texture, bulk density, and sorghum crop yields for the 1994 and 1995 rainy seasons. The data from the report by De Pauw *et al.*, (1983) were sorghum root and shoot growth characteristics, soil water holding capacities, and potential evapotranspiration (ET_o).

The rainfall storm volumes, runoff volumes, and soil water holding capacity were used to calculate ten days effective rainfall volumes and percolation losses. The ten days effective rainfall volumes were used to calculate actual crop evapotranspiration (ET_a) values. Water available in root zone for each time interval of computation was obtained using water balance equation by adding effective rainfall in the interval to water available at the end of the previous time interval and subtractng ET_a of the previous interval. The ET_a were computed using the assumption that when soil water is half of the AWC the ET_o starts to drop linearly to zero when soil water content reaches permanent wilting point. The model developed by Doorenbos and Kassam (1979), simulating relationship between the ratio of actual crop yields (y_a) over potential crop yield (y_m) and the ratio of ET_a over ET_o was used to check the accuracy of estimating crop yields using ET_a values computed using both, measured and estimated available soil water.

3 Results and discussion

3.1 Testing the tomasella and hodnett (1998) PTFs

The summary results of testing the PTFs developed by Tomasella and Hodnett (1998) are as shown in Table 1. Generally the PTFs would have been good if both R and b were more or less equal to one and the intercept, a, was more or less equal to zero. Thus, the equations are not satisfactory in estimating SWRCs for soils found in the study area.

Table 1 Mean differences (MD), RMSD and R between measured and estimated soil water contents using Tomasella and Hodnett (1998) PTFs

Matric potential (Kpa)	a*	b*	Correlation Coefficient (R)	MD ($cm^3 \cdot cm^{-3}$)	RMSD ($cm^3 \cdot cm^{-3}$)
1	–16.059	1.290 0	0.83	–0.05	0.07
10	3.9038	0.918 6	0.82	0.02	0.05
33	8.4198	0.705 0	0.79	0.02	0.06
100	6.0834	0.808 0	0.81	0.02	0.06
1,500	1.4127	0.880 8	0.94	-0.01	0.04
AWC	10.035	–0.547 5	–0.11	0.02	0.05

* Values are for equation $V_p = bV_m + a$, where V_p is predicted water content and V_m is measured water content

Only soil textures (% clay and silt) were used by Tomasella and Hodnett (1998) to develop the equations for the Brazilian soils. The soil physical properties which have shown to influence soil water retention such as bulk density , structure, and soil organic carbon (Saxton *et al.*, 1986; Vereecken *et al.*, 1989) were not included due to inconsistency of the properties from the data points used in developing the regression equations (Tomasella and Hodnett, 1998).

3.2 Locally derived PTFs

Table 2 shows some of the regression equations locally developed to predict soil water retention for particular matric potentials. Soil water retention at 1 kPa and AWC is shown to be related to clay and organic carbon content. Soil water retention at other matric potentials is shown to be related to the percentage clay, organic carbon and bulk density. Percentage silt has insignificant contribution for most of the developed equations except for regression equation estimating SWR at 1,500 kPa. This is probably due to the fact that the studied soils in the SUA farm have low silt contents (1%—15 %) and this explains the reported poor predictions of the SWRCs using the Tomasella and Hodnett equations.

Table 2 PTFs developed from the study area (values in brackets are the standard error)

Eq. No.	Matric potential (kPa)	Intercept	Clay (%)	Silt (%)	OC (%)	BD (g/cm^3)	R
1	0.1	35.22	0.10 (0.03)		3.09 (1.03)		0.66
2	1	16.19	0.27 (0.03)		5.03 (1.12)		0.89
3	10	–4.37	0.32 (0.04)		5.16 (1.14)	11.84 (5.34)	0.89
4	20	–8.76	0.32 (0.04)		5.36 (1.13)	13.59 (5.30)	0.88
5	33	–12.33	0.31 (0.04)		5.52 (1.12)	15.33 (5.25)	0.88
6	50	–12.62	0.31 (0.04)		5.37 (1.10)	15.06 (5.15)	0.89
7	100	–13.35	0.31 (0.03)		5.01 (1.07)	14.38 (5.01)	0.89
8	1,500	–23.60	0.41 (0.02)	0.03 (0.13)	1.25 (0.65)	16.15 (2.83)	0.97
9	AWC	8.75	–0.09 (0.02)		3.59 (0.89)		0.60

The regression equations slopes, intercepts, and the correlation coefficents show the equations to be good predictors of water content for all the matric potentials (Table 3). The correlation coefficient for the AWC equation is low (see Table 3). Batjes (1996) and van den Berg *et al*. (1997) suggested that predicting AWC is most accurate when direct correlation is made between the differences in measured water content at FC and PWP and easily measured soil physical properties. Testing of this suggestion showed that practically there was no improvement in the correlation coefficient resulting from regressing measured AWCs against those estimated.

Variables used in developing regression equations to predict soil water retention contributed significantly (p<0.05) at all matric potentials except for OC at PWP. This is probably due to the fact that the retained soil water contents at lower matric potentials is more related to soil texture than other properties. The average of the MD between measured soil water contents and those estimated using PTFs was not significantly different from zero (0.0009). Therefore, sufficient estimates of SWR at different matric potentials can be obtained using the PTFs for soils with similar properties used in developing the regression equations. The main limitations of the developed PTFs is the range of soil types used , their spatial locations versus climatic variations and the size of samples. However, the results show that developing locally accurate PTFs using large data base is of potential use in soil and water management.

Table 3 Mean differences (MD), RMSD and R between measured and estimated soil water contents using locally derived PTFs

Matric potential (KPa)	a*	b*	Correlation Coefficient (R)	MD ($cm^3 \cdot cm^{-3}$)	RMSD ($cm^3 \cdot cm^{-3}$)
1	0.000	1.000	0.83	0.020	0.074
10	0.000	1.000	0.88	0.020	0.054
33	0.000	0.000	0.88	0.020	0.057
100	0.000	0.991	0.88	0.018	0.054
1,500	0.000	1.000	0.97	0.007	0.032
AWC	0.000	1.000	0.60	0.012	0.041

* Values are for equation $V_p = bV_m + a$, where V_p is predicted water content and V_m is measured water content

The measured soil water holding capacity at the ARI, Hombolo research plots was 100 mm/m and that estimated using the PTFs was 75 mm/m. The crop yields from the WHRP plots and estimated ratios of actual/expected crop yields over potential yields computed using Doorenbos and Kassam (1979) equation based on crop ET_a rates and measured available soil moisture (y_a/y_m) and those estimated using PTFs (y_{es}/y_m) are shown in Table 4. The regression equations between the ratios and the crop yield are as shown in equations 1 and 2. Although the PTFs were not accurate enough in estimating the AWC, estimation of moisture availability effects on yield show to be comperatively as accurate as those estimated using measured soil moisture. If the accuracy of the PTFs to estimate AWC can be improved (possibly by considering variations in matric potentials at FCs and PWPs for different soils) (Landon, 1991), they can be greatly useful in soil water management modelling; e.g. assessing effects of moisture limitations to crop yields and effects of soil erosion to productivity.

Table 4 Estimated crop yield reduction ratios due to limited soil moisture and the actual crop yield from plots at ARI, Hombolo

y_{es}/y_m		y_a/y_m		Crop yields from plots (t/ha)	
1994	1995	1994	1995	1994	1995
0.8	0.62	0.9	0.7	3.159	2.000
0.8	0.62	0.9	0.7	3.798	1.684
0.8	0.62	0.9	0.7	2.991	1.723

$$\text{Yield} = 7.5683\, y_a / y_m - 3.4955 \quad (R = 0.944) \tag{1}$$
$$\text{Yield} = 8.4092\, y_{es} / y_m - 3.4114 \quad (R = 0.944) \tag{2}$$

4 Conclusion

Pedotransfer function have potential use is soil and water management if developed for certain geographical location using sufficient data base. Soil water retention characteristic as one of the soil's hydraulic properties when accurately estimated, crop consumptive water use and yield response can be reasonably estimated. This is useful in assessing the sustainability of soil water management and productivity.

Acknowledgement

The authors are grateful to SACCAR/GTZ for the financial support in conducting this research work

References

Batjes, N.H. (1996). Development of a World data set of soil water retention properties sing pedotransfer rules. *Geoderma*, 71: 31-52.

Blake, G.R. and Hartge, K.H. (1986). Bulk density. In: Klute, A. *et al*. (eds.) *Methods of Soil Analysis, Part 1*. 2nd Edition. American Society of Agronomy, Inc. Soil Science Society of America, Monograph No. 9, Madison, Wisconsin, USA, 363-375.

Bouma, J. (1981). Soil survey interpretation: estimating using potentials of clay soil under various moisture regimes. *Geoderma*, 26: 165-177.

Day, P.R. (1965). Particle fractionation and particle size analysis. In Black, C.A., Evans, D.D., White, J.L., Ensmingere, L.E. and Clark, F.E. (eds.). *Methods of Soil analysis part 1*. American Society of Agronomy, Wisconsin. pp. 545-566.

De Jong, R., and Loebel, K. (1982). Empirical relations between soil components and water retention at 1/3 and 15 atmosphere. *Canadian Journal of Soil Science*. 62: 343-350.

FAO 1990. *Guidelines for Soil Profile Description*, Food and Agricultural Organization of the United Nations, Rome. pp 70.

Hatibu, N., Mahoo, H. F., Kayombo, B., Mbiha, E., Senkondo, E. M., Mwaseba, D., and Ussiri, D. 1995. Final technical report: Soil and Water Management in Semi-arid Tanzania. Research Project, Sokoine University of Agriculture, Tanzania.

Kaaya, A.K. (1989) *Soil Survey and Land Suitability Evaluation of Central Part of Sokoine University of Agriculture Farm, Morogoro, for Rainfed Crops*. MSc. Thesis, SUA, Morogoro, Tanzania, pp 173.

Kapele, W. (2000). *Establishment of criteria for classification and mapping of soil erosion at farm scale level: Case study of Sokoine University of Agriculture farm, Morogoro, Tanzania*. MSc. Thesis, SUA, Morogoro, Tanzania, pp 93.

Landon, J.R. (1991). *Booker Tropical Soil Manual*: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman Scientific and Technical Publishers. Essex, pp 474.

Nelson, D. W. and Sommers, L.E. (1996). Total nitrogen, organic carbon and organic matter. In: Page, A. L. *et al*. (eds.) *Methods of Soil Analysis part 2*. Agronomy 9: 539-579.

Schaap, M.G., Leij, F.J., and van Genuchten, M. Th. (1999). *Development of pedotransfer functions and related computer programs*. U.S. Salinity Laboratory, Riverside, CA, pp 7.

Tietje, O., and Tapkenhinrichs, M. (1993). Evaluation of pedo-transfer functions. *Soil Science Society of America Journal*, 57: 1088-1095.

Tomasella, J. and Hodnett, M.G. (1998). Estimating soil water retention characteristics from limited data in Brazilian Amazonia. *Soil Science*, 163 (3): 190-202.

van den Berg, M. Klamt, E., van Reeuwijk, L.P., and Sombroek, W.G. (1997). Pedotransfer functions for the estimation of moisture retention characteristics of Ferralsols and related soils. *Geoderma,* 78: 161-180.

Young, M.D.B., Gowing, J.W., Hatibu, N., Mahoo, H.M.F. and Payton, R.W. (1999). Assessment and development of pedotransfer functions for Semi-Arid Sub-Saharan Africa. *Physics and Chemistry of the Earth –European Geophysical Society (B),* Elsevier Science Ltd. 24: 845-849.