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Estimating the Volume of Surface Runoff from *in Situ* Measured Soil Sorptivity

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Abstract: There are many surface water collecting technologies such as water harvesting, micro catchment and spate irrigation. It is still not possible to apply the technologies due to inaccurate estimations of the volume of runoff water. For this reason, we examined the possibility of estimating the volume of runoff using field measured sorptivity. Our experimental field was located in the Oromia region of central Ethiopia. Sorptivity values of different soil moisture contents were measured by a disc tension permeameter. Meteorological data such as rainfall, air temperature, relative humidity, sunshine radiation and wind speed were also measured in the experimental field. A small reservoir was constructed for collecting the surface runoff water from a watershed adjacent to the experimental field. A pressure sensor in the reservoir was installed for observing the volume of actual runoff water. At first, we calculated the volume of runoff with several rainfall events using the Curve Number method introduced by Soil Conservation Services, USDA. Secondly, we estimated the runoff volume for each rainfall event using the measured sorptivity values. Finally, parameters of Chong's model were optimized using the observed runoff volume for each rainfall event resulting in better estimation of runoff volume.

Key Words: Curve Number method, Disc permeameter, Ethiopia, Infiltration, Water harvesting

1. Introduction

Water availability is the main limiting factor in dry-land agriculture, throughout arid and semi-arid regions, due to low annual rainfall depth and its non-uniform temporal and spatial distribution. Water harvesting has been used for thousands of years to supplement scarce water resources in dry areas (Sharma *et al*., 1986). The major advantages of water harvesting are that it is simple, cheap, replicable, efficient and adaptable. Water harvesting can improve soil moisture storage, prolong the period of moisture availability, and enhance growth of agricultural, horticultural and forest crops (Carter and Miller, 1991; Li *et al*., 2000).

On the other hand, Kitanaka *et al*. (2010) conducted irrigation water balance simulation for crop cultivation with consecutive irrigation reservoir system composed of hierarchical reservoirs under unstable rainfall conditions in Ethiopia. These reservoirs using water harvesting technique were used to collect and store precipitation surface runoff so that stored water could be used for supplemental irrigation during long dry seasons. However, the application of water harvesting technologies is still limited due to inaccurate estimating of the volume of surface runoff water. For this reason, we examined the possibility of estimating the volume of surface runoff using field measured sorptivity.

2. Methodology and Study Site

2.1. Evaluation of the volume of Surface Runoff using the Curve Number (CN) method

Runoff estimates are often needed for ungauged watersheds for engineering design of hydraulic structures, watershed the U.S. Department of Agriculture (USDA) - Soil Conservation Service (SCS) developed a method for estimating rainfed runoff volume based on measured total rainfall and direct runoff, and physical watershed features (SCS, 1972). This method is simple to use and requires basic descriptive inputs that are converted to numeric values for estimation of watershed direct-runoff volume. The curve number (CN) method is widely used by engineers and hydrologists as a simple watershed model, and as the runoff-estimating component in more complex, watershed models. The method depends on using measured watershed runoff and rainfall data to develop a CN value that reflects the CN value that should be developed from measured data.

The maximum potential retention(S) can be calculated from the CN value which is able to be determined in considering hydrological, soil property, land use and surface conditions and soil moisture content before runoff occurs (Mishra and Singh, 2003). However, the CN method does not consider rainfall intensity and there are questions as to whether it is applicable for areas outside of the United States (Yamashita *et al*., 2006).

On the other hand, Chong *et al*. (1983) introduced the following Eq.(1) which combining with the SCS rainfall-runoff

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equation and the maximum potential retention(S) of a watershed in order to estimate the value of sorptivity. This equation shows that it is possible to estimate the volume of rainfall runoff from a watershed, if there is a relationship between sorptivity values and initial soil moisture contents.

$$S = \frac{1}{2} R_i^{-1/2} K_{Sat}^{-1/2} \left[Sp(\theta)\right]^2 \cdots (1)$$

where S is the maximum potential retention. $S_p(\theta)$ is soil sorptivity, K_{sat} is saturated soil hydraulic conductivity, R_i: rainfall intensity. The term "sorptivity" was introduced by Philip (1957) in his well-known two-term infiltration equation. As described by Philip, sorptivity, $S_p(\theta)$, is a measure of the uptake of water by soil without gravitational effects. According to the Philip two-term equation, this coefficient is one of the most important soil parameters governing the early portion of infiltration.

Therefore, we tried to clarify the relationship between sorptivity values and soil moisture contents and estimated the maximum potential retention using equation (1) with rainfall intensity and saturated soil hydraulic conductivity. Finally, the estimated surface runoff volumes (Q_{sp}) for each rainfall event were calculated using sorptivity. On the other hand, surface runoff volumes (Q_{CN}) using the CN method were also estimated in order to compare the Q_{sp}.

2.2. Study site and data collection

Our study site (**Fig. 1**) is located in Adami Tule Agricultural Research Center (hereafter ATARC) in the Oromia region, Ethiopia. A water reservoir to measure rainfall runoff volume from a catchment area was constructed in an experimental field with covered plastic film sheet to prevent percolation into soils. In order to measure the water level of this reservoir, a water pressure sensor with a data logger was installed at the bottom of the reservoir. At the same time, we measured the atmospheric pressure using another pressure sensor with a data logger so that we can get a water depth in the reservoir to calculate a difference value of both pressure sensors. Other meteorological data such as air temperature, relative humidity, wind speed, solar radiation and rainfall were also collected in the experimental field. The catchment area is approximately 4400 m^2 (**Fig. 2**). The observation period was from June to December, 2008.

2.3. Measurement of sorptivity using the disc tension permeameter

We fabricated a disc tension permeameter (Smettem and Clothier, 1989) in order to measure water infiltration in the soil, which is characterized by *in situ* saturated and unsaturated soil hydraulic properties. It is mainly used to provide estimates of sorptivity and the hydraulic conductivity of the soil near

Fig. 1. Location map of Adami-Tule agricultural research station.

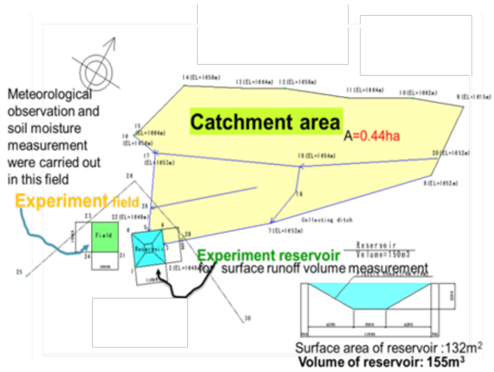

Fig. 2. Layout plan of experimental reservoir, catchment area, canals and experiment field.

saturation. In order to clarify the relationship between sorptivity values and initial moisture contents in soils in the catchment area, we carried out an experiment using the disc tension permeameter near the catchment area located in ATRAC. The steps for measuring sorptivity are as follows: Firstly, surface top soils of in 2 to 3 cm thickness are moved out and a metal cylinder of diameter 15 cm is vertically inserted into soils. The disc tension permeameter with 4 cm suction is installed on the cylinder. After starting infiltration into soils of the metal cylinder, accumulated infiltration amounts at each elapsed time are measured. We also supplied water to surface soil close to the cylinder in order to change soil moisture content of top soils so that sorptivity values under different soil moisture conditions could be measured. Undisturbed soil cores were collected using a 100 cm^3 soil sampler to measure the moisture content of the soil surface close to the cylinder so that the relationship between sorptivity values and initial soil moisture content could be clarified for each sorptivity measurement. **Table 1** shows basic soil properties in the catchment area.

Soil texture was sandy clay loam using the textural triangle classification of the International Society of Soil Science.

Table 1. Soil properties in catchment area.

Dry density ($g\ cm^{-3}$)	Saturated hydraulic conductivity ($mm\ hour^{-1}$)	Soil particle (%) sand	silt	clay	Soil texture (ISSS)	Ignition loss ($g\ g^{-1}$)	$EC_{(1:5)}$ (mS/cm)	pH
0.97	66.3	73.0	10.5	16.5	SCL (sandy clay loam)	0.085	0.223	8.2

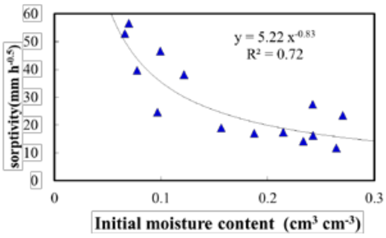

Fig. 3. Relationship between soil moisture content and sorptivity in catchment area.

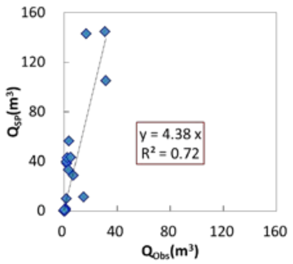

Fig. 4. Comparison between measured (Q_{obs}) and estimated (Q_{sp}) surface runoff volume using sorptivity values.

3. Results and Discussion

3.1. Relationship between soil moisture content and sorptivity value

Figure 3 shows the relationship between soil sorptivity values and moisture contents which was measured in the study site.

Sorptivity values decrease with increasing soil moisture content. The following regression Eq. (2) can be used to determine the value of sorptivity when rainfall event occurs.

$$Sp(\theta) = 5.2239\theta^{-0.831} \cdots (2)$$

where $Sp(\theta)$ is sorptivity, θ is volumetric soil moisture content.

3.2. Comparison between measured and estimated surface runoff volume using sorptivity values

Figure 4 shows the comparison between measured and estimated surface runoff volume using sorptivity values.

There is a tendency between the observed volume of surface runoff and the estimated volume using sorptivity values. However, the method using sorptivity values overestimated the Q_{sp} values of surface runoff and these were four times larger than the Q_{obs}. This led us to develop a more accurate equation to determine maximum potential retention (Eq. (1)) by using the optimal parameter values.

3.3. Comparison of measured and estimated surface runoff volume using the CN method

Figure 5 shows the comparison of measured and estimated surface runoff volume using the CN method. There is large variation in the relationship between the measured and the estimated surface runoff volume using the CN method.

The measured runoff volume was 136 m^3 during the 32 rainfall events. On the other hand, the estimated volume is 698 m^3 which is five times or more than that observed. Therefore, we should consider optimizing the parameter values in Equation (1) in order to optimize the result. Chong and Teng (1986) and Gan (2002) determined the maximum potential retention (S) in order to optimize the parameters in Chong's equation (1). According to their method, we can recalculate the maximum potential retention (S) using optimized parameter values (a, b, c, d) in Eq. (1). The result of recalculation is as follows in Eq. (3);

$$S = 0.0012K_{Sat}^{0.5}R^{0.7}Sp(\theta)^{2.25} \cdots (3)$$

where S is the maximum potential retention, $S_p(\theta)$ is soil sorptivity, K_{sat} is saturated soil hydraulic conductivity, R_i: rainfall intensity. Consequently, substituting each value of K_{sat}, R_i and S_p into the above equation gives the value of S for each rainfall event.

3.4. Comparison of maximum potential retention using observed runoff volume and maximum potential retention using optimized parameters

Figure 6 shows the comparison of maximum potential retention using observed runoff volume S (mm) and maximum potential retention using Eq. (3). Here there is little scatter about the line of equivalent. This result shows good agreement between the observed and the estimated maximum potential retention values. The Residual Mean Square Error (RMSE) has the dimensions of the observations and so the smaller the RSME the better the prediction.

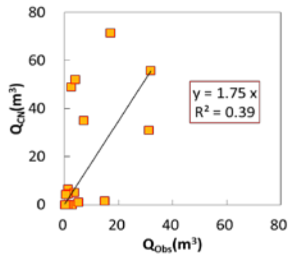

Fig. 5. Comparison of measured and estimated surface runoff volume using the CN method.

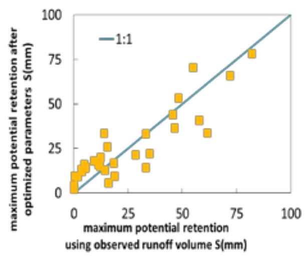

Fig. 6. Comparison of maximum potential retention using the observed runoff volume and maximum potential retention after optimizing parameters (RMSE = 10.5 mm).

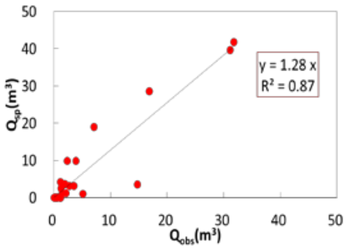

Fig. 7. Comparison of the estimated Q_{obs} and the estimated Q_{sp} after optimizing parameter vales.

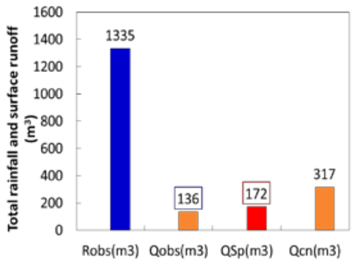

Fig. 8. Comparisons of the observed and the estimated volume during the 32 rainfall events.

3.5. Comparison of the estimated Q_{obs} and the estimated Q_{sp} after optimizing parameter values

Figure 7 shows the comparison between the estimated Q_{obs} and the estimated Q_{sp} after optimizing parameter values.

This result shows good agreement between the observed and the estimated surface runoff volume. After optimizing the parameter vales in Eq. (3), we recalculated the surface runoff volume using two methods which are the CN method and sorptivity value method. **Figure 8** describes the comparisons to the observed Q_{obs} and the estimated surface runoff volume Q_{Sp} for the 32 rainfall events during the observation period. It is seen that the estimated result using the sorptivity value agrees well with the observed surface runoff volume. But the result Q_{cp} using the CN method is less accurate in comparing with using the sorptivity values.

4. Conclusion

It was recognized that there was a relationship between soil sorptivity and soil moisture content in the catchment area. The volumes of surface runoff from each rainfall event could be estimated using sorptivity values measured in the experimental field, however the values were five times larger than those observed. After optimizing parameter values, it was clear that there was a good agreement with between the estimated volume of surface runoff and the observed. Our proposed method which was used by *in situ* measured sorptivity value will be expected to apply to estimations of the surface runoff volume for the water harvesting system in Ethiopia. We also conclude that the concept of sorptivity and its practical field measurement will be very useful in estimating surface runoff volume in this study area. A growing interest in characterizing spatial and temporal variability of soils in catchment areas will likely encourage the use of sorptivity methods which are sufficiently simple and economical to make possible the extensive sampling required.

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References

Carter D.C., Miller S. (1991): Three years experience with on-farm water catchment water harvesting system in Botswana. *Agric. Water Manage*, **19**: 191 - 203.

Chong S.K., Green R.E. (1983): Sorptivity measurement and its application, *Proc. National Conference on Advances in infiltration.* ASAE Publication, Michigan, 82-91.

Chong S.K., Teng T.M. (1986): Relationship between the Runoff curve number and hydrologic soil properties. *Journal of Hydrology*, **84**: 1-7.

Gan T.Y. (2002): Behavior of theoretical curve number with respect to soil and rainfall properties. *Lowland Technology International*, **4**: 21 - 36.

Kitanaka M., Hotta T., Nakamura K., Suzuki S., Nishimaki R., Takahashi S. (2010): Verification study on water collecting characteristic of water-harvesting technique in Ethiopia - Consecutive irrigation reservoir system with water-harvesting for NERICA in semi-arid area (2) - (Japanese). *Journal of Arid Land Studies*, **20**(3):151-158.

Li X.Y., Gong J.D., Wei X.H. (2000): In situ rainwater harvesting and gravel mulch combination for corn production in the dry semi-arid region of China. *J. Arid Environ.*, **46**: 371-382.

Mishra S.K., Singh V.P. (2003): *Soil conservation service Curve Number (SCS-CN) methodology*. Kluwer Academic Publishers.

Philip J.R. (1957): The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil Science*, **84**: 257-264.

Sharma K.D., Pareek O.P., Singh H.P. (1986): Micro-catchment water harvesting for raising jujube orchards in an arid climate. *Trans. Am. Soc. Agric. Eng.*, **29**: 644 - 649.

Soil Conservation Services (SCS) (1972): Section 4, Hydrology. *National Engineering Handbook*, U.S. Department of Agriculture, Washimgton, D.C.

Smettem K.R.J., Clothier B.E. (1989): Measuring unsaturated sorptivity and hydraulic conductivity using multiple disc permeameters. *European Journal of Soil Science*, **40**: 563-568.

Yamashita M., Ichikawa A., Satoh F., Shibata H. (2006): Quantitative approach and problems of river hydrological simulation models. *Japanese Journal of Limnology*, **67**: 267 - 280