Infiltration and Runoff: Point and Plot Scale

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Abstract

Point scale measurements of infiltration and plot scale measurements of infiltration and runoff were made on three, 2 m by 6 m, rainfall simulator plots on an instrumented sub-watershed within the USDA-ARS Walnut Gulch Experimental Watershed (WGEW). Point measurements were made at three different pressure heads using a tension infiltrometer. Plot scale infiltration and runoff measurements were made using a variable intensity rainfall simulator at a range of intensities and two different soil moisture conditions. A distributed, process-based hydrologic model was used along with measured plot characteristics to determine distributed infiltration parameters using the plots as micro-watersheds. The objective of the study was to determine if tension infiltrometer measurements would lead to similar estimates of infiltration and hydraulic conductivity as the rainfall simulator measurements. Differences in infiltration rate and calculated hydraulic conductivity values were found between the two methods. The implications of measurement method, scale, and the complexity of hydrologic processes are discussed.

Keywords: infiltration, runoff, scale, rainfall simulator

Introduction

The relationship between hydrologic processes and scale is one of the more complex issues in surface water hydrology. Infiltration processes are often measured at the point or plot scale while landuse managers and hydrologic models often are interested in rainfall-runoff processes at the hillslope or watershed scale. The measurement of the infiltration process and quantification of its spatial variability is difficult due to inherent differences with the measurement methods and the scales at which they are applied (Merzougi and Gifford 1987, Paige and Stone 1996). In general, the spatial variability of infiltration decreases with increasing measurement scale (Sisson and Wierenga 1981) and its importance and impact on runoff and erosion decreases as the magnitude of the rainfall increases (Goodrich 1990).

Goodrich et al. (1996) presented a good relationship among hydraulic conductivity estimates from tension infiltrometer, rainfall simulator, and small catchment measurements on the Lucky Hills brush dominated rangeland site. These estimates were determined from different studies conducted on the same rangeland site, but not the same locations. For this paper, two of those measurement methods were used to measure infiltration on the same locations on a semiarid rangeland watershed. The methods, a tension infiltrometer and a variable intensity rainfall simulator measure infiltration at different scales and under different conditions.

The objective of the study was to determine if point measurements of infiltration distributed over a rainfall simulator plot using a tension infiltrometer and rainfall –runoff measurements from a rainfall simulator on these same plots would yield similar estimates of infiltration and hydraulic conductivity. Tension infiltrometer measurements were made within three of five rainfall simulator plots on an instrumented grassland sub-watershed. The results from the two methods are compared and evaluated with each other in the context of rainfall-runoff process at the hillslope and watershed scales.

Methods

The research for this study was conducted on Kendall watershed 112 within Walnut Gulch Experimental Watershed (WGEW). Kendall 112 is a zero order grassland

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watershed of 1.91 hectares with an average slope of 9.4%. Kendall 112, as well as the entire WGEW, is within the Natural Resources Conservation Service (NRCS) Major Land Resource Area (MLRA) 41-3. It is classified as a Loamy upland - Limy slopes. Loamy upland is the dominant classification with inclusions of Limey slopes. The soils are mapped as an Elgin-Stronghold complex. In general, the soil complex is classified as a gravelly fine sandy loam with slopes ranging anywhere from 3 to 30 percent (NRCS 1993). The average measured soil bulk density is 1.40 g/cm^3.

Lane et al. (1995) identified three overland flow paths, one on each of the three hillslopes within the sub-watershed. Each profile originates at the upper boundary of the hillslope and terminates at the outlet of the watershed. Infiltration measurements were made along profile 1 using a disc permeameter to determine the variability of saturated hydraulic conductivity (Ks) along the profile (Gallo 2000). The resulting infiltration rates and Ks values from the ponded infiltration measurements were very high (70 to 330 mm/h).

Rainfall simulator experiments were conducted on five 2 m by 6 m rainfall simulator plots using a variable intensity rainfall simulator that applies intensities between 50 and 178 mm/h. Plots 1-3 were installed along profile 1 and plots 5 and 6 were installed on an adjacent hillslope, along profile 2. The vegetative canopy and surface ground cover were measured at 480 points on each plot. Two rainfall simulator runs, a dry run under initial soil moisture conditions and, one hour later, a wet run, were conducted on each plot using the prototype of the Walnut Gulch Rainfall Simulator (WGRS) (Paige et al., in review). For each simulator run, the rainfall application was continuous and started with the higher intensities and decreased incrementally to 50.8 mm/h. Each rainfall intensity was applied until steady state runoff was maintained for a minimum of 5 minutes. The steady state infiltration rate was calculated for each rainfall intensity by subtracting the observed steady state runoff rate from the applied rainfall intensity (Paige et al. 2002).

Point scale infiltration measurements were made on three rainfall simulator plots along profile 1 (Plots 1-3) using a tension infiltrometer. Measurements were made at three different negative supply heads, 3 cm, 5 cm, and 10 cm and were made at a minimum of three locations down the length of each plot using all three pressure heads. The measurements were made on "soil" areas within each plot. Loose gravel and litter were removed, being careful not to disturb the soil surface. Infiltration rates were measured continuously at a single location starting with a 10 cm negative pressure head. Once steady-state infiltration was observed, the pressure head was changed. Initial and final soil moisture measurements were made using gravimetric samples.

Hydraulic conductivity parameters

Hydraulic conductivity parameters were determined using the steady-state infiltration rates from the infiltrometer and rainfall simulator measurements. The method used to calculate the hydraulic conductivity from tension infiltrometer infiltration measurements was presented in Reynolds and Elrick (1991). The unsaturated hydraulic conductivity, $K(\Psi)$, is determined from two or more measurements (Q_1, Q_2, Q_3,…) made at different supply heads (ψ_1, ψ_2, ψ_3,…) at the same location.

The hydrologic simulation model KINEMAT, a research version of the KINEROS2 (Smith et al. 1995), using the Green-Ampt Mein-Larson (GAML) equation (Mein and Larson 1973). The model was used as a tool to determine the effective hydraulic conductivity term (K_e) using the data from the rainfall simulator experiments (Paige et al. 2002).

Two different sets of K_e values were determined for each plot. Each plot was parameterized and modeled as a single plane using a plot average K_e values. The plots were also parameterized using a strip model approach, with the flow length of the planes oriented parallel to the direction of flow. In this case, the parameters and K_e values for each plane were based on the measured plot cover characteristics and the observed runoff rate. For the bare soil areas, the K_e value was determined from the observed time to ponding. In both cases, the K_e values were determined using the measured runoff volume from the dry runs and validated using the runoff volumes for the wet runs. Details of the methods used to determine the hydraulic conductivity values and plane discretizations for each of the plots using the model were presented in Paige et al. (2002).

Results and Discussion

There was a large range in infiltration rates from the point scale measurements made using the tension infiltrometer. The infiltration rates are lowest for the 10 cm pressure head and increase with decrease in negative pressure head as one would expect (Table 1). The infiltration rates not only varied among plots and among pressure heads but the Coefficient of Variability (CV) of the replicates ranged from 0.01 to 0.76. Plot 3 had the lowest average infiltration rates for each of the pressure heads but the highest CVs.

Table 1. Average infiltration rates from the tension infiltrometer measurements on the 3 plots. The CV is in parentheses.

	infiltration rate (mm/h)		
Tension	Plot 1	Plot 2	Plot 3
10 cm	6.2	10.5	4.9
	(0.05)	(0.23)	(0.76)
5 cm	16.2	26.9	12.6
	(0.01)	(0.22)	(0.23)
3 cm	29.9	41.4	19.2
	(0.20)	(0.26)	(0.28)

The relationship between the applied tension and the measured infiltration rates for the three plots is presented in Figure 1. Fitted power functions are used to illustrate the relationships among the plots. The infiltration rates on plot 2 were consistently higher than the other 2 plots. The rates from the 10 and 5 cm tensions for plots 1 and 3 are similar; however, the fitted curve for plot 3 is flatter and there is an increased difference as the tension decreases.

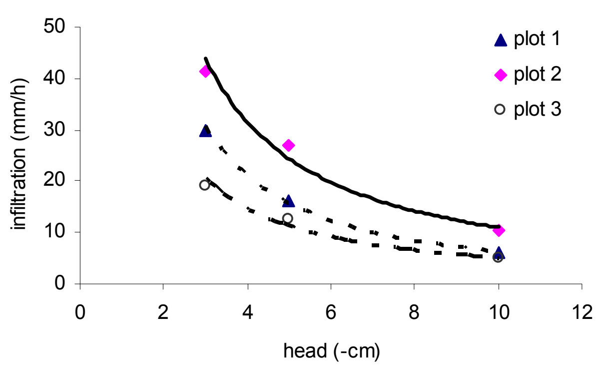

Figure 1. Tension - infiltration curves from the point measurements.

The steady-state infiltration rates from the rainfall simulator experiments were determined for each rainfall intensity applied for both the dry and wet rainfall simulator runs. The steady state infiltration rates from the rainfall simulator runs increased with increasing rainfall intensity indicating the spatial variability of the infiltration capacity across the plot (Hawkins 1982, Paige et al. 2002). The rates were higher for the dry runs than for the wet runs as expected due to the differences in antecedent soil moisture, and there was a difference among plots in the range of infiltration rates (Table 2). An infiltration rate equal to the rainfall intensity means that there was no observed runoff and that the infiltration capacity is greater than the applied intensity for that antecedent moisture condition. The fact that the infiltration rate was still increasing at the higher application rates indicates that even at 177.8 mm/h there are portions of the plots that are not contributing to the measured runoff and have an infiltration capacity greater than 177.8 mm/h.

Table 2. Steady state infiltration rates as a function of rainfall intensity calculated from the rainfall simulator experiments for the dry and wet runs.

	Rainfall intensity (mm/h)	Dry run Infiltration (mm/h)	Wet run infiltration (mm/h)
Plot 1	177.8	93.8	57.0
	127.0	65.3	42.9
	76.2	42.2	35.8
	50.8	38.9	33.3
Plot 2	177.8	121.7	101.3
	127.0	98.9	83.3
	76.2	72.9	68.2
	50.8	50.8	50.8
Plot 3	177.8	80.6	61.9
	127.0	67.2	47.2
	76.2	58.7	42.2
	50.8	50.8	38.9

Hawkins (1982) suggested a relationship between the infiltration rate, $f_s(i)$ (mm/hr), and application rate, i (mm/hr), assuming an exponential distribution of infiltration capacity over an area as

$$f_s(i) = u_f\left(1 - e^{-\frac{i}{u_f}}\right) \tag{1}$$

where u_f (mm/hr) is the average aerial infiltration rate when the entire area is contributing to runoff. This relationship is illustrated in Figure 2 using the results from the wet rainfall simulator runs. The infiltration rates from plot 2 are consistently higher and the intensity - infiltration curve is increasing even at the high intensities. The curves from plots 1 and 3 are very similar and appear to level out at an intensity of about

180 mm/h. This indicates a plot average infiltration capacity of approximately 50 mm/h.

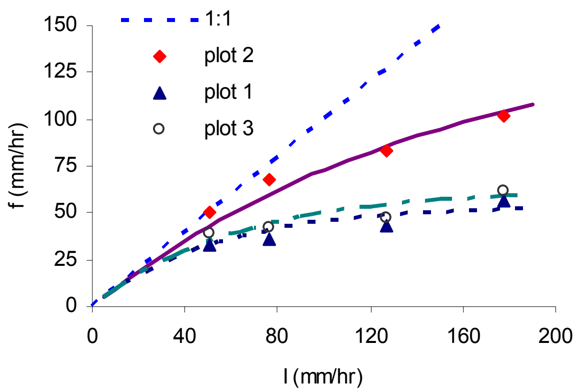

Figure 2. Intensity - infiltration curves from the wet rainfall simulator runs.

Tension infiltrometers measure infiltration at the point scale, in this case a 314 cm^2 area, using a constant pressure head. The infiltration rates determined using the rainfall simulator are averaged over a larger area (12 m^2- in this case) and the pressure head at the soil surface is spatially varied.

The point infiltration rates measured with the tension infiltrometer are, in general, much lower than the plot average infiltration rates calculated from the rainfall simulator runs. For plot 1, the average infiltration rate at 3 cm of tension (29.9 mm/h) is just slightly lower than the 33.3 mm/h infiltration rate for the wet run on plot 1 at 50.8 mm/h intensity. The same relationship held true for plot 2 as well, but not for plot 3. There does appear to be a common trend in both measurement results. The measured infiltration rates for both methods are higher for plot 2 than plot 1 or 3 and the resulting rates from plots 1 and 3 are very similar. This is evident in Figures 1 and 2.

Hydraulic conductivity

The range of average hydraulic conductivity values calculated from the tension infiltrometer measurements was similar to the infiltration rates as one would expect. The values range from 4.1 mm/hr on plot 1 at 10 cm of tension to 33.7 mm/hr on plot 2 at 3 cm of tension (Table 3). The CVs ranged from 0.07 to 0.46, a smaller range than for the infiltration rates (Table 1); however, they still indicate a significant amount of variability among the measurements.

Table 3. Average hydraulic conductivity from the tension infiltrometer measurements on the 3 plots. The CV is in parentheses.

	hydraulic conductivity (mm/h)		
Tension	Plot 1	Plot 2	Plot 3
10 cm	4.1	6.4	4.2
	(0.15)	(0.23)	(0.46)
5 cm	12.4	21.1	8.6
	(0.07)	(0.12)	(0.26)
3 cm	28.0	33.7	15.6
	(0.31)	(0.27)	(0.40)

The hydraulic conductivity values calculated from the dry runs of the rainfall simulator experiments were in general, much higher than those from the tension infiltrometer (Table 4). The single plane K_e values are very high, 26.7 to 52 mm/h, and the multiple plane K_e values range from 12 mm/h to greater than 178 mm/h. As with the results from the tension infiltrometer, plot 2 had the highest K_e values. The single plane values were similar for plot 1 and 3 for the single plane; however, the values for the multiple plane configurations are very different.

Table 4. Hydraulic conductivity values determined from the dry runs of the rainfall simulator experiments. The representative areas for each plane are in parentheses.

	hydraulic conductivity (mm/h)		
	Plot 1	Plot 2	Plot 3
Single plane	26.7	52.0	28.0
Multiple plane Bare soil area	26.7 (9.0%)	33.2 (13.3%)	12.0 (58.3%)
Cover area	22.9 (82.25%)	58.8 (77.3%)	102.0 (41.7%)
Shrub area	NC* (8.75%)	NC (9.4%)	N/A**

* NC means that the plane has a K_e value greater than the applied rainfall intensity and is therefore not contributing to runoff.
** Plot 3 had no shrubs.

The K_e values from the rainfall simulator experiments were not calculated directly from measured infiltration rates but indirectly by matching the measured runoff volume using the hydrologic simulation model (Paige et al. 2002). This is especially important to note when evaluating the single plane K_e values. These values represent the average conductivity rates for these plots for a large range of rainfall intensities (50 to 177 mm/h) that were applied during each simulator run. Using these plot average parameters in the simulation model, the runoff volume was matched however the runoff hydrograph was overestimated for the peak flow at the highest intensity and underestimated at the low intensities (Paige et al. 2002).

The K_e values for the multiple plane configurations show the same relationship among the plots. The values for plot 2 are consistently higher. The multiple plane approach resulted in large range in K_e values for each plot and in general a much better fit of the observed runoff hydrographs for both the dry and wet simulations (Paige et al. 2000). From the calculated infiltration rates (Table 2), it was known that there were portions of each plot that were not contributing to the observed runoff. Therefore, it was assumed that the shrub portion of each plot had an infiltration capacity greater than the highest applied intensity (Paige et al. 2002).

There is overlap in the K_e values from the tension infiltrometer and the derived values for the multiple plane configurations; the 5 and 3 cm values ranged from 9 to 34 mm/h while the bare soil and cover area values ranged from 12 to 102 mm/h. The 10 cm results were much lower than any of the parameters determined from the rainfall simulator experiments, indicating that the infiltration rate of the soil during rainfall is greater than the measured infiltration rate at this tension. In general, there is no clear relationship between the results from two methods and their application range at this site.

The K_e values from the tension infiltrometer and rainfall simulator measurements were both determined from steady state infiltration rates on the same plots; however, they were determined from different methods, measuring different processes at different scales at a range of tensions and intensities. The tension infiltrometer directly measured the infiltration rate of the soil under different pressure heads over a 314 cm^2 area, while the rainfall simulator indirectly measured the infiltration rate of the soil and vegetation components of the plot over a 12 m^2 area.

Both methods have advantages and limitations. Point measurements using a tension infiltrometer can be used to quantify the variability of infiltration within an area, however, they do not account for the runon-runoff processes that can occur during rainfall infiltration. The rainfall simulator results are plot averages and do not necessarily reflect the variability of infiltration capacities that can occur within the plot. However, by using a range of rainfall intensities, one is able to define the range of infiltration rates for that plot. Results from several plots (3 to 6) across a hillslope should be able to characterize the ranges in infiltration and runoff from a large range of rainfall intensities.

In an earlier study, Goodrich et al. (1996) presented good agreement between the tension infiltrometer and rainfall simulator results from Lucky Hills. The results, however, were from a single intensity (60 mm/h) rainfall simulator run and a single tension infiltrometer measurement at 5cm of tension. In this study, the methods were applied at a range of application rates or tensions. Though there is a correspondence between the infiltration rates at 3 cm tension and an intensity of 50.8 mm/h, the relationship between the measurement tension and rainfall intensity is still unclear. A modeler does not know apriori to use an infiltration parameter from 7 cm or 4 cm of tension to parameterize a simulation model.

Conclusions

The results from both measurement methods illustrated the variability of infiltration rates within the rainfall simulator plots, as well as the differences in infiltration rates among the plots. However, it evident from the results that the two methods are measuring different processes and that the merits of one method over another would be application dependent.

To measure the infiltration rate of the soil and quantify its spatial variability across an area, point measurements using a tension infiltrometer could be used. The measurements are simple and easy to make and do not require a lot of resources. However, the relationship among these measurements and the infiltration and runoff processes at the plot scale and larger is still unknown.

Plot scale measurements using a variable intensity rainfall simulator are expensive, time consuming, and require more personnel than the tension infiltrometer measurements. However, significant information can be obtained from these measurements in terms of the infiltration, runoff, and erosion processes that occur at the plot and hillslope scale. Land use managers are interested in sustaining the long-term productivity of the soil and vegetation resources; this includes minimizing runoff and soil loss, and increasing infiltration and biomass. The productivity of a site is often evaluated at the hillslope scale.

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