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Measurement Methods to Identify and Quantify Spatial Variability of Infiltration on Rangelands

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Abstract

This paper summarizes the current state of the art in measuring the spatial variability of infiltration on rangeland watersheds. Infiltration is known to vary extensively across spatial and temporal scales due to heterogeneities in the soil properties as well as the vegetation and cover characteristics. Studies conducted to measure the spatial variability of infiltration on rangelands have found that the ability to measure the spatial variability of infiltration is a function of both the method and the scale of measurement. Current measurement methods are primarily conducted at point or small plot scale and measure either saturated (ponded) infiltration or unsaturated (rainfall) infiltration. The benefits and limitations of these methods as well as areas for future research are discussed.

Introduction

Hydrologic processes which occur on rangelands are highly variable in space and time due to the nature of the climatic input, topography, soils, and vegetation. Infiltration, an important component of the rainfall-runoff process, is significantly affected by both the temporal variability of rainfall and snow melt and the spatial variability of soil and vegetation properties. The hydrologic response of an area is influenced significantly by the characteristics and areal extent of the cover and soil variability. Rangeland vegetation is composed of communities or complexes of species and can include trees, shrubs, grasses and forbes, each which influence the soil surface and sub-surface characteristics in a different manner. A single infiltration rate or a lumped average is often used to define the infiltration capacity of a watershed without considering the location of areas of high and low infiltration capacity (Morin and Kosovsky, 1995). Lumping of distributed parameters can lead to distortions in the results of distributed process based models (Lane et al., 1995). Measurement of the variability of vegetation and soil properties is relatively easy, quantifying the effects of that variability on the infiltration process and subsequent impacts on runoff generation is much more difficult. This is due in part to difficulty in measuring the infiltration process.

Spatial variability is first attributed to the inherent heterogeneity of the rangeland infiltration characteristics, and second to the method of measurement itself (Jury, 1985; Aboulabbes, 1984; Merzougi, 1982). The scale of infiltration measurement has ranged from watershed studies using natural rainfall, to large and small plot studies using a variety of rainfall simulators, to point studies using infiltrometers (Branson et al., 1972). Many of the point infiltration methods are now being used to characterize the spatial variability of infiltration across an area. Infiltrometers and rainfall simulators are the two predominant methods which have been

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used to measure infiltration and its spatial variability on rangelands, though other methods have been used. Both methods have limitations in their ability to simulate infiltration as it occurs under natural rainfall conditions.

Since the 1980s, a number of studies have used point measurements with geostatistics in an attempt to quantify the spatial variability of hydrologic processes (Bosch and Goodrich, 1996). Point measurements can be limited in their ability to characterize the spatial variability of infiltration in relationship to hydrologic characteristics such as topography, elevation, soil, and other watershed characteristics. Other important factors which need to be considered are: 1) the portion of the measurement area or watershed contributing to infiltration and runoff (partial area contribution); 2) the method and scale of measurement; and 3) the sampling design (random, grid, transect, irregular spacing).

Field Observations

Infiltrometers

The majority of the studies conducted to measure the spatial variability of infiltration across a watershed have used point measurements such as ring infiltrometers or disk permeameters. These types of measurements have several advantages: the infiltration rate is measured directly, the measurement time is relatively quick, and the cost of the experiment is low so that many measurements can be made. A summary of the studies reviewed which were conducted using infiltrometers is presented in Table 1.

One of the first studies to measure the spatial variability of soil hydraulic properties in the field was conducted by Nielsen at al. (1973). Steady state infiltration measurements were made at twenty 6.5 m square plots. The infiltration rate varied from 0.5 mm/hr to 50 mm/hr, with a CV of 91%. Steady infiltration rate fit a log-normal distribution; the infiltration rate was highly correlated with the percent saturation, but not correlated with water content. Sharma et al. (1980) used a double ring infiltrometer (inner ring diameter of 46 cm) to measure the spatial variability of infiltration and sorptivity at the R-5 watershed near Chickasha, Oklahoma. Measurements were made at 26 sites in the watershed in a regular grid pattern with a spacing of about 60 m. Steady state infiltration rates were always reached within 60 min. No obvious pattern in the distribution of the infiltration parameters was found with respect to soil type or position in the watershed. The frequency distribution, however, was found to be log-normal. Subsequent studies using infiltrometers have also found that the results were best described by a log-normal distribution (Sharma et al., 1983; Loague and Gander, 1990; Achouri and Gifford, 1984; Merzougi and Gifford, 1987; Grah et al., 1983).

Variability studies of infiltration have used both classical statistics and spatial statistics to describe the variability and resulting distributions of the measured values (Bosch and Goodrich, 1996). The coefficient of variation (CV) has commonly been used to describe the variability of infiltration capacity (Warrick and Nelson, 1980) which characteristically has a large CV (Tables 1 and 2). The CV, however, is only an indicator of the extent of and not the distribution of the variability over an area. In order to describe the spatial distribution of the variability, researchers began to use geostatistical methods. Geostatistical methods and kriging had been successfully used to determine the spatial variability of infiltration and sampling requirements on an agricultural field in Davis, California (Vieira et al., 1981). When applied to rangeland watersheds, geostatistical methods have often found correlation lengths ranging from several meters (Aboulabbes et al., 1985; Grah et al., 1983) to no variance structure at all (Merzougi and Gifford, 1987; Achouri and Gifford, 1984). The scale of the measurement used in proportion to the sample spacing and the size of the area being measured has been found to be very important in determining the spatial variability.

Geostatistical methods were used to determine the optimum sampling procedure at R-5 watershed, based on 50 initial steady-state infiltration measurements made along a transect at 5-m intervals (Loague and Gander, 1990). A total of 157 measurements were taken across the watershed using a 25-m grid spacing based on the range suggested from the semivariogram of the initial transect. A final transect of 40 steady-state measurements was made at 2-m intervals. They found that the range of spatial persistence for infiltration on the R-5 catchment was very small and that the 25-m grid was not sufficient to map the infiltration variability. The scale of spatial correlation between measurements was found to be less than 20-m.

Achouri and Gifford (1984) and Merzougi and Gifford (1987) used a 2-m interval sampling grid on grazed and ungrazed sites in Utah. Each study used a double ring infiltrometer to measure 70 and 104 locations at each site, respectively. The results from both studies suggest that the infiltration rates are randomly distributed for the sample interval of 2 m. In each case kriging could not be used to interpolate between measurements as no variance structure was found to exist.

Grah et al. (1983) investigated the distribution of infiltration relative to slope position and overland flow paths on a small watershed on the Wasatch plateau in central Utah. Infiltration rates were measured at 5 minute intervals using double ring infiltrometers. The infiltration rate was highly correlated with both vegetation cover and soil bulk density for all sampling times. A significant relationship was found between 55 minute infiltration rates and overland flow distance. The range of spatial correlation increased with an increase in infiltration time from 3.4 m at the 1 minute interval to 17.4 m at the 55 minute interval along the flow path. This suggests that the spatial correlation of infiltration rate varies with time during the infiltration process, becoming more homogeneous over time as the affect of the suction term in early infiltration decreases with the increasing soil moisture.

Aboulabbes (1984) compared the semi-variograms from two different transects on the same watershed in Morocco. Steady state infiltration measurements were made with double ring infiltrometers at 1 m intervals along both transects. The two transects had significantly different space dependence structure, indicating that neither one could be used to represent the spatial variability of infiltration across the watershed. A Gaussian model, used for one of the transects, showed a spatial correlation distance of 18 m. The other transect could only be fit with a linear model using 25 m of the transect. In general, all the semi-variograms indicated a large nugget effect and a spatial correlation structure over a very short distance.

Other Infiltrometer Methods

Disk permeameters and tension infiltrometers (White et al., 1992; Elrick and Reynolds,

1992) are variations of the cylinder infiltrometer method. The infiltration rate into the soil surface can be measured under ponded (disk permeameter) or unponded (tension infiltrometer) conditions. Whitaker (1993) measured infiltration at 10 m intervals along a 300 m transect on the Walnut Gulch Experimental Watershed in southeast Arizona using both a disk permeameter and a tension infiltrometer. Measurements, with both the disk permeameter and the tension infiltrometer, were made at each site approximately 20 cm apart within a 5-day period. The disk permeameter was used with a positive hydraulic head of 0.5 cm and the tension infiltrometer was set at a hydraulic head of -5 cm. An average infiltration rate of 266 mm/hr with a standard deviation of 231 and a CV of 87 % was found for the 30 sites using the disk permeameter. The average infiltration rate using the tension infiltrometer and a -5 cm head was 53.8 mm/hr with a standard deviation of 22 and a CV of 42 %. The CV for infiltration was much lower with the tension infiltrometer than the disk permeameter, though the average initial moisture contents were similar. The average infiltration rate measured with the tension infiltrometer is comparable with infiltration rates determined using WEPP (Water Erosion Prediction Project, USDA, 1995) rainfall simulator plots on the same watershed. The infiltration rates from the rainfall simulator varied from 49 to 57 mm/hr for the dry, wet, and very wet runs, with an average of 53.2 mm/hr.

Rainfall Simulators

Infiltration measurements on rangelands using rainfall simulators usually measure the infiltration rate indirectly. The steady state infiltration rate is often calculated as the difference between rainfall application rate and the equilibrium runoff rate. The initial infiltration rate is assumed to equal the application rate until runoff commences. The rainfall simulator plots have varied in size from 1 m^2 to over a hectare (Meyer, 1994). Small simulators are often used as ponded infiltrometers, taking measurements at several locations across an area to determine the spatial variability of infiltration. Studies using large simulators, such as the rotating boom simulator used in the WEPP studies, often measure the variability of the cover characteristics within plots and relate it to the calculated infiltration rates. A summary of the studies reviewed which were conducted using small rainfall simulators and disk permeameters is presented in Table 2.

Small Simulators

Aboulabbes (1984), and Merzougi and Gifford (1987) compared infiltration measurements from ponded infiltrometer rings with those from a modular rainfall simulator plots under both wet and dry conditions. Both methods exhibited large variability in infiltration rates across the watershed (Table 2). Infiltration rates were found to be exponentially distributed in most cases. As expected, a significant difference was also found between the two methods. The ponded ring infiltration rates were much higher than the modular simulator except at very low application rates. The infiltration rates from the double-ring infiltrometers were significantly affected by initial moisture conditions. The results of the autocorrelation and semi-variogram analyses conducted were similar to the results found by Achouri and Gifford (1984). Merzougi and Gifford (1987) found that the infiltration measurements were not spatially correlated, i.e. there was a complete lack of variance structure and the measurements were all independent. Only 18-36% of the variance could be explained by cover characteristics. A significant difference was found however, between grazed and ungrazed sites and between rainfall simulator and double ring infiltrometer measurements. The infiltration rates measured with the double ring infiltrometer were 2 to 3 times higher than the rates determined by the rainfall simulator. These results are similar to the findings of Aboulabbes et al. (1985).

Springer and Gifford (1980) found the distribution of measured infiltration rates for a site in south western Idaho could be described by either a normal or a log-normal distribution. Data reported by Gifford and Busby (1974) were used to describe the spatial distributions of infiltration. A sprinkler infiltrometer was used to measure infiltration rates in twenty four 0.23 m^2 plots over a five year period on thirteen dates. The sprinkler infiltrometer was run for a 25 minute period at an intensity of 76 mm/hr. The average infiltration rate varied from 56 mm/hr to 28 mm/hr, while the CV varied from 0.68 to 0.34 over the 5 year period. The results were similar to those predicted by Rao et al. (1979).

The Green and Ampt (1911) infiltration equation, or some modification of it (Mein and Larson, 1973; Chu, 1978), is often used to determine infiltration parameters from rainfall runoff field studies in spatially varied rangelands (USDA, 1995; Kidwell et al., 1996). Devaurs and Gifford (1986) used the Green and Ampt infiltration equation with parameters determined from field data and soil textural properties to characterize infiltration on spatially varying rangelands. Using a least squares method to fit the field data, they found limitations in the ability of the Green and Ampt equation to describe the observed variable infiltration patterns on rangelands. When using Green and Ampt parameters predicted from soil texture data, the method was most appropriate for disturbed sites with infiltration rates less than 30 mm/hr.

Simulated rainfall was also used to compare infiltration rates and erosion at 28 study sites in 5 different watersheds in the Great Basin area of Nevada (Blackburn, 1975). Infiltration rates were positively correlated with slope and negatively correlated with soil moisture. Percentage of large diameter (>2 in.) rock cover was poorly correlated with infiltration; whereas, the percent small diameter rock cover was positively correlated with infiltration. Percent bare ground was strongly correlated with infiltration rates. Poesen et al. (1990) found soil surface rock cover increases the infiltration rate into the soil, and the effect of the rock cover on the infiltration rate is proportional to the percent cover.

Large simulators

The rainfall application rate is an important factor to consider when using rainfall simulators to determine the spatial variability of infiltration at both the point and plot scales (Aboulabbes et al., 1985; Hawkins, 1982). A comparison between point and plot scale measurements using rainfall simulators found that the point measurements were unable to describe the infiltration at the plot scale at low rainfall intensities (Cundy, 1982). The ability of the point measurements to describe the infiltration processes at the plot scale improved at higher rainfall intensities. Dunne et al. (1991) found that infiltration rate varied with flow depth, and that rainfall intensity had a strong effect on the apparent infiltration rate on short hill slopes. Rainfall intensity influenced flow depth along the slope and therefore had a secondary effect on the spatial pattern of infiltration. The apparent infiltration was also found to be affected by the microtopography, as well as the hill slope length and gradient. At high rainfall intensities the onset of runoff is more likely to be determined by the rainfall intensity.

Lane et al. (1987) used a rotating boom rainfall simulator to measure infiltration and evaluate the effects of cover characteristics on infiltration. They found final infiltration rates decreased as the vegetative canopy cover and rock and gravel cover decreased. Tromble et al. (1974) found that the soil- vegetation complex and antecedent moisture had a significant effect on infiltration rates. Tisdall (1951) found antecedent soil moisture had a significant effect on infiltration rate. Bolton et al. (1990) found vegetation had a slight, but significant, effect on infiltration rates. Busby and Gifford (1981) and Simanton et al. (1991) found that removing canopy cover had little direct effect on infiltration and runoff processes.

Discussion

The spatial variability of rangeland soils and soil hydraulic properties is well recognized, however, the methods to measure and characterize the spatial variability are limited. Current methods used to measure infiltration are limited in their ability to measure the process in the field under natural conditions and to quantify the spatial variability. Studies that have used point measurements across a watershed have often found large variations in final infiltration rates and large CVs. These measurements are not realistic in measuring the infiltration process during a rainfall event, or in quantifying the interactions between soil, cover, topography, and rainfall intensity. Larger scale measurements made with rainfall simulators, often measure variability within a plot (vegetation and cover, slope, micro-relief, etc.) but then relate this variability to a lumped infiltration rate for the entire plot which was determined indirectly.

Classical statistical methods measure changes over distance and determine the number of samples necessary to characterize an area based on the frequency distribution of the observations, but provide no information about the variability of the observations with respect to the position or coordinates of the area (i.e. spatially) (Vieira et al., 1981). Rogowski (1972) proposed a variability criteria to indicate the size and type of an area that is sufficiently uniform to be represented by a single soil property or characteristic such as infiltration. Geostatistical techniques, autocorrelograms and semi-variograms have recently been used to determine the range of correlation of infiltration values in space. As discussed earlier, the spatial correlation of infiltration on rangelands has been found to be very small, often less than 2 m, using current geostatistical methods (Loague and Gander, 1990). Grah et al. (1983) found spatial correlation distance increases with longer infiltration periods and when evaluated along flow paths. The ability of the autocorrelogram to compute the spatial variability of infiltration is dependent on the length of the transect measured (Peck, 1983). Vieira et al. (1981) suggested measuring infiltration rates at the finest grid possible with enough samples to detect the spatial structure before determining the appropriate variogram model. They also emphasized that the semi-variogram (not the autocorrelogram) should be used to determine sampling distance because it represents the average for all directions.

The measurement scale has been found to have a direct impact on the resulting variability of the infiltration measurements. Sisson and Wierenga (1981) and Baily (1995) found that the infiltration rate increased and the variance decreased with an increase in measurement area. Jury (1985) conducted a critical review of the studies of the spatial variability of soil physical parameters in solute migration. Five studies were evaluated where scaling theory was used to interpret the variability of measured parameter values at different sample sites. The scaling factors inferred from the measurements of soil parameters depended critically on the method of measurement. A significant correlation was found between the correlation length of a parameter and the sample size spacing used to develop the variogram, indicating that the correlation length parameters depend on the sample grid spacing used to obtain the variogram or correlogram. This implies that neither scaling factors nor correlation length parameters are measurable field properties using current methodologies (Jury, 1985), and that sampling and measurement methods to determine the spatial variability of soil parameters controlling transport needs further study. Russo and Jury (1987) analyzed the effects of grid size on the ability to estimate correlation scale. Reasonable correlation estimates were found when the sampling distance was smaller than the scale of the underlying process being measured.

Vegetation has been found to be one of the primary factors influencing infiltration on rangelands (e.g. Lane et al., 1987; Blackburn et al., 1992). Gifford and Busby (1974), however, found measuring the cover characteristics did not improve the potential to predict the hydrologic response of a big sage brush site which had been highly modified. Dunne et al. (1991) found empirical studies in the literature to be confusing as to how vegetation affects infiltration processes on rangelands. Of the many factors controlling infiltration on rangelands, the role of desert and range vegetation and desert or erosion pavement are not well understood or quantified (Lane et al., 1987). Percent vegetation cover was found to be consistently positively correlated with final infiltration rates (Aboulabbes, 1984). Stepwise multiple regression analysis, however, was not successful in predicting the infiltration rates from other measured watershed and soil properties including vegetation.

There is a need to measure both the spatial variability of infiltration and the spatial characteristics of the structural properties and cover characteristics which influence infiltration at the same time (Bosch et al., 1993). Multiple geostatistical analysis (e.g. Co-kriging) using slope, vegetation and cover characteristics, and soil structural properties should be tested. The development of a new method or variations of existing measurement methods and sampling designs should be used to incorporate landscape topography and overland flow processes.

Suggested Topics for Future Research Include:

- Integration of methods: e.g. tension infiltrometers and large rainfall simulators used on the same plot.

- Incorporate topography and dominant flow paths as well as sample spacing into sampling design for infiltrometers.

- Determine a relationship between the scale of measurement and the measurement method in order to minimize the affect of the method (or size of the measurement) on the resulting spatial variability.

- Measure both the spatial variability of infiltration and the spatial characteristics of the structural properties and cover characteristics which influence infiltration at the same time.

- Multi-variable geostatistical methods should be considered as a framework for measuring the spatial variability of infiltration on rangelands.

Table 1. Infiltration rates and associated CVs for selected rangeland sites using infiltrometers.

Study	Method	Infiltration mm/hr	CV (%)	Number	Location	Comments
Nielsen et al. 1973	single ring	6.1	91	20	Fresno, CA	log-normal
Sharma et al. 1980	double ring	47	60	26	R-5 Chickasha, OK	log-normal
Loague & Gander 1990	1-m ring grid transect 1 transect 2	 56.8 76 23.4	 73 48 43	 157 50 50	R-5 Chickasha, OK	log-normal no spatial correlation
Achouri 1982	double ring ungrazed grazed	(range) 116 - 216 45 - 76	 54-73 36-49	 70 70	Utah	no variance structure log-normal
Grah et al. 1983	double ring	412	72	120	Utah	correlation distance ≤17 m along flow path correlation with vegetation
Aboulabbes 1984	double ring 20 -cm dry 20-cm wet 30 cm dry 30 cm wet	 334 169 304 148	 73 92 67 129	 53 53 53 53	Morocco	correlation distance ≤ 18m
Merzougi & Gifford 1987	double ring ungrazed grazed	 124.4 49.2	 44 37	 104 104	Eureka, Utah	cover explained 36% of the variance

Table 2. Infiltration rates and associated CVs for selected rangeland sites using small simulators and disk permeameters.

Study	Rainfall intensity/ initial condition	Infiltratio n mm/hr	CV (%)	Number	Location	Comments
Small Simulators:						
Aboulabbes 1984	75 mm/hr dry 75 mm/hr wet 100 mm/hr dry 100 mm/hr wet	25 32 34 32	76 68 88 74	53 53 53 53	Morocco	30 cm diameter
Springer & Gifford 1980 (Gifford & Busby 1974)	75mm/hr Native Sagebrush plowed/ seeded plowed/seeded/grazed plowed/seeded/grazed	55 36 - 56* 28 -34*	34 43 - 68* 40 - 64*	22 20 - 24* 19 - 24*	Southern Idaho	5 years normal & log-normal
Devaurs & Gifford 1986	very wet (64 mm/hr) unfenced fenced tilled	15 20 9	30 21 14	22 45 27	Reynolds Creek Boise, Idaho	small ($0.37\ m^2$) plots with large rainfall simulator plots
Merzougi & Gifford 1987	grazed ungrazed	17 31	110 75	104 104	Eureka, Utah	randomly distributed pure nugget effect
Disk Permeameter:						
Whitaker 1993	Ponded h = 5 cm Unponded h = -5 cm	266 54	87 42	30 30	Walnut Gulch Tombstone, AZ	300 m transect

* range of values for the five year period.

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