Modeling Infiltration In Constructed Micro-catchments

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Abstract

Micro-catchments (MCs) have successfully been used in arid regions to promote infiltration of rainfall and water availability for plants (e.g. Malagnoux, 2008; Oweis, 2017). In addition to these beneficial outcomes, MCs also have the ability to reduce soil erosion and sedimentation in arid and semiarid rangelands. The Vallerani® System was developed in 1988 to efficiently harvest runoff by creating a series crescent-shaped MCs with oscillating ripper and plow blades (Oweis et al. 2011). The Vallerani System has been used in degraded rangeland settings in numerous countries (Malagnoux, 2008, Oweis, 2017). Like any engineered structure, MCs need to be sized and spaced adequately for optimal function and cost effectiveness, and better understanding of the infiltration capacity of MCs would allow better engineering of these structures. The research described here tests the ability of a numerical infiltration model to emulate field measurements for a set of constructed MCs.

Field work for this study was performed at a Bureau of Land Management (BLM) experimental research site at Bedell Flat that is located north of Reno, Nevada. The soil at the study area is a coarse-loamy aridic argixeroll with underlying bedrock at approximately 1-2 m depth. Eight MCs were created on two transects along the hillslope contour. One transect was located at the hillslope toe where the slope was 5-8%. The second transect was located 50 m uphill where the slope was 10-15%. MCs were constructed using a small tractor with two offset plow shovels. MCs were then manually shaped to approximate the width, depth and berm of pits created by a Vallerani Plow. Each MC was approximately 350 cm long, 150 cm wide, and 30 cm deep. A digging bar was used to break up soil along the centerline of the pit down to an additional 10-15 cm in order to approximate the ripper of the Vallerani system.

Three dimensional models of each MC were created using handheld photography and Agisoft Photoscan software. Eight control targets around the pit were surveyed with a Nikon NPR 352 total station to accurately project the 3-D models in space. The Photoscan software created digital elevation models (DEMs) that were accurate to within 0.5 cm, and these DEMs were imported to ArcMap GIS software where the surface volume tool was used to capture the 3-D surface area and volume across a range of depths. Polynomial relationships were then developed to relate water stage in each MC to the corresponding wetted surface area (4^{th} order polynomial) and volume (2^{nd} order polynomial) of the pit.

Multiple soil samples around the pits were measured for bulk density and soil particle size distribution (PSD) at five 10-cm depth intervals, as well as from the soil berm and the bottom of the pit. A Guelph permeameter (GP) was used to measure soil conductivity (K_s) at depths of 15 cm, 25 cm, 35 cm, 45 cm, 55 cm on each side of an MC, as well as 15 cm within the MC berm. GP measurements were obtained using a single ponded height, since vertical heterogeneity of the soil profile can cause erroneous results with two ponded heights (Elrick et al., 1989). Measurements were taken with the GP set to 10 cm of water pressure, and the water level was recorded at minute intervals until three recordings of a steady rate of infiltration were observed (10-25 minutes).

A Walnut Gulch Rainfall Simulator (WGRS) was used to simulate two rainfall events over each MC. The rainfall simulator applied water with two events of variable intensity and duration, delivering 3-5 cm of water at an intensity of 10-15 cm/hr. A rill simulator then simulated concentrated flow from upslope. Flow from the rill simulator was maintained for at least 15 minutes after water overtopped the MC. When the rill simulator was shut off, the level of water in the MC was continuously measured using both an ISCO bubbler and a vented KPSI 700 level transducer. The polynomial relationship between depth and volume allowed the calculation of the infiltration rates and volumes with time. One MC (upper site #2) was removed from the study, since the water opened up an animal burrow and the pit drained.

The MC field experiments were simulated using the Hydrus 2D/3D software package. A representative cross-section was derived from each of the two hillslope positions by overlapping the multiple 3D models of pit geometries for low versus high slopes. A model domain was created that characterized the soil profile based on soil measurements made in the field. The model domain for upper and lower sites was approximately 500 cm wide by 500 cm tall. Seven soil layers were specified: 0-5 cm, 5-15 cm, 15-25 cm, 25-35 cm, 35-45 cm, >45 cm, and the unconsolidated berm material (Fig. 1). The properties that were assigned to the berm were also specified for a wedge of soil at the bottom of the pit to represent the 10 cm of unconsolidated soil created with the digging bar.

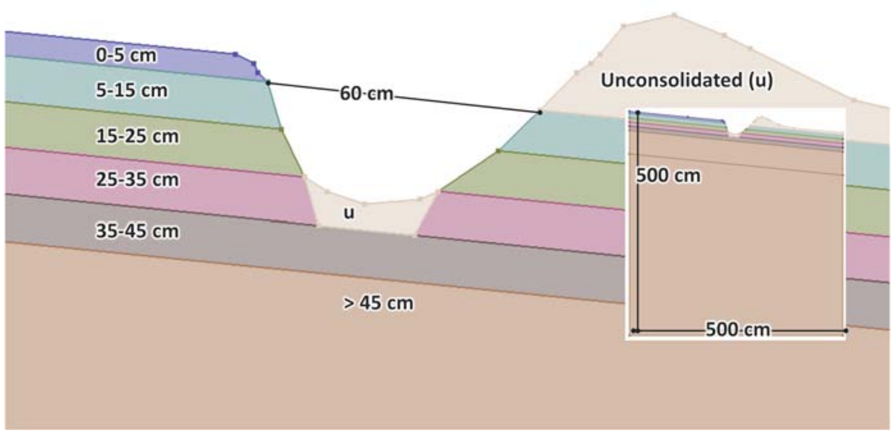

Figure 1. Hydrus model geometry.

The Hydrus 2D model was set up in the vertical plane with a simplified soil profile based on field measurements. The profile was converted to a finite element (FE) mesh using the MESHGEN software in Hydrus, with a targeted element size of 10 cm that was refined to 1 cm at the soil surface. The shape of the water retention curve was defined by the van Genuchten – Mualem hydraulic model with no hysteresis, and water flow parameters were originally specified based on measured PSD data for each depth interval. Water retention parameters (Q_r, Q_s, Alpha, n, I) were held constant for each simulation and were based on predictions from PSD data. The saturated conductivity (K_s) at each soil layer was specified based on the maximum K_s measurement at each depth interval measured in the field and averaged between upper and lower hillslope positions. A time-varying head boundary at the soil surface was used to simulate the height of ponded water within each MC, based on changes in the measured height of ponded water for each pit. The simulation was run for 400 minutes with a one-minute time step.

Water velocity estimates around the pit boundary from the Hydrus model (Fig. 2) were averaged for each 1 cm depth interval in the pit and multiplied against the corresponding surface area for that interval to provide a volumetric flow rate for infiltration. A summation of all depth intervals provided a total flow rate at each time step of the model. Differences between the modeled volumetric flow rates and field measured values were calculated for each pit for 6 time steps of the Hydrus simulation that were separated by 5 minutes after the rill simulator was shut off and the water level receded.

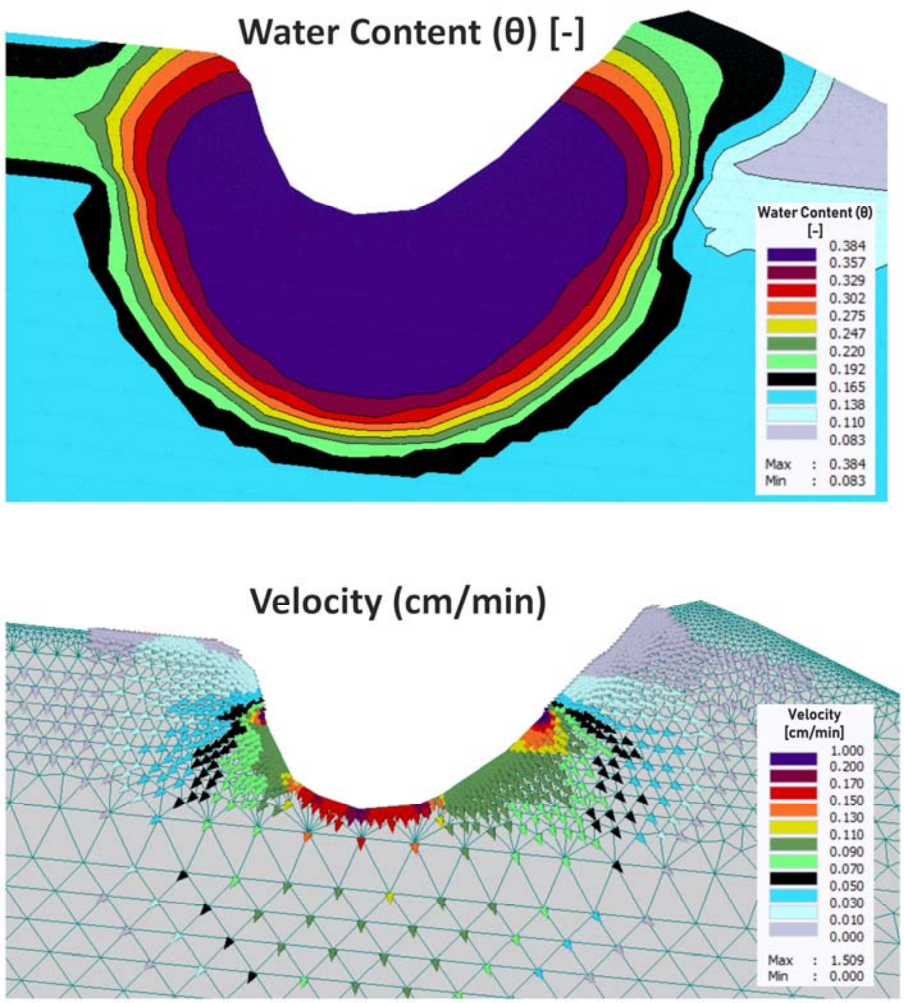

Figure 1. Hydrus output for lower site 1 at 255 minutes displaying water content and velocity.

On a MC-by-MC basis, disagreement between field measured and modeled rates of infiltration was as high as 90%. As a group, the Hydrus model underestimated infiltration at lower sites by 20% and overestimated upper sites by 30%. However, without any direct calibration of the Hydrus model, average error across all MCs on the hillslope was less than 1% (Fig. 3).

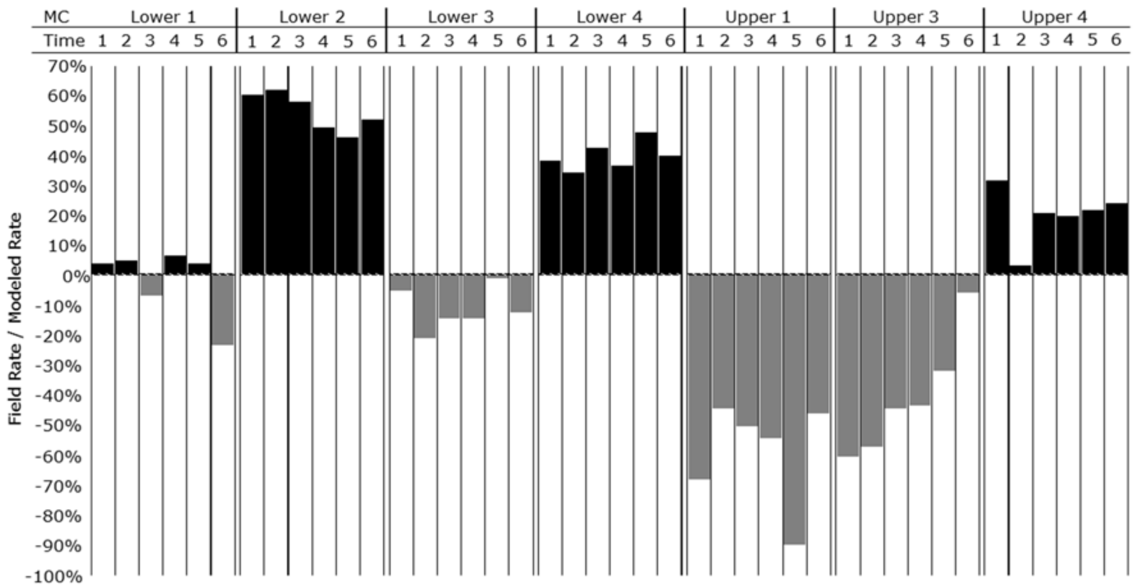

Figure 2. Relative error of Hydrus model estimates compared to field measures for six time steps.

Given the innately high level of heterogeneity in soil properties and the generalization of a single model domain for each hillslope position, it is not surprising that individual MCs would perform differently. The results of the modeling effort were encouraging, and point to a number of topics that should be studied to improve results. These include determination of the required density of PSD and GP measurements for model parameterization, and determination of whether the different biases of upper and lower slopes were an artifact of small sample size or a factor that might be addressed in the model. Future work could adapt such simulations to represent weather patterns over a seasonal time scale in order to develop a flow budget for the MCs, including quantification of total water stored in the soil profile or simulation of plant growth. The Hydrus model could also be used in conjunction with physically-based erosion models to simulate how different configurations on the hillslope might reduce erosion and to predict how quickly the MCs would fill with sediment.

References

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