PIPE FLOW IMPACTS ON EPHEMERAL GULLY EROSION

G.V. Wilson, USDA-ARS National Sedimentation Laboratory, 598 McElroy Dr, Oxford, MS, gvwilson@ars.usda.gov; R.F. Cullum, USDA-ARS National Sedimentation Laboratory, 598 McElroy Dr, Oxford, MS, rcullum@ars.usda.gov; M.J.M. Römkens, USDA-ARS National Sedimentation Laboratory, 598 McElroy Dr, Oxford, MS, mromkens@ars.usda.gov.

Abstract: Rills and ephemeral gullies are major sources of sediment yet, their development is not well understood. Lateral flow through soil pipes over water-restricting horizons has been postulated to facilitate the development and head cut migration of ephemeral gullies. The objective was to determine the effect of subsurface pipe flow above a water-restricting horizon on ephemeral gully formation during rainfall events and specifically to quantify the effects of hydraulic head on ephemeral gully erosion. A rainfall simulator applied rainfall at 65 mm/h to a 1.5 m long by 1 m wide soil bed of 5% slope. Rainfall was applied for 1 hour on dry antecedent soil conditions, followed 30 minutes later by a 30 minute rainfall on wet soil, then 30 minutes later a final 30 minute rainfall on very wet soil. The soil profile consisted of 30 cm of Providence silt loam packed to a bulk density of 1.35 g cm^{-3} over a 5 cm thick water restricting layer packed to 1.57 g cm^{-3}. Pipe flow was simulated using a 2 cm diameter porous pipe that extended 50 cm into the soil bed from the upper end. Pipe flow was controlled under a constant head of 0 (no pipe flow) and 30 cm. Tensiometers with pressure transducers were inserted into the soil bed at 12 positions to monitor soil water pressure dynamics during flow events. Rainfall and pipe flow individually did not result in mass wasting, however, their combination did produce pop-out failures. The total soil losses by sheet erosion were 2-3 times higher with rainfall and pipe flow combined than by rainfall alone. The total soil loss by ephemeral gully erosion was 5 times higher than sheet erosion as a result of pipe flow combined with rainfall.

INTRODUCTION

Soil erosion by water remains a major problem in many regions of the US. More streams on the US EPA 303(d) list are impaired by sediment than by any other contaminant. Nutrients, heavy metals and pesticides are transported with sediment. Predicting and controlling the movement of sediment in a watershed requires a thorough knowledge and understanding of the runoff, erosion, and sediment transport processes. While substantial efforts have been made over the years to describe sheet erosion processes, there is an incomplete understanding of the basic mechanisms governing ephemeral gully erosion.

Ephemeral gullies can be a major source of sediment, yet the mechanisms of their development are not well understood. The relationship of gully erosion to rainfall, soil surface and subsurface conditions is poorly quantified. This knowledge gap hinders the development of accurate sediment delivery models and control techniques. Significant progress has been made in characterizing the role of surface flow processes on ephemeral gully development. The role of subsurface flow and soil water pressures has been shown to be important to rill initiation and growth (Römkens et al., 1997 and Froese et al., 1999). However, the contribution of subsurface flow to ephemeral gully erosion is less well known.

The two mechanisms of subsurface flow induced erosion are seepage flow and pipe flow (Dunne, 1990). Seepage flow is common, particularly at toe-slopes and streambanks (Wilson et al., 2005), where restriction of downward percolation results in lateral flow that emerges from the soil surface or streambank. Liquefaction of soil particles entrained in the seepage flow results in development and headward migration of gullies. Development of vertical gully faces enhances the process as undercutting of the gully face results in mass wasting or sapping of gully walls. In contrast, rapid and often turbulent preferential flow through macropores or soil-pipes erodes the periphery of the macropore when the shear forces exceed the frictional strength binding soil particles. Pipe erosion, also termed tunnel scour, can cause gully development when macropores collapse (Dunne, 1990).

Many studies have demonstrated the significance of subsurface flow through macropores to stream flow (Wilson et al., 1991a,b) and mass wasting (Sidle et al., 2000) under forested hillslope conditions. However, the contribution of macropore flow under agronomic conditions to ephemeral gully erosion is uncertain. Preferential flow can cause abrupt soil water pressure rises (Sidle et al., 200) and in loess soils with fragipans this results in perched water tables. In these soils it is common to observe ephemeral gullies eroded down to the fragipan. Soil pipes have been observed at the head of such ephemeral gullies as shown in Figure 1. Quantification of the conditions under which pipe flow contributes to ephemeral gully erosion is seriously lacking.

Figure 1 An ephemeral gully cut down to the surface of a fragipan horizon with a 3 cm diameter soil pipe at the head of the gully.

The objectives of this study were to quantify the soil physical and hydrologic properties under which preferential flow through soil-pipes results in ephemeral gullies. This paper reports preliminary analysis of the initial series of pipe flow experiments.

MATERIALS AND METHODS

Rainfall simulations were conducted on soil beds in a rectangular flume at 5 % slope with and without subsurface flow through an artificial soil-pipe. The flume (Figure 2) was 1.5 m long by 1 m wide by 50 cm high and constructed from 2 cm thick plexiglass. The endplate at the lower end was removed after packing the soil bed such that gully development would not be hindered by the endplate during flow events. The upper end had a port for connecting an artificial soil-pipe, at the topsoil-restrictive layer interface, to a water reservoir. The hydraulic head on the soil-pipe was controlled by a Mariotte device. The soil-pipe was a 2 cm i.d. soaker hose that extended 50 cm from the upper end into the soil bed with the end of the pipe left open.

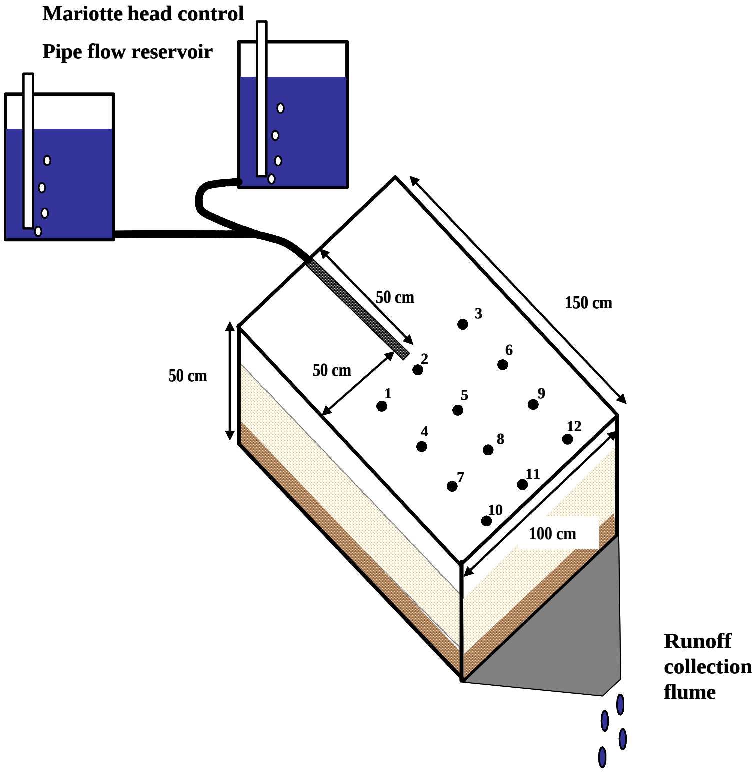

Figure 2 Illustration of the soil bed with a porous soil-pipe at the upper end and an open face lower end. Tensiometer locations are indicated by solid circles with their numbering scheme indicated. The water reservoir for the soil pipe has a Mariotte device for head control.

Bulk topsoil was collected from a depth of 0 to 10 cm from a Providence silt loam (fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) soil on the Holly Springs Experiment Station (HSES) of the Mississippi Agricultural and Forestry Experiment Station. Soil was sieved to < 2 mm and maintained in field-moist conditions (water content of 0.19 g g^{-1}) until packing. The bottom 5 cm of the soil bed mimicked a water restrictive layer by packing clay loam material to the average bulk density (1.57 g cm^{-3}) of fragipans in this area (Rhoton and Tyler, 1990). The topsoil was packed to a bulk density of 1.35 g cm^{-3} above the clay layer to form a 30 cm silt loam layer. Soil was packed in 2.5 cm lifts using field-moist soil after accounting for the measured water content.

Tensiometers were inserted vertically into the soil bed (Figure 2) such that the ceramic cup was positioned 1 cm above the water restrictive layer. Twelve tensiometers were installed in a 4 row by 3 column array. The 4 rows were spaced 30 cm apart starting 5 cm from the end of the soil pipe at distances of 55, 85, 115, and 145 cm from the upper end. The middle column was positioned at the center of the soil, with a column on each side spaced 20 cm from the middle column (distances of 30, 50, and 70 cm from the side of the soil bed). Tensiometers were monitored by a CSI data logger.

Subsurface flow through the soil-pipe was simulated under a constant pressure head of 15 or 30 cm. The rainfall simulator (Meyer, 1960) consisted of a series of oscillating Veejet nozzles (80100) located approximately 3 m above the soil surface. Nozzles traversed the area horizontally in two dimensions in order to apply a uniform rainfall application with an impact energy of 211 kJ ha^{-1} mm^{-1}. Rainfall was applied at a rate of 65 mm h^{-1} for 1 h under antecedent soil-water conditions (dry run), followed 0.5 h later by a 0.5 h duration rainfall (wet run), and a final 0.5 h duration rainfall (very wet run) 0.5 h after the wet run. Ground water from wells on the HSES was used for soil-pipe and rainfall applications to mimic soil-water ionic strengths.

Four runs were made with the following combinations of treatments: (1) pipe flow only with 30 cm pressure head, (2) rainfall only, (3) rainfall and pipe flow with a 15 cm head, and (4) rainfall and pipe-flow with a 30 cm head. The time of runoff and/or seepage flow initiation was recorded and the runoff rate measured by collecting runoff for 15 sec every 3 minutes until rainfall was terminated, at which point runoff was collected for 15 sec every minute until runoff ceased. Runoff volume was recorded and sediment content analyzed by decanting excess water and then evaporating to oven-dryness (105° C). The timing and soil loss by mass wasting were recorded. Slumped material was collected, weighed, and sampled to determine water content. The dry mass of sediment loss by mass wasting was calculated after correcting for the water content.

RESULTS AND DISCUSSION

Pipe Flow Impact: Pieziometric observations on loess soils with a fragipan have indicated that perched water tables can reach the soil surface during winter storm events. The hydraulic head established will therefore be governed by the depth to the fragipan horizon. Fragipan depths are highly variable due to past erosion but typically range from 15 to 112 cm at the HSES (Rhoton and Tyler, 1990). This is typical of the loess region. Therefore, the simulated hydraulic head of 30 cm on the artificial pipe is clearly reasonable.

The tensiometers prior to establishment of the 30 cm pressure head for pipe flow alone exhibited a gradient from the upper end, just 5 cm downslope of the pipe outlet, of -35 cm to the lower end, just 5 cm from the open face, of -47 cm matric head. The first response to head establishment on the pipe for all four rows was by the middle tensiometers. The time to response was 2 min at T2, 15 min at T5, 47 min at T8, and 141 min at T11, Figure 3. Seepage began after 132 minutes of head. It is interesting to note that, seemingly contrary to Richards outflow law which states that positive matric heads are required for flow out of the soil through an open face, the tensiometers 5 cm from the face were still under negative matric heads. The last row of tensiometers had not begun to respond. The reason is likely due to the tensiometer cups being positioned 1 cm above the interface of the water restricting layer. Seepage response clearly indicated hydraulic non-equilibrium conditions caused by preferential flow immediately above the surface of the restrictive layer. The observation of seepage occurring under apparently unsaturated conditions due to preferential flow over a restrictive layer is consistent with findings by Wilson et al. (2005) and Fox et al (2005) for streambank failure due to seepage erosion.

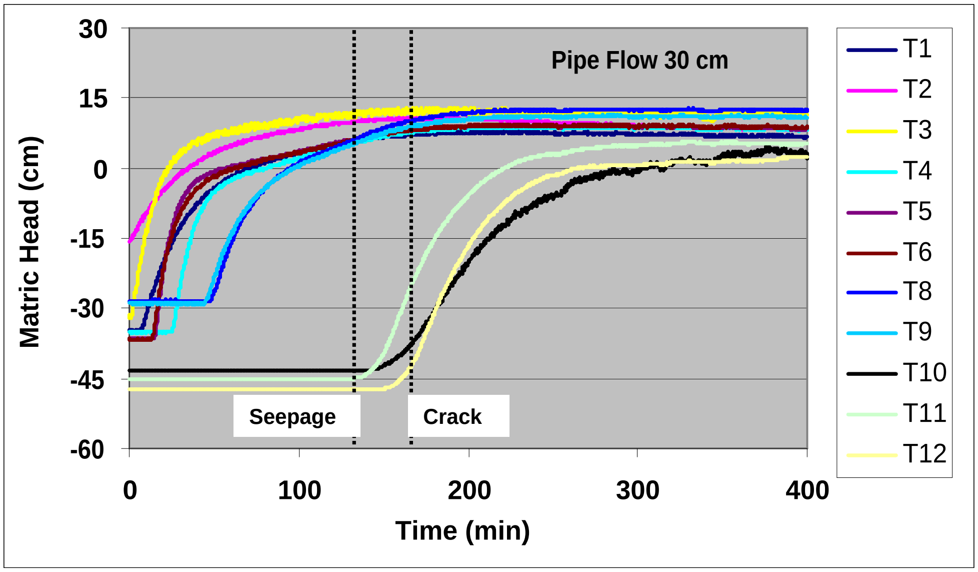

Figure 3 Tensiometer response to establishment of 30 cm head on the soil pipe. Vertical dashed lines indicate time to seepage initiation and tension crack development.

Wilson (unpublished data) observed an ephemeral gully on a loess soil in this region with a 3 cm diameter pipe at the head. Pipe flow rates entering the ephemeral gully following rainfall events, with rainfall and runon excluded from the gully, were typically around 33 L/d with sediment concentrations less than 1 g/L. Total soil losses from the pipe flow alone were typically less than 10 g over the course of a flow event. However, formation of the ephemeral gully constituted a soil loss of roughly 200 kg from a single event. The average pipe flow rate in the laboratory soil bed was 126 L/d. This value is higher than the field measurements, however, the conservative nature of the field measurements suggest that the laboratory flow rates were reasonable. Additionally, the laboratory pipe flow rate represents flow into the soil bed and not the seepage flow rate out of the bed. Pipe flow expressed on a per area basis using the known geometry of the soil bed (i.e., consistent with units for runoff/seepage rates) equaled 0.35 cm/h, Table 1. The seepage flow rate, i.e. runoff rate, out of the soil bed from pipe flow alone averaged 0.01 cm/h, which equates to a flux of 4 L/d. The difference between the pipe flow rate and the seepage rate is due to water storage within the soil bed.

Seepage flow rates for pipe flow alone were low, sediment concentrations were negligible and the soil bed did not exhibit mass wasting. Therefore soil loss in the runoff from pipe-flow alone was negligible. However, it did develop two tension cracks along the front face after 390 minutes of continuous flow through the soil-pipe. These cracks extended from the surface down to 5 and 11 cm depths at distances of 47 and 70 cm from the left side, respectively. This experiment was repeated with almost identical results. Tension cracks are commonly observed as precursors to bank failure (Fox et al., 2005).

Table 1 Hydrometric response to pipe flow and rainfall applications. The rates of runoff, Ro, and pipe flow, PF, and the sediment concentration are averages over the total time.

Trt	Seep Time	Ro Time	Pop-Out Time	Runoff Rate	PF Rate	Sed. Conc.	Ro Soil Loss	MW soil Loss
	min	min	min	cm/h	cm/h	g/L	kg	kg
1	132	na	na	0.01	0.35	0	0	0
2	na	4.5	na	5.30	na	128	2.22	0
3	110	2.0	144	5.88	0.08	238	4.92	18.04
4	128	15.0	162	6.17	0.35	376	6.61	37.42

PF rate is the pipe flow rate as measured at the reservoir tanks.
MW is the total mass wasted by pop-out failures.

Rainfall Impact: The hydrologic response to rainfall alone was more dynamic than for pipe-flow alone. Surface runoff was initiated within 4.5 min of rainfall and the average runoff rate was 5.3 cm/h, Table 1. The antecedent conditions were similar to the pipe flow only experiment with matric heads between -43 to -51 cm. Unlike the pipe-flow experiment where tensiometric response sequentially tracked the arrival of a lateral wetting front, tensiometric response for the spatially uniform rainfall indicated random arrival of the vertical wetting front. The middle two rows of tensiometers were the first to respond, ranging from 24 to 37 minutes, and the last to respond was the most upslope (36 to 106 min) and downslope (56 to 188 min) rows, Figure 4. Perched water above the restrictive layer was not developed until after 57 minutes of rainfall. Thus, runoff was by Hortonian flow processes and not throughflow processes. The sediment concentrations in the surface runoff were fairly dynamic (Figure 4) during the first rainfall event, with a peak concentration of 210g/L at the initiation of runoff and decreasing to 116 g/L as runoff continued with an average of 130 g/L. The second event had stable sediment concentrations around 160 g/L, while the concentration increased during the third event from 137 to 194 g/L but averaged the same as the second event. The average sediment concentration over the three events was 129 g/L for a total soil loss by sheet erosion of 2.22 kg (6.6 ton/acre). Similar to pipe flow, rainfall alone failed to produce mass wasting of the soil bed.

Synergistic Effect of Pipe Flow with Rainfall: The synergistic effect of pipe flow with rainfall was simulated for a 15 cm pressure head and for a 30 cm head. The prescribed hydraulic head was established on the pipe until seepage from the soil bed was established before the three sequential rainfall events were initiated. The 15 cm head required 110 minutes to produce seepage whereas the 30 cm head required 128 minutes, Table 1, and the respective rainfall events were initiated at 120 and 135 minutes. The more rapid response to the lower head was due to wetter antecedent conditions (matric heads around -10 cm), however at the time of rainfall the soil beds had similar soil water conditions. The 30 cm head did have the higher pipe flow rate (flow into the pipe). The synergistic response of pipe flow with rainfall is clearly seen in the runoff rates as the 15 cm head had higher average runoff than rainfall alone, and the 30 cm head had a higher runoff rate than the 15 cm head. As found by Wilson et al. (2004), the average sediment concentration by sheet erosion increased as the runoff rate increased. Soil losses by sheet erosion (14.6 and 19.6 ton/acre, respectively for 15 cm and 30 cm heads) were two to three times greater with pipe flow active during rainfall events.

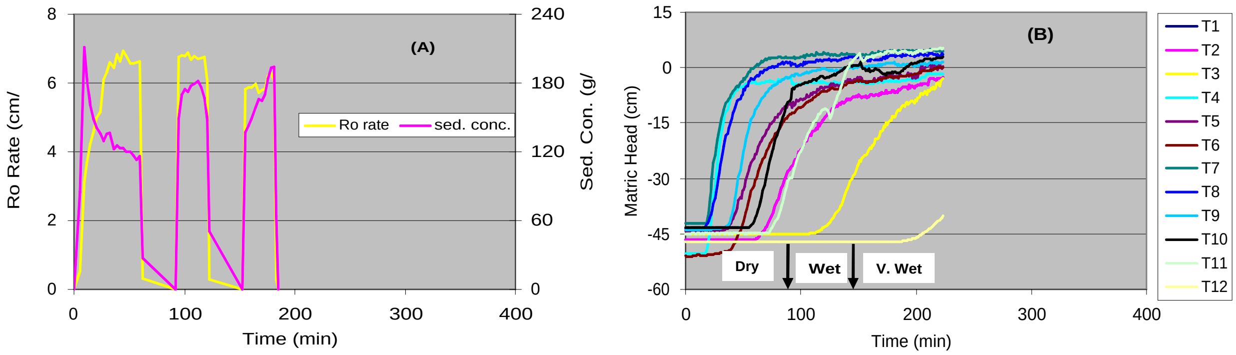

Figure 4 (A) Runoff hydrograph and sedigraph for the rainfall only experiment. (B) Tensiometer response to rainfall with no pipe flow. Arrows indicate time to start of the wet and very wet runs.

The main difference between rainfall or pipe flow alone and rainfall with pipe flow is in the mass wasting. Mass wasting failures occurred within 24 min and 27 min of rainfall initiation for the 15 and 30 cm heads, respectively (144 min and 162 min total time, respectively). The mass wasting from pipe flow occurred as pop-out failures. Mass wasting by pop-out failures is consistent with the findings of Simon et al. (1999) for soils with contrasting permeabilities that result in soil-water pressure increases. But it is in contrasts to cantilever type failures reported by Wilson et al. (2005) and Fox et al. (2005) where such contrasting layers resulted in seepage erosion that undercut gully banks. Rainfall with pipe flow under a 15 cm head produced two pop-out failures during the first (dry) rainfall event and two more during the third (very wet) rainfall event. The total soil loss by mass wasting, 18.0 kg (53.6 ton/acre), was almost five times greater than soil loss by sheet erosion. Rainfall with pipe flow under a 30 cm head was even more hydrodynamic with seven pop-out failures during the dry rainfall event. The total soil loss by mass wasting for the 30 cm head was 37.4 kg (111.2 ton/acre) which was more than five times greater than the sheet erosion losses.

CONCLUSIONS

Water restrictive layers, e.g. fragipans, which are common in loess soils, are known for causing perched water tables that result in lateral flow. Preferential flow through macropores above the restrictive layer can result in development of soil pipes. Soil pipes have been observed at the head of ephemeral gullies suggesting that pipe flow erosion by tunnel scour, is an important process of ephemeral gully development and head-cut migration. Flow through soil pipes can continue for days following a rainfall event. The impact of pipe flow alone, such as following a rainfall event, was investigated under a 30 cm head. The result of pipe flow alone was negligible soil loss. The impact of rainfall alone was investigated using three sequential rainfall events. Rainfall alone resulted in rapid runoff with soil losses by sheet erosion of 6.6 ton/acre but did not result in ephemeral gully development or head-cut migration. In contrasts, rainfall with pipe flow produced a synergistic effect that not only resulted in two to three times higher sheet erosion but caused pop-out failures. The result of pipe flow during rainfall events was gully erosion rates of over 50 to 100 ton/acre for a single event. The degree of sheet and ephemeral gully erosion was highly dependent upon the hydraulic heads on the soil pipe. These findings demonstrate the potential significance of pipe flow on erosion when water-restricting layers perch water during rainstorms.

REFERENCES

Dunne, T. (1990). “Hydrology, mechanics, and geomorphic implications or erosion by subsurface flow,” In Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms, Higgins CG and Coates DR (eds). Geological Society of America Special Paper 252: Boulder, CO.

Fox, G.A., G.V. Wilson, R. Periketi, and R.F. Cullum. (2005). “Sediment transport model for seepage erosion of streambank sediment,” J. Hydrologic Engineering, ASCE (in review).

Froese, J.C., R.M. Cruse and M. Ghaffarzadeh. (1999). “Erosion mechanics of soils with an impermeable subsurface layer,” Soil Sci. Soc. Am. J. 63:1836-1841.

Meyer, L.D. (1960). “Use of the rainulator on runoff plot research,” Soil Sci. Soc. Am. Proc. 24:319-322.

Rhoton, F.E., and D.D. Tyler. (1990). “Erosion-induced changes in the properties of a fragipan soil,”Soil Sci. Soc. Am. J., 54:223-228.

Römkens, M. J. M. , S.N. Prasad and K. Helming. (1997). “Effect of negative soil water pressures on sediment concentration in runoff,” In Management of Landscapes Disturbed by Channel Incision. Wang, S.S.Y., E.H. Langendoen and F.D. Shields (eds.), The University of Mississippi, Oxford, S. 1002-1007.

Sidle, R.C., Y. Tsuboyama, S. Noguchi, I. Hosoda, M. Fujieda, and T. Shimizu. (2000). “Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm,” Hydrological Processes, 14:369-385.

Simon, A., A. Curini, S. Darby, and E.J. Langendoen. (1999). “Streambank mechanics and the role of bank and near-nbank processes in incised channels,” In Incised River Channels, S.E. Darby and A. Simon (eds.), John Wiley & Sons Ltd.

Wilson, G.V., P.M. Jardine, R.J. Luxmoore, L.W. Zelazny, D.A. Lietzke and D.E. Todd. (1991a). “Hydrogeochemical processes controlling subsurface transport from an upper subcatchment of Walker Branch Watershed during storm events: 1. Hydrologic transport process,” J. Hydrol. 123:297-316.

Wilson, G.V., P.M. Jardine, R.J. Luxmoore, L.W. Zelazny, D.E. Todd and D.A. Lietzke. (1991b). “Hydrogeochemical processes controlling subsurface transport from an upper subcatchment of Walker Branch Watershed during storm events: 2. Solute transport process,” J. Hydrol. 123:317-336.

Wilson, G.V., S.M. Dabney, K.C. McGregor, and B.D. Barkoll. (2004).”Tillage and residue effects on runoff and erosion dynamics,” Trans. ASAE 47:119-128.

Wilson, G.V., R. Periketi, G.A. Fox, S. Dabney, F.D. Shields, and R.F. Cullum. (2005). “Seepage erosion processes contributing to streambank failure,” Earth Surface Processes and Landforms. (in review).