EROSION PROCESSES IN GULLIES MODIFIED BY ESTABLISHING GRASS HEDGES

S. M. Dabney, F. D. Shields, Jr., D. M. Temple, E. J. Langendoen

ABSTRACT. *Concentrated flow can cause gully formation on sloping lands and in riparian zones of floodplains adjacent to incising stream channels. Current practice for riparian gully control involves blocking the gully with an earthen embankment and installing a pipe outlet. Measures involving native vegetation would be more attractive for habitat recovery and economic reasons. To test the hypothesis that switchgrass (*Panicum virgatum *L.) hedges planted at 0.5 m vertical intervals within a gully would control erosion, we established a series of hedges in several concentrated flow channels. Two of the channels were previously eroded trapezoidal channels cut into compacted fill in an outdoor laboratory. The other channels were located at the margin of floodplain fields adjacent to an incised stream channel (Little Topashaw Creek) in Chickasaw County, Mississippi. While vegetation was dormant following two growing seasons, we created artificial runoff events in our test gullies using synthetic trapezoidal−shaped hydrographs with peak discharge rates of approximately 0.03, 0.07, and 0.16 $m^3 s^{-1}$, flow rates similar to those observed during natural runoff events in gullies at Topashaw. During these tests, we monitored flow depth, velocity, turbidity, and soil pore water pressures. Flow depths were generally <0.3 m, and flow velocities varied spatially and exceeded 2.0 $m s^{-1}$ at the steepest points in some tests. Erosion rates remained modest for the conditions tested, as long as slopes were less than 3 horizontal to 1 vertical (33%) and step height between hedges was less than 0.5 m. Stability modeling of soil steps reinforced with switchgrass roots showed that cohesive forces were 3 times greater than shearing forces for 0.5 m step heights, and that therefore mass failure was unlikely even with the surcharge weight of a 0.2 m depth of ponded water. For step heights greater than 1 m, however, mass failure was observed and predicted to be the dominant erosion mechanism.*

Keywords. *Buffers, Erosion, Runoff, Soil conservation, Vegetative barrier.*

Where floodplains are farmed adjacent to deeply incised stream channels, large gullies may form where overbank runoff concentrates. These edge−of−field gullies have been referred to as “waterfall erosion” (Ramser, 1935), “valley side−wall gullies” (USDA−SCS, 1966), and “bank gullies” (Poesen et al., 2003). In the U.S. today, such gullies are often controlled with drop−pipe structures comprised of earthen dams drained with a pipe culvert (Shields et al., 2002; Trest, 1997). Drop−pipes have proved to be quite effective, but require substantial capital investment and eventually deteriorate due to corrosion (metal pipes) or by burning in wild fires (plastic pipes). Chutes, rock sills, and check dams made using brush, logs, wire, stone, or sheet piling have also been used for gully control (Ramser, 1935; Finkel, 1986).

In tropical areas, planting vetiver grass (*Vetivaria zizainoides* L.) hedges has been used as a soil and water conservation practice for over 50 years (Vélez, 1952), and the World Bank has urged adoption of vetiver grass with backing from the National Research Council (Grimshaw, 1989; National Research Council, 1993). Where winter temperatures drop below −15°C, switchgrass (*Panicum virgatum* L.) forms more robust hedges than vetiver grass. Switchgrass is a tall, coarse species with the longest root system of all grasses comprising the native American prairie (Weaver, 1968). Some switchgrass accessions form aerenchymous roots that help the plants survive waterlogged conditions. Switchgrass roots also form rhizomes. These are very short in most strains so that the grass is generally characterized as a bunch grass, but when planted in a single row, most accessions can form a functional hedge.

Hedgerows as narrow as 0.5 m and comprised of a variety of species have been show to reduce soil erosion and have been proposed as an alternative to terraces in some situations (Abujamin et al., 1985; Kiepe, 1996; Ritchie et al., 1997; Thapa et al., 1999; Angima et al., 2002). In 2001, the USDA Natural Resources Conservation Service (NRCS) added the use of grass hedges to the *National Handbook of Conservation Practices*, with the title “Vegetative Barrier, Code 601.” In this article, we will use the more descriptive term “grass hedge” interchangeably with the more general “vegetative barrier.” The Vegetative Barrier practice standard includes the purpose of reducing ephemeral gully erosion, but control of gullies on non−cropped areas is not considered.

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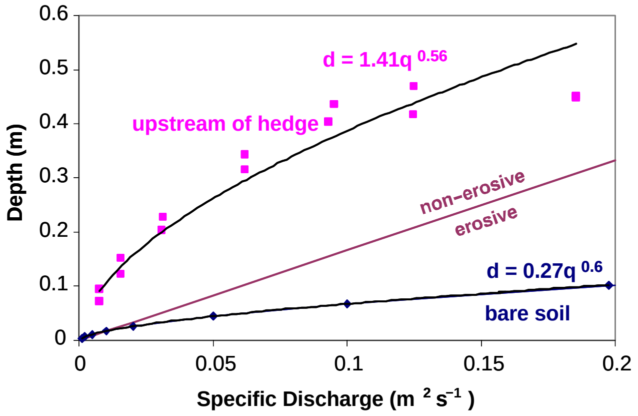

Figure 1. Water depth measured upstream and downstream of a one−row switchgrass hedge (Temple and Dabney, 2001) compared with flow depth for a bare−earth channel predicted by Manning's equation (n = 0.025) and with the minimum flow depth needed to keep average velocity below the critical level of 0.6 m s^{-1}. All measurements and calculations made with a bed slope of 5%.

Flume studies have shown that switchgrass hedges can remain erect in unit discharges as large as 0.2 m^2 s^{-1}, producing backwater depths as large as 0.4 to 0.5 m and reducing velocity to non−erosive, depositional levels (Temple and Dabney, 2001). An observed rating curve for the region immediately upstream of a single switchgrass hedge in a laboratory channel with smooth, vertical walls is shown in figure 1, along with a similar curve for a bare−earth channel (n = 0.025). Also shown is a straight line representing the depth−unit discharge relation for critical conditions (mean velocity = 0.6 m s^{-1}). Although the information in figure 1 is based on calculations and data for a 5% channel bed slope, flow depth upslope of grass hedges is rather insensitive to bed slope (Dabney et al., 1996).

We concluded from these flume studies that grass hedges could keep upstream flow velocities below critical limits for unit discharges up to 0.2 m^2 s^{-1} and hypothesized that grass hedges placed at 0.5 m vertical intervals would protect the gully bed from erosion (fig. 2). Grass hedges would have advantages over rock and brush check dams (e.g., Heede, 1976) because their root systems would add cohesion to the soil and because they could re−grow when partially buried by sediment. Installation of the hedges would require planting sod in a series of trenches running perpendicular to the gully axis, and providing protection from washouts during an establishment period of one or two growing seasons (Dabney et al., 2002). If successful, this solution would be less capital−intensive than structural controls, and would create habitat associated with a stand of native warm−season grass.

The success of the practice, however, is uncertain because some erosion would be expected to occur between the hedges before the slope stabilized, and because the steps created between hedges might be unstable. Erosive flow velocities would be expected to develop downslope of each grass hedge during lower flows when backwaters would not fully cover the regions between hedges. Erosion in these areas combined with sediment trapped upslope of each hedge would produce a series of steps over time. During this "mature" phase, slopes between hedges would be reduced so that hydraulic conditions would be non−erosive for all flows, while the grass roots would play an important role in preventing mass failure of soil blocks and in attenuating the scour effects of the reverse roller developed below each overfall (fig. 2).

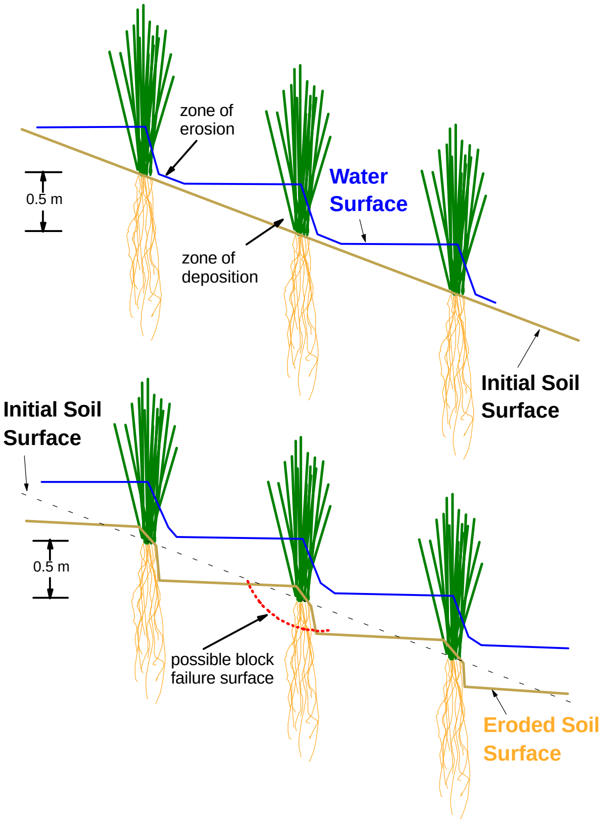

Figure 2. Schematic illustration of concept for stabilizing steep concentrated flow channels with a series of grass barriers spaced with a vertical interval of about 0.5 m.

The objectives of this study were to evaluate the effectiveness of a series of vegetative hedges in controlling concentrated flow erosion within gullies and to identify the mechanisms of any failures observed as a function of soil type, vertical hedge spacing, slope steepness, and flow rate.

MATERIALS AND METHODS

We tested the practice of using grass hedges to control edge−of−field gullies along a 2.3 km sinuous study reach of Little Topashaw Creek (33.7457° N, 89.1750° W) in Chickasaw County, Mississippi. At the study location, the stream channel was incised about 6 m from its flood plain, had a top bank width of about 35 m, had a bed slope of about 0.002, and drained a watershed of about 37 km^2. Adjacent to the study reach, five fields comprising 75 ha were cropped to cotton (*Gossypium hirsutum* L.) and corn (*Zea mays* L.). The dominant soil type was Arkabutla silt loam (fine−silty, mixed, active, acid, thermic Fluvaquentic Endoaquepts). Surface runoff left these fields and entered the stream through about 26 discrete gullies. We selected six of these gullies for treatment with grass hedges. Three of the treated gullies were shaped to smooth contours with a track hoe prior to planting grass hedges, and three gullies were planted with grass using only hand labor. A contractor transplanted switchgrass during June 2000. Details of grass establishment methods are provided by Dabney et al. (2002). One of the treated, shaped

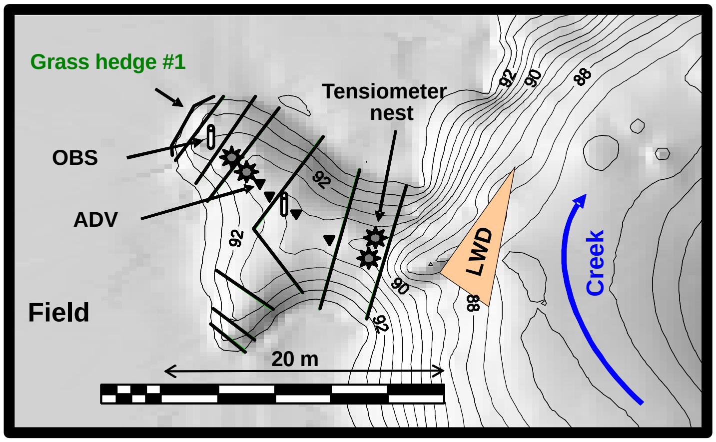

Figure 3. Pre−test topographic map (0.5 m contour interval) of the L3 test site indicating locations of grass hedges, turbidity sensors (OBS), acoustic Doppler depth and velocity transducers (ADV), and tensiometer nests. Flow was introduced only into the northern arm of the gully. The location of a large woody debris structure that trapped creek sediments at the toe (LWD) is also indicated.

gullies, designated L3 (fig. 3), was subjected to pumped inflow tests during February 2002 as part of the current study.

To provide a more controlled environment and a different soil material, we also established a series of six grass hedges in each of two outdoor test channels ("gullies") at the USDA−ARS Hydraulic Engineering Research Laboratory at Stillwater, Oklahoma (fig. 4). The gullies were initially constructed as trapezoidal channels with 0.91 m wide bases and 1:1 side slopes cut into compacted fill (1.78 Mg m^{-3}) borrowed from the 0.2 to 1.5 m depth of a nearby Pulaski fine sandy loam soil (coarse−loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents). The channels were built with 1:3 (18°) slope, lined with bermudagrass (*Conodon dactylon* (L) Pers.), and used for simulating erosion of embankment dams

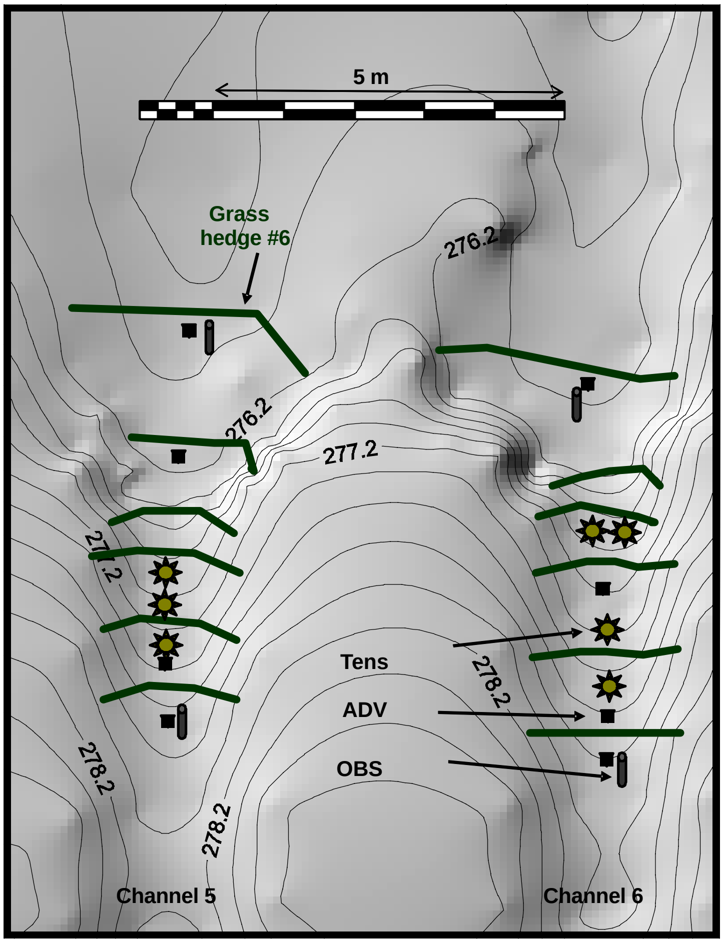

Figure 4. Shaded relief contour map (0.2 m contour interval) of pre−test conditions of test gullies at Stillwater, Oklahoma, showing the extent of grass hedges, locations of turbidity sensors (OBS), acoustic Doppler depth and velocity transducers (ADV), tensiometer nests (Tens), and pre−existing unshaped headcuts at the toe of each gully.

subjected to overtopping (Temple and Hanson, 1998). Each channel was tested in 1997 with a flow rate of 1.1 $m^3 s^{-1}$ for 64 to 75 h, resulting in the formation of a gully with an approximately 1 m deep headcut near each toe (fig. 4). These headcuts were left to weather in the eroded condition until the switchgrass hedges were transplanted in spring 2000 and then for an additional two years while the switchgrass became established and shaded out remnant bermudagrass. Runoff was excluded from both Stillwater test gullies during switchgrass establishment, and supplemental irrigation was applied to ensure adequate grass growth. A pool of water was maintained in a depression near the crest of each channel to create a phreatic surface within the underlying soil in order to simulate worst−case conditions typical of riparian gullies draining saturated fields. Although water pools were maintained for several weeks, downslope seepage did not occur prior to pumped flow tests.

Preliminary studies (Dabney et al., 2002) of natural runoff in selected riparian gullies along the Little Topashaw Creek study reach were used to determine the hydrograph characteristics to be used in pumped flow tests. Runoff was measured in two gullies using 0.45 m H flumes, and depths and velocities were monitored for varying periods in the thalwegs of six of the riparian gullies using incoherent, acoustic Doppler velocity loggers (Shields et al., 2001). Eighty−five gully flow events were experienced with specific discharges up to 0.2 $m^2 s^{-1}$. Thus, the centerline specific discharges recorded through the Topashaw gullies were great enough to cause serious erosion where flow was not retarded by vegetation (fig. 1).

We tested the two gullies at Stillwater (fig. 4) and the one at Topashaw Creek (fig. 3) using synthetic hydrographs with peak discharge rates of 0.03, 0.07, and 0.16 $m^3 s^{-1}$ and durations ranging from 0.5 to 3 h. Synthetic hydrographs had relatively brief rising and falling limbs and prolonged, nearly steady peaks (fig. 5). Water for pumped tests was obtained from the creek at the Topashaw site and from a reservoir at Stillwater. During each hydrograph, we monitored depth and velocity at 1 min intervals at four locations using acoustic Doppler gauges, turbidity at two points using two optical backscatter instruments, and positive and negative soil water potentials at depths of 0.15, 0.3, 0.45, 1.0, and 1.5 m using tensiometers. High water marks were flagged during each peak discharge to establish water surface profiles. Additionally, at Stillwater, static manometers were placed upstream of each hedge. Following each test, we used a total station to survey high water marks and thalwegs. We determined particle size distributions with a combination of sieving and pipet techniques of samples taken from each horizon of the soil profile at the Topashaw site. Textural properties of the Stillwater embankment were determined on samples collected from each of 32 lifts during construction.

The turbidity instruments used were OBS−3 (D and A Instruments, Port Townsend, Wash.) calibrated so that 2 V output was equivalent to 4000 nephelometric turbidity units (NTU). Turbidity data were converted to concentrations based on calibration equations developed in the laboratory from soil samples collected within the Topashaw and Stillwater gullies. Soil samples were air dried and ground to pass a 2 mm sieve. Weighed amounts of soil were sequentially added to 3 L of tap water agitated in a bucket with a propeller stirrer that maintained all added sediment in suspension. Calibrations were performed with and without addition of 75 mL of a dispersant solution (50 g $Na(PO_4)_6$ L^{-1}). Six discrete samples obtained at varying times during the flow tests at Stillwater were also analyzed for both turbidity and concentration.

In order to study the effect of grass hedges on step stability, we utilized the ARS−developed Bank Stability Model v.3.4 (Simon et al., 2000; http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/bank.html, accessed September, 2003) that calculates a slope factor of safety (F_s) as the ratio of resisting strength to shearing force for a planar failure surface. We separately and jointly compared the offsetting influences of increased cohesion due to root reinforcement and the destabilizing force of the extra weight of ponded water. Because we were interested in the stability of step heights less than 1 m high, we modified the model to permit the effect of switchgrass root reinforcement on apparent soil cohesion to be distributed through three shallow soil layers using data presented by Simon and Collison (2002): 30 kPa for 0 to 0.2 m, 10 kPa for 0.2 to 0.5 m, and 1.1 kPa for 0.5 to 1.0 m. We further modified the model to account for the additional horizontal hydrostatic force on the grass hedge and the verti−

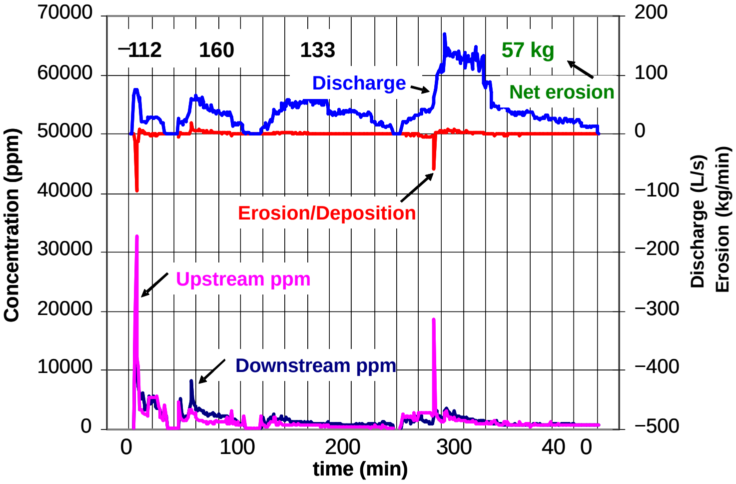

Figure 5. Discharge, concentration inferred from turbidity measurements, and apparent erosion (deposition) during the tests at L3 gully along Little Topashaw Creek (February, 2002). Net erosion (deposition) in kg during each of the four hydrographs is indicated at the top of the figure. Time intervals between hydrographs have been deleted.

Table 1. Soil characteristics of the Topashaw stream bank and the Stillwater constructed embankment.

Location and Depth	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)	ρ_b (Mg m^{-3})	K$_{sat}$ (mm h^{-1})	ϕ' (°)	c' (kPa)
Topashaw								
0 to 0.15 m	1.80	34	55	11	1.28			
0.15 to 0.3 m	0.53	66	25	8	1.42	34.8		
0.3 to 0.6 m	0.35	76	18	6	1.53	34.9	28	3.3
0.6 to 0.9 m	0.50	60	31	9			24	2.3
0.9 to 1.5 m	0.35	73	20	7			22	1.3
Stillwater								
0 to 1.2 m	0.27	57	30	13	1.78	4.8	40	0

cal force on the soil failure block due to the weight of ponded water. We ran: (1) a sensitivity analysis of F_s for a headcut in a silty soil as a function of step height, and (2) a stability analysis using the measured field conditions of our study sites. Soil cohesion and friction angle were determined from borehole shear tests (Luttenegger and Hallberg, 1981) at Topashaw and from unconfined compression testing (U.S. Navy, 1986) at Stillwater. We determined soil permeability by the shallow−well pump−in method (Amoozegar and Wilson, 1999).

Hedge vegetative characteristics were determined prior to testing by counting all stems within 0.5 m sections of each hedge; measuring the width of each hedge (in the direction of water flow) at both ends of this counted section at elevations of 0.05 and 0.3 m above the soil surface; determining the internode diameter of three representative stems at heights of 0.05, 0.3, 0.6, and 1.0 m in each hedge; and determining the largest gap in each hedge by inspection. On the test of gully 5 at Stillwater, a screen was set up in the drainage channel downslope of the test section that caught stems washed from the hedges.

RESULTS AND DISCUSSION

SOIL CHARACTERISTICS

Characteristics of the soils at the study sites are summarized in table 1. The biggest difference in soils was the greater bulk density (ρ_b) and lower saturated conductivity (K$_{sat}$) of the constructed embankment at Stillwater compared to the natural alluvial deposits at Topashaw. The particle size distributions of the surface soils were quite similar, with 54% of each lying between 32 and 250 µm. Neither site had appreciable cohesion (c') when saturated, and both sites had soil friction angles (ϕ') between 22° and 40°.

VEGETATION CHARACTERISTICS

Properties of hedge vegetation prior to testing at each site are characterized in table 2. Hedges were wider at Topashaw, but the more mature hedges were denser and had fewer gaps between plants in the steeper channels at Stillwater, perhaps because flow was excluded during the establishment period. The product of stem density, modulus of elasticity, and moment of inertia of individual stems (MEI), an indicator of a hedge's ability to resist concentrated runoff (Kouwen, 1988), was less than the value of 50 N reported to resist specific flow rates of 0.2 m^2 s^{-1} by Dunn and Dabney (1996). The lower MEI values were the result of lower stem densities due to competition between hedges planted close together on steep slopes, compact and/or infertile soil conditions, and washouts during the establishment period.

TURBIDITY MEASUREMENTS

Turbidity sensor calibrations for each site are presented in figure 6. The Stillwater soil created 40% greater turbidity than an equivalent amount of Topashaw soil, reflecting greater clay content. Dispersant, which insured complete disaggregation of samples into primary particles, increased the turbidity from each soil by 15% to 20%. Since turbidty is indicative of the number of particles, this difference reflects the degree of aggregation that remained when dried, sieved samples were added to water without dispersant. Field samples collected during the Stillwater tests fell close to or between the dispersed and undispersed calibration lines. Field samples were not collected during the Topashaw test, but the difference between dispersed and undispersed was even smaller for Topashaw soil than for the Stillwater material.

Using the calibration without dispersant (fig. 6), since we used surface water for inflow, we transformed turbidity data obtained during the controlled inflow tests into suspended sediment concentrations (fig. 5). We computed 1 min sediment loads by multiplying concentration by flow rate and estimated erosion and/or deposition as the difference in load between the locations of the two sensors at the L3 site of Little Topashaw Creek (fig. 3). Results (fig. 5) demonstrate that each time flow was increased to new highs, there was a brief period of increased turbidity during which there was net

Table 2. Average characteristics of switchgrass hedges in each gully prior to testing.

Location	Hedge Width at 0.05 m height (m)	Hedge Width at 0.30 m height (m)	Stems per Meter of Hedge (m^{-1})	Stem Internode Diameter (mm)	Average Maximum Gap in Hedge (m)	MEI[a] at 0.15 m (N)
Topashaw L3	0.45	0.65	107	4.6	0.18	25
Stillwater 5	0.25	0.54	178	5.1	0.12	51
Stillwater 6	0.23	0.52	199	4.4	0.08	32

[a] Product of stems per m^2, modulus of elasticity assumed to be 3.5 GPa, and moment of inertia calculated from average stem diameter (Dunn and Dabney, 1996).

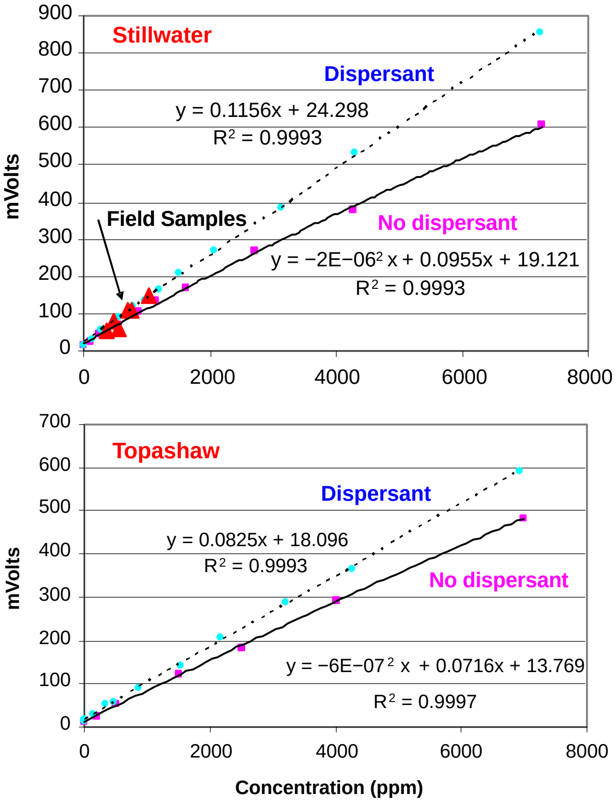

Figure 6. Calibration of turbidity sensor for soil samples collected from both locations, with and without sodium hexametaphosphate dispersant, and six field samples from the Stillwater tests.

deposition between the turbidity monitoring points. This was followed by longer periods of lower turbidity when there was slow erosion of the gully (fig. 5).

Flow Characteristics

Average flow characteristics for each run are summarized in table 3. The depth, velocity, and depth−velocity product (VD) presented are the range of time−averaged values recorded by four ADV probes (figs. 3 and 4) during the subjectively defined period of “peak” discharge. Temporal variation in flow conditions at a given point (CV = 11% for depth; CV = 29% for velocity; CV = 31% for VD) was less extreme than variation between sampling points. This reflects the different conditions immediately upslope and downslope of individual grass hedges. However, even the variation between the four ADV loggers (table 3) does not fully reflect the total variation in flow depth recorded with surveys and static manometers (fig. 7). Flow was characterized by a series of hydraulic jumps. Usually, a jump began upslope of a hedge but did not reach its sequent depth before passing the hedge (solid line in fig. 8). Some water flowed through the hedge, but more passed over the top in the jump, and then cascaded down either as free−fall or adhering to bent−over grass stems until plunging into the soil surface or a backwater pool created by the next downslope hedge. Water depth was least, and velocity and VD greatest, in the overfall nappe downslope of hedges on steep slope segments.

Total discharge for the runs was similar (within 20% of the mean) for all three gullies (table 3), with the following exceptions. Total discharge during run 1 at Topashaw was about twice as large as the Stillwater average as a result of our briefly exceeding the design discharge rate (fig. 5). This overshoot period was not considered in calculating the peak flow characteristics of this run (table 3). Total discharge during run 4 at Topashaw was only 60% of those at Stillwater because failure of one of the two pumps caused the peak to be briefer than planned (fig. 5).

The range of measured VD (table 3) exceeded the range of specific discharges previously tested in unit channels (fig. 1). The higher observed VD is evidence of flow concentration at the ADV locations. Earlier tests (fig. 1) featured grass hedges that had similar widths to those observed at Topashaw (table 2) but were denser (approximately 300 stems per meter of hedge) because they grew widely spaced in well−watered channels and thus were not subjected to competition or washouts (Temple and Dabney, 2001). Maximum measured velocities at specific points dur−

Table 3. Total discharge during each run, flow characteristics during the quasi−steady peak of each run, and total erosion or deposition between the two turbidity sensors.

Location and Run	Total Discharge (m^3)	Flow at Peak ($m^3\ s^{-1}$)	Velocity at Peak ($m\ s^{-1}$)	Depth at Peak (m)	VD[a] at Peak ($m^2\ s^{-1}$)	Erosion (+) or Deposition[b] (kg)
Topashaw						
Run 1	84	0.043	0.15 to 0.66	0.12 to 0.18	0.02 to 0.06	−112
Run 2	203	0.069	0.39 to 0.87	0.09 to 0.23	0.06 to 0.09	160
Run 3	353	0.064	0.35 to 0.85	0.10 to 0.22	0.06 to 0.11	133
Run 4	676	0.138	0.46 to 0.66	0.14 to 0.27	0.09 to 0.18	57
Stillwater 5						
Run 1	48	0.035	0.14 to 0.18	0.08 to 0.22	0.03 to 0.04	16
Run 2	198	0.079	0.16 to 2.46	0.10 to 0.29	0.04 to 0.37	40
Run 3	296	0.067	0.09 to 1.67	0.07 to 0.21	0.02 to 0.24	42
Run 4	1085	0.166	0.71 to 2.08	0.09 to 0.22	0.16 to 0.36	272
Stillwater 6						
Run 1	32	0.020	0.06	0.12 to 0.14	0.01	45
Run 2	201	0.082	0.03 to 1.51	0.10 to 0.25	0.01 to 0.17	87
Run 3	308	0.069	0.15 to 1.36	0.09 to 0.19	0.03 to 0.13	200
Run 4	1116	0.169	0.08 to 1.71	0.09 to 0.20	0.01 to 0.21	296

[a] Product of velocity and depth.
[b] Between turbidity sensors.

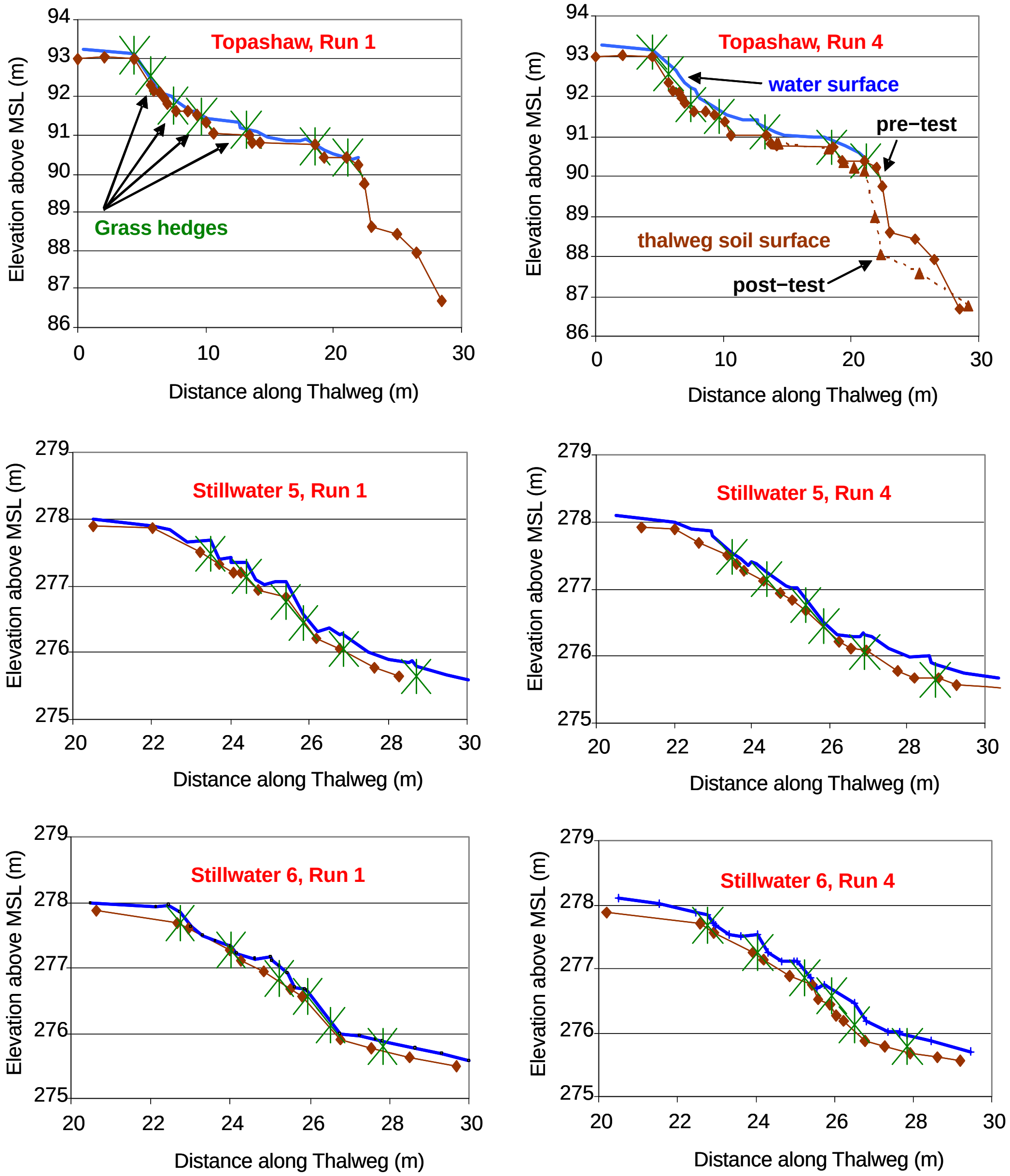

Figure 7. Gully thalweg, high water profiles, and grass hedge locations during the first and last run at each location. Thalweg changes were not measurable except as noted for Topashaw.

ing the peak of each run at Topashaw only exceeded the critical value of 0.6 m s^{-1} for bare soil by 10% to 45% (fig. 1). Since the soil was somewhat vegetated between switchgrass hedges at this site, it is not surprising that soil loss by interhedge scour, as measured by turbidity (table 3, fig. 5) and thalweg surveys, was small and did not increase with flow rate. In contrast, peak velocities during runs 2 through 4 in both Stillwater gullies exceeded the critical value by 200% to 400%. These locally high velocities were associated with “failure” (overtopping and bending) of the vegetative hedges, causing non−uniformity in flow conditions across the gully. High local velocity and VD values were associated with increased soil erosion inferred from turbidity data (table 3). Erosion rates might have been considerably higher if the Stillwater soil had not been compacted to a bulk density of 1.78 Mg m^{-3}, since erodibility of this material can decrease by two orders of magnitude if bulk density is increased from 1.7 to 1.85 Mg m^{-3} (Hanson and Temple, 2002).

The total number of stems recovered from below Stillwater gully 5 was: 4 after run 1, 22 after run 2, 11 after run 3, and 127 after run 4. Thus, overtopping bent over many segments of the hedges, but broke off and removed less than 10% of the stems originally present in the dormant hedges. Stem removal would presumably be smaller if the hedges were green and growing rather than in the dormant condition tested.

MASS FAILURE

The dominant erosion feature observed at Topashaw was the mass failure of soil blocks, one of which contained part of the most downslope hedge (fig. 7). This block failure followed deepening and widening of the plunge pool below the overfall, which initially was between 1 and 2 m high. Pre− and post−test surveying indicated a volume of 53 m^3 was eroded during the tests. Most of the removal came from creek sediments previously deposited in and around a large woody

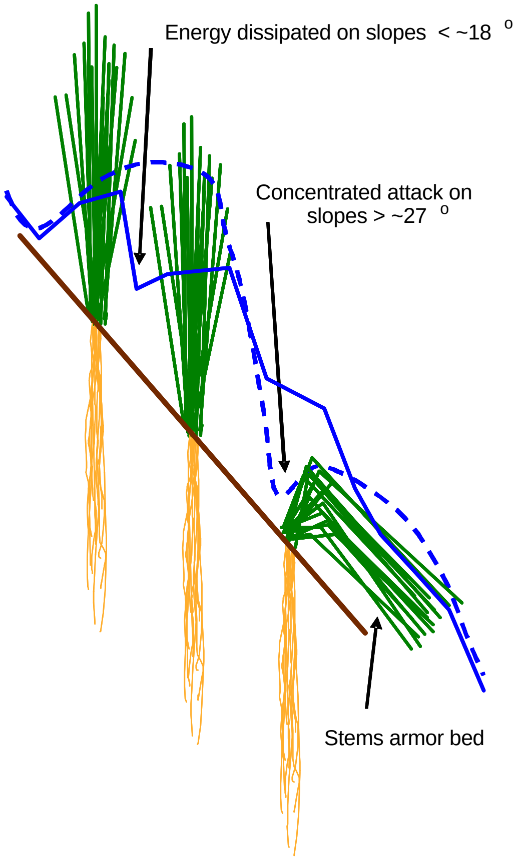

Figure 8. Schematic illustration of hydraulic jumps created by a series of grass hedges. Sequent depth may not be reached before flow passes the hedge. Observations at Stillwater suggest that for 18° slopes, energy is dissipated in individual jumps (solid line), while on slopes steeper than 27° (dashed line) a jump may skip a hedge, increasing erosivity.

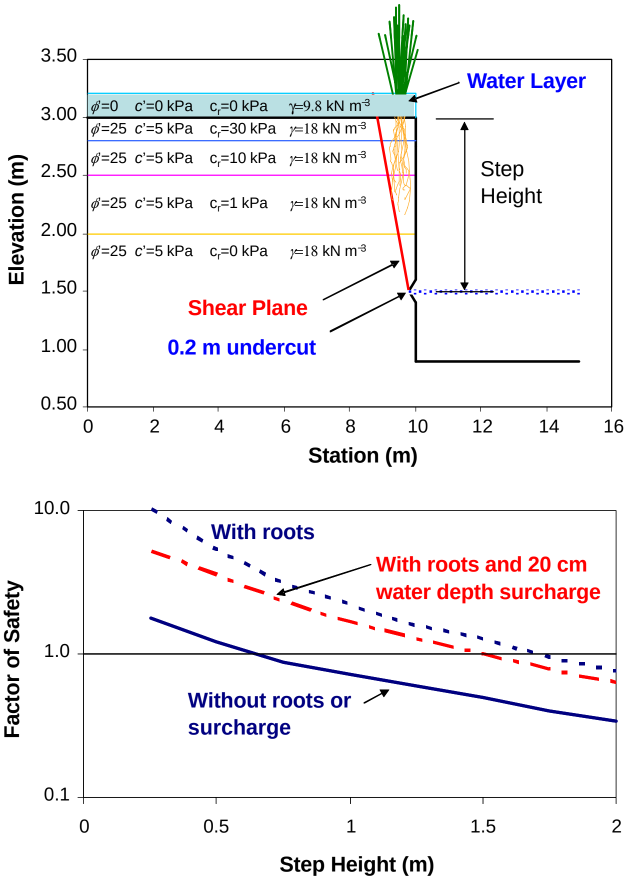

Figure 9. Use of bank−stability model to determine the effect of switchgrass hedges on the likelihood of mass failure of steps in a silty soil as a function of step height and the presence or absence of added cohesion due to switchgrass roots (c_r; based on data from Simon and Collison, 2002). Example shows a 1.5 m step height with a shear plane emerging at the soil surface 1.2 m from the bank edge.

debris structure and from older creek bank materials (fig. 3). Much of the erosion was associated with widening of the gully downslope of the lowest hedge and is therefore not fully reflected in thalweg profile (fig. 7). Based on the volume of erosion and estimates of sediment and bank bulk density (table 2), the mass of soil lost through migration of the gully headcut was 65 to 75 Mg, roughly 200 times that lost due to erosion between the turbidity sensors (table 3). No similar block failure occurred at Stillwater where step heights between hedges did not exceed 0.5 m.

Figure 9 schematically illustrates how we employed the bank stability model to conduct an analysis of the influence of vegetative hedges on the likelihood of mass failure as a function of step height. In each test, we assumed that a 57.5° (recommended for the given soil friction angle and cohesion) shear plane emerged at a 0.2 m undercut of a vertical bank made up of uniform silty material (friction angle = 30°; cohesion = 5 kPa; saturated unit weight = 18 kN m^{-3}). We calculated the factor of safety (F_S) for step heights of 0.25 to 2.0 m under three test cases: (1) saturated step with no grass roots; (2) saturated step with added cohesion due to switchgrass roots (c_r; Simon and Collison, 2002) in layers 2, 3, and 4 (fig. 8); and (3) a 20 cm deep water surcharge (layer 1) on top of a bank reinforced with switchgrass roots.

Modeled results indicate that the saturated step would be unstable for heights exceeding 0.7 m, while a saturated step reinforced with switchgrass roots would be stable up to a height of 1.7 m. Even with the extra weight of ponded water, the vegetated step was predicted to be stable to a height of about 1.5 m. However, this level of stability would be achieved only if the roots intersect the shear plane. As step height increases, the shear plane moves away from the step edge and from the root zone of a narrow strip of vegetation located at the edge. As illustrated in figure 9, the shear plane from a 1.5 m step height would emerge 1.2 m from the bank edge and could bypass much of the zone of soil reinforced by roots of a narrow grass hedge. For root reinforcement to have the modeled effect, the width of the hedge would have to increase as step height increased. For step heights up to 0.5 m, used as a design value in the current study, the shear plane would be completely contained within the root−reinforced zone of even a narrow hedge. For this design step height, F_S = 3.6 even with a 20 cm water surcharge, so no mass failure would be expected. In fact, even when soil cohesion was set to zero other than that provided by switchgrass roots, the model predicts $F_S > 1$ for step heights up to 1 m. The reader is cautioned that this analysis does not apply to cracking soils, where roots might be severed by desiccation cracks.

When we applied the bank stability model to the pre−test Topashaw thalweg profile (fig. 7), without any undercutting or root reinforcement, using geotechnical data from table 1 and assuming a saturated profile, the estimated F_S = 0.97. Thus, the initial profile approximates an equilibrium bank shape for the site without vegetation or water surcharge. At the time that mass failure was observed at Topashaw, measured pore water pressures included a saturated surface horizon, an unsaturated zone with pore water pressure = −5 kPa between 0.5 and 1.0 m depth, and another deeper saturated zone with artesian pressure of 4 kPa below 1.0 m. The scour hole created a 30 cm undercut at the toe of the plunge pool, where the shear plane emerged at a depth of 1.6 m below the hedge (about 89 m above , fig. 7). When we modeled these conditions, $F_s = 0.78$ without root reinforcement and $F_s = 1.72$ with root reinforcement. We believe that in this case, the shear plane bypassed much of the switchgrass root zone (see below) so that root reinforcement was incomplete, resulting in mass failure. When applied to the Stillwater gullies, F_s was above 10 for the duration of the tests.

ROOT REINFORCEMENT

After the Topashaw test was completed, we counted 2200 roots/m^2 protruding from the 60 cm deep failed block that had been broken and washed free by subsequent flow. The mean root diameter was 1.0 mm, median diameter was 0.6 mm, and root area ratio (ratio of the total root cross−sectional area to planer soil surface sampled) was 0.0028, similar to that reported for switchgrass at 20 cm depth by Simon and Collison (2002). This suggests that our application of their data for c_r in the mass failure analysis was appropriate. However, prior to the Topashaw block failure, and in addition to the deepening and widening of the plunge pool at the base of the overfall (Alonso et al., 2002), we observed progressive oozing and sloughing of soil away from roots as a result of seepage flow (Crosta and di Prisco, 1999) and adhesive flow (Oliveira, 2001). Thus, prior to shearing failure, some of the roots on the overfall side and below the root ball of the vegetative hedge were hanging in the air as a curtain.

After the tests at Stillwater, inspection showed that there had been some local scour of soil between hedges 3 and 4 (counted from the top, fig. 4) in gully 5 and between hedges 4 and 5 in gully 6. Both locations were on lower portions of the steepest regions of the gully (approximately 2:1, or 27°, fig. 4). Root counts made at exposed surfaces located about 30 cm below the plant crown showed that root density was higher than at the Topashaw site, but root size and root area ratio were smaller. In gully 5, we counted 3700 roots/m^2 protruding, the mean root diameter was 0.38 mm, median diameter was 0.1 mm, and root area ratio was 0.0015. In gully 6, we counted 2900 roots/m^2 protruding, the mean root diameter was 0.69 mm, median diameter was 0.4 mm, and root area ratio was 0.0022. This curtain of exposed roots undoubtedly disrupted the impinging wall jet (Alonso et al., 2002) and reduced local scour during the period of our tests but may not have provided sufficient protection during prolonged flows. This local scour could have been more severe for a less compact, more erodible soil.

DISCUSSION

Soil erosion by concentrated flow is typically described in terms of excess shear stress and a rill erodibility coefficient (e.g., Nearing et al., 1990). Shear stress, in turn, is usually calculated in terms of the slope of the channel (e.g., Mamo and Bubenzer, 2001). The rill erodibility coefficient has been calibrated as a bulk parameter based on total erosion by concentrated flow for a given set of test conditions, even though rill erosion has long been recognized to be "a complex combination of headcuts (knickpoints), detachment of soil by the shearing action of flow, and slumping of undercut sideslopes with subsequent removal by flow" (Meyer et al., 1975). In rill erosion studies, when knickpoints form and migrate, erosion rates increase substantially. A series of grass hedges encourages the development of steps and knickpoints. On the other hand, their tall thick stems greatly increase the roughness of the channel, slowing flow, and their dense root systems add to the cohesion of the soil. The question becomes: can the vegetative hedges that encourage the development of steps prevent knickpoint migration?

Conceptually, control of concentrated flow erosion by grass hedges can be divided into three flow regimes. During low flow, backwater depth is insufficient to protect the entire upstream reach between hedges, and erosion below the hedge with deposition above the hedge is the dominant process (fig. 2, top). Through an intermediate flow range, the hedges remain upright, tailwater protects the areas immediately downstream of the hedges, and the erosion/deposition processes are substantially damped (fig. 2, bottom). For higher flows, the hedges are locally overtopped or fail, flow is concentrated, and the protective capability of the hedges results from a combination of the prone stems reducing velocity near the bed, the ponding effect reducing mean velocity, and the energy loss associated with the resulting high turbulence in some areas, where boundary adjustment rates depend on soil erodibility (fig. 8).

Our test conditions were worst case, since hedges were dormant and the inflow was essentially clear. Thus, plant density and resilience were minimized, erosivity was maximized, and there was little opportunity for sediment deposition. Only early during the first run at Topashaw, where loose soil in the forebay scoured, was any deposition observed. Also at the Topashaw site, an extreme runoff event was simulated while the creek level remained at base flow. Under normal runoff conditions in a riparian gully, elevated creek stages would provide a backwater downstream from the lowest hedge that would dissipate flow energy and would provide hydrostatic pressure to balance bank weight and so increase F_s.

Erosion by mass failure was not observed or predicted to occur if the step height between grass hedges was kept close to the design height of 0.5 m. On the other hand, it was the dominant failure mechanism when step height at the lowest hedge exceeded 1 to 2 m. The observed block failure at Topashaw occurred during the run with the greatest flow, the longest duration, and a day after the initial tests had evidently saturated deeper portions of the soil profile.

Observations at Stillwater suggest that there is a practical upper limit to the gully slope that can be successfully be treated with grass hedges even when vertical intervals are <0.5 m because of: (1) retardation of hedge development due to plant crowding, and (2) the dimensions of hydraulic jumps. Switchgrass is a plant that thrives in full sunlight. When planted at a vertical spacing of 0.5 m, horizontal spacing would be only 1.0 m on a 2:1 (horizontal to vertical) slope. This crowding would cause competition that would limit hedge growth and development (hedge width, stem density, stem diameter). The situation would be aggravated in northern−facing or deeply incised gullies.

The upstream Froude number controls the height, length, and shape of a hydraulic jump (Chow, 1959). Increasing bed slope generally increases the Froude number, increases the height and length of a hydraulic jump, and moves the jump initiation point downslope closer to a hedge. When the sequent depth of the jump exceeds the flow depth at a hedge, the maximum flow depth is not reached until the flow is passed the hedge and the jump takes the form of a "standing swell," which describes well the observations in our tests (figs. 7 and 8). On the steepest portion of the Stillwater gullies, the overfall nappe leaving the swell bypassed the next successive hedge and plunged into the backwater created by the second downslope hedge together with the change in slope at the toe. This greater fall allowed acceleration of the overfall nappe and the subsequent wall jet (Alonso et al., 2002) and enhanced the local scour that exposed roots. Such bypass cascades were not observed with hedges placed on 3:1 slopes but were observed in both gullies with 2:1 slope segments. These results suggest that 3:1 (18°) slopes may be a practical limit to the ability of a series of vegetative hedges to dissipate energy and resist washout by concentrated flows. Empirical relationships provided by Chow (1959) concerning the height and length of hydraulic jumps on steep slopes support the conclusion that a 0.5 m vertical hedge spacing on a 3:1 slope would allow each hedge to create its own jump and backwater without being bypassed.

CONCLUSION

The results of this study indicate that stabilizing gullies with a series of vegetative hedges has potential, but more research is needed to determine the reliability of the practice. Established switchgrass hedges placed with about a 0.5 m vertical interval at slopes less than or equal to 3:1 (horizontal to vertical) were effective in preventing measurable erosion of concentrated flow channels during 6 h of testing with specific discharges up to 0.2 $m^2 s^{-1}$. Energy was effectively dissipated in a series of cascading hydraulic jumps. Erosion by mass failure was not observed or predicted to occur when step height between vegetative hedges was less than or equal to 0.5 m. However, mass failure was the dominant failure mechanism where conditions at the gully mouth produced a hedge with a 1 to 2 m overfall. More research is needed to determine the success of gully control by a series of grass hedges under real−world conditions over several seasons or years, and to quantify the risk that soil sloughing from around roots as a result of seepage forces, combined with scour from impinging wall jets, could undermine hedges on more erodible soils.

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