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FLOW PATHWAYS AND SEDIMENT TRAPPING IN A FIELD-SCALE VEGETATIVE FILTER

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ABSTRACT. *Vegetative filters (VF) are a best management practice installed in many areas to control sediment movement to water bodies. It is commonly assumed that runoff proceeds perpendicularly across a VF as sheet flow. However, there is little research information on natural pathways of water movement and performance of field-scale VF. The objectives of this study were: (1) to quantify the performance of a VF where the flow path is not controlled by artificial borders and flow path lengths are field-scale, and (2) to develop methods to detect and quantify overland flow convergence and divergence in a VF. Our hypothesis is that flow converges and diverges in field-scale VF and that flow pathways that define flow convergence and divergence areas can be predicted using high-resolution topography (i.e., maps). Overland flow and sediment mass flow were monitored in two 13 × 15 m subareas of a 13 × 225 m grass buffer located in Polk County in east-central Nebraska. Monitoring included a high-resolution survey to 3 cm resolution, dye tracer studies to identify flow pathways, and measurement of maximum flow depths at 51 points in each subarea. Despite relatively planar topography (a result of grading for surface irrigation), there were converging and diverging areas of overland flow in the buffer subareas. Convergence ratios ranged from −1.55 to 0.34. Predicted flow pathways using the high-resolution topography (i.e., map) closely followed actual flow paths. Overland flow was not uniformly distributed, and flow depths were not uniform across the subareas. Despite converging and diverging flow, the field-scale VF trapped approximately 80% of the incoming sediment.*

Keywords. *Flow convergence, Grass filters, Overland flow, Sediment trapping, Vegetative filters.*

Vegetative filters (VF) are a best management practice installed in many areas to control sediment movement to water bodies. The use of VF has increased in part because of the National Conservation Buffer Initiative implemented by the USDA Natural Resources Conservation Service. VF that are characterized by concentrated flow should be less effective at sediment removal than VF with shallow, uniformly distributed overland flow (Dillaha et al., 1989). Results from Dosskey et al. (2002) indicated that for their study in southeastern Nebraska, concentrated flow through riparian buffers can be substantial and that filtering effectiveness may be limited. Helmers et al. (2005) found through modeling that converging flow areas can negatively impact the performance of a VF depending on the degree of convergence in the VF. While there has been a significant amount of research on the performance of VF, little research is available on pathways of water movement through VF. In particular, there is little information on the performance of VF where the pathways are not bounded by artificial borders and where flow pathways are field-scale. Borders may impact the natural flow patterns of the overland flow because the flow is confined between the borders and lateral flow into and/or out of the bordered area cannot occur. These altered flow patterns could have a reduced overland flow velocity, and thus the sediment transport capacity would be reduced because lateral inflow into the bordered area is prevented. As a result, this alteration of flow patterns could result in overpredicting VF sediment trapping in comparison to "natural" flow conditions. In addition, within the bordered plots, there is the potential for flow convergence, which could increase the transport capacity. The presence of borders may inhibit water from following the natural topography or even microtopographic features on relatively uniform cross-slope filters. Thus, the borders could force the water to flow through pathways it would not travel if the borders were not present. This could have a positive or negative effect on sediment transport capacity depending on whether flow converges or diverges compared to its natural flow pathway. Microtopography likely causes some level of convergence or divergence in most VF studies. Since little information is available on flow through a VF with unconfined flow pathways, there is a need for information on the pattern of flow through VF systems where flow pathways are not confined to better understand VF performance.

The objectives of this research were: (1) to quantify the performance of a VF where the flow path is not controlled by artificial borders and flow path lengths are field-scale, and (2) to develop methods to detect and quantify overland flow convergence and divergence in a VF. Our hypothesis is that

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flow converges and diverges in field-scale VF and that flow pathways that define flow convergence and divergence areas can be predicted using high-resolution topographic data.

BACKGROUND ON VEGETATIVE FILTER STUDIES

There has been an extensive amount of research on the sediment-trapping ability of VF both from a monitoring and modeling perspective. In this article, we discuss the monitoring aspects of VF performance; Helmers et al. (2005) discuss in greater detail modeling of sediment trapping in a VF. A summary of experimental studies on VF, specifically the sediment-trapping performance of these systems, is shown in table 1. Many of the studies had small source area to buffer area ratios, often well below the value expected in typical applications. An area ratio greater than 20:1 may be expected under most field conditions. Of the studies reported, 50% had an area ratio less than 5:1 (fig. 1). NRCS (1999) guidelines for the ratio of drainage area to filter strip area allow for maximum area ratios between 70:1 and 50:1 depending on the RUSLE-R factor in the region. Typically, NRCS designs are based on a 30:1 ratio.

Most past studies were performed on plot-scale VF systems, in particular, bordered plots. We refer to the case of bordered plots as a confined flow path condition, with the case of unbordered plots being an unconfined flow path

Table 1. Summary of studies on sediment reduction by vegetative filters.

Reference	Location	Length of Filter (m)	Area Ratio	Site Condition: Slope (%)	Site Condition: Soil Texture	Site Condition: Range of Inflow Rate ($L\ m^{-1}\ s^{-1}$)	Mass Reduction of Sediment (%)	Comments
Arora et al. (1996)[a]	Iowa	20.12	30:1	3	SiCL		83.6	1 event (E6)
		20.12	15:1	3	SiCL		87.6	1 event (E6)
Arora et al. (1993)[a]	Iowa	20.12	15:1	3	SiCL		45.8	1 event
		20.12	30:1	3	SiCL		40.6	1 event
Barfield et al. (1998)[b]	Kentucky	4.57	4.84:1	9	SiL		97	2 events
		9.14	2.42:1	9	SiL		99.9	2 events
		13.72	1.61:1	9	SiL		99.7	2 events
Coyne et al. (1995)[b]	Kentucky	9	2.46:1	9	SiL	0.21	99	1 event, no till upslope
		9	2.46:1	9	SiL	0.25	99	1 event, conventional tillage upslope
Coyne et al. (1998)[b]	Kentucky	4.5	4.1:1	9	SiL		95	2 events
		9	1.5:1	9	SiL		98	2 events
Daniels and Gilliam (1996)[c]	North Carolina	3	29:1	4.9	SL to CL		59	2 growing seasons
		6	14:1	4.9	SL to CL		61	2 growing seasons
		3	29:1	2.1	SL to CL		45	2 growing seasons
		6	14:1	2.1	SL to CL		57	2 growing seasons
Dillaha et al. (1989)[b]	Virginia	9.1	2:1	11	SiL		97.5	6 events
		4.6	4:1	11	SiL		86	6 events
		9.1	2:1	16	SiL		70.5	6 events
		4.6	4:1	16	SiL		53.5	6 events
		9.1	2:1	5 (cross-slope = 4%)	SiL		93	6 events
		4.6	4:1	5 (cross-slope = 4%)	SiL		83.5	6 events
Hall et al. (1983)[a]	Pennsylvania	6	3.67:1	14	SiCL		76	1 growing season
Hayes and Hairston (1983)[a]	Mississippi	25.7 (2.6 m wide)		2.35	SiC and SiCL	0.01 to 1.53	60	2 plots: 18 events (plot 1), and 16 events (plot 2)
Lee et al. (2000)[b]	Iowa	7.1	3.11:1	5	SiCL		70	2 events
Magette et al. (1989)[b]	Maryland	9.2	2.39:1	2.7	SL		81.1	
		4.6	4.78:1	2.7	SL		71.2	
		9.2	2.39:1	2.7	SL		94.7	
		4.6	4.78:1	2.7	SL		77.3	
		9.2	2.39:1	4.1	SL		70.4	
		4.6	4.78:1	4.1	SL		48.5	
Munoz-Carpena et al. (1999)[a]	North Carolina	4.3	9:1	5-7	SiL	0.03 to 0.57	86	5 events
		8.5	4.5:1	5-7	SiL	0.36 to 0.63	93	2 events
Parsons et al. (1994)[a]	North Carolina	4.3	8.6:1	1.9	SCL		78	11 events
		8.5	4.35:1	1.9	SCL		81	11 events
Parsons et al. (1990)[a]	North Carolina	4.3	8.6:1	2.5-4	SCL		75	1 event
		8.5	4.35:1	2.5-4	SCL		85	1 event

Reference	Location	Length of Filter (m)	Area Ratio	Site Condition: Slope (%)	Site Condition: Soil Texture	Site Condition: Range of Inflow Rate ($L\ m^{-1}\ s^{-1}$)	Mass Reduction of Sediment (%)	Comments
Patty et al. (1997)[a]	France	6	8.33:1	7	L		93	1 event
		12	4.17:1	7	L		100	1 event
		18	2.78:1	7	L		100	1 event
		6	8.33:1	10	L		100	1 event
		12	4.17:1	10	L		100	1 event
		18	2.78:1	10	L		100	1 event
		6	8.33:1	15	L		99	1 event
		12	4.17:1	15	L		100	1 event
		18	2.78:1	15	L		100	1 event
Schmitt et al. (1999)[d]	Nebraska	7.5	10.8:1	6-7	SiCL	0.42	95	1 event, 25-year-old grass
		15	5.4:1		SiCL	0.42	99	1 event, 25-year-old grass
		7.5	10.8:1		SiCL	0.42	85	1 event, 2-year-old grass
		15	5.4:1		SiCL	0.42	96	1 event, 2-year-old grass
Sheridan et al. (1999)[c]	Georgia	8	33:1	2.5	LS		81	103 events
Tingle et al. (1998)[b]	Mississippi	0.5	55:1	3	SiC		85	6 events
		1	22:1	3	SiC		90	6 events
		2	11:1	3	SiC		90	6 events
		3	7.33:1	3	SiC		91	6 events
		4	5.5:1	3	SiC		96	6 events
Van Dijk et al. (1996)[d]	Netherlands	1		5.2		0.50	49.5	2 events
		4		5.2		0.50	78.5	2 events
		5		5.2		0.50	60	1 event
		10		5.2		0.50	92	1 event
		5		2.3		0.50	73	2 events
		10		2.3		0.50	94	2 events
		5		2.5		0.50	64.5	2 events
		10		2.5		0.50	99	2 events
		10		4.3		0.50	84	1 event
		5		8.5		0.50	92	2 events
		10		8.5		0.50	97.5	2 events
		1		8.5		0.50	58	1 event
		4		8.5		0.50	89	1 event
		5		7		0.50 to 1.00	74.7	3 events

[a] Plot study, natural rainfall.
[b] Plot study, simulated rainfall.
[c] Field study, natural rainfall.
[d] Plot study, simulated runoff.

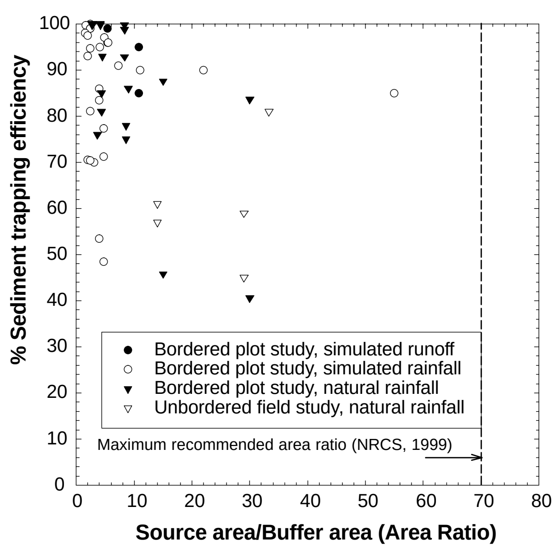

Figure 1. Sediment trapping efficiency as a function of area ratio for ratios ≤80 (based on references listed in table 1).

condition. A potential problem with confined flow paths is that the natural flow paths are disrupted, which can reduce flow or accentuate flow concentration compared to natural conditions (as in the case of Dillaha et al., 1989). In some cases, flow that would enter the plot is prevented from doing so, and the discharge rate out of the plot would be less than for the case where the flow is not confined. This reduction in discharge rate may impact the transport capacity of the water flow through the VF.

The studies by Daniels and Gilliam (1996) and Sheridan et al. (1999) were the only studies found that were performed on unbordered, field-scale VF (unconfined flow path). Daniels and Gilliam (1996) state that even though VF are an accepted and highly promoted practice, little quantitative data exist on their effectiveness under unconfined flow path conditions. Their study provided some data on the variability of the water quality along the field edge and within the VF but not how this variability may have been affected by the topography or microtopography of the land surface.

Dillaha et al. (1989) reported results from experiments on two filter-strip plots with a cross-slope that encouraged concentrated flow against the border. However, the predominate slope of these plots was different from that of the plots without a cross-slope, making it difficult to assess the comparative effects of the concentration of flow on filter efficiency. Dillaha et al. (1989) also concluded that the effectiveness of the VF decreased with time as sediment accumulated in the filter strip.

Materials and Methods

Site Description

Overland flow and sediment mass flow into and through a vegetative filter (VF) were monitored at the Clear Creek Buffer, Polk County, Nebraska. The 13 × 250 m VF was established in the spring of 1999, with a mix of big bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*), and Indiangrass (*Sorghastrum nutans*). The area upstream of the VF is a furrow-irrigated field with furrow lengths of approximately 670 m and a crop row spacing of 0.762 m. Water is applied to the furrows using gated pipe. The slope of the field is about 1%, and corn was grown in the field during the investigation. The field, including the filter, had been graded for furrow irrigation many years prior to this project. The soil at the site is a Hord silt loam (fine-silty, mixed, mesic Pachic Haplustolls) (USDA-SCS, 1974). Two specific areas (east grid and west grid) were selected for investigation. Each area extends approximately 13 m in the primary direction of flow and 15 m in the direction perpendicular to the primary direction of flow.

The vegetation in the grid areas was control burned on 10 April 2001 and subsequently not mowed or fertilized. The grass in the buffer was distributed in clumps, with bare soil between the clumps. From vegetation density measurements taken at the site, the number of stems per unit area ranged from approximately 700 to 1100 stems m^{-2}, which is lower than the densities commonly reported for other grass species. Haan et al. (1994) provide grass densities for a variety of vegetation types based on Temple et al. (1987). The lowest density was for a grass mixture, with approximately 2150 stems m^{-2}, and the maximum grass density was for a Bermuda grass, with a density of about 5380 stems m^{-2}. Temple et al. (1987) report multiplying these densities by 1/3, 2/3, 1, 4/3, and 5/3 for poor, fair, good, very good, and excellent covers, respectively. Based on these reports, the buffer would be classified with poor to fair cover.

Topography

Detailed topographic maps, termed high-resolution topography, were created for each grid (fig. 2). The contours were developed with Surfer version 6.04 (Golden Software, 1997) using the kriging interpolation scheme. The location and elevation data (*x-y-z* coordinates) were obtained during the fall of 2001 using a total station (Nikon DTM-520) with measurement points on a 1.5 m grid in the 13 × 15 m area and on a 3 m grid outside the 13 × 15 m area. Additionally, measurements (*x-y-z* coordinates) were taken at the locations of the monitoring equipment (discussed below) at the site.

An initial survey had been performed at the site in the spring of 2000 and is termed the low-resolution topography. In this survey, conducted using a laser level, contours with approximately a 6 cm interval were followed and points approximately 8 m apart were located along the contour. A mapping-grade Global Positioning System (GPS) with sub-meter accuracy was used to determine the *x-y* coordinates of the contours. Again, contours were developed with Surfer version 6.04 (Golden Software, 1997) using the kriging interpolation scheme.

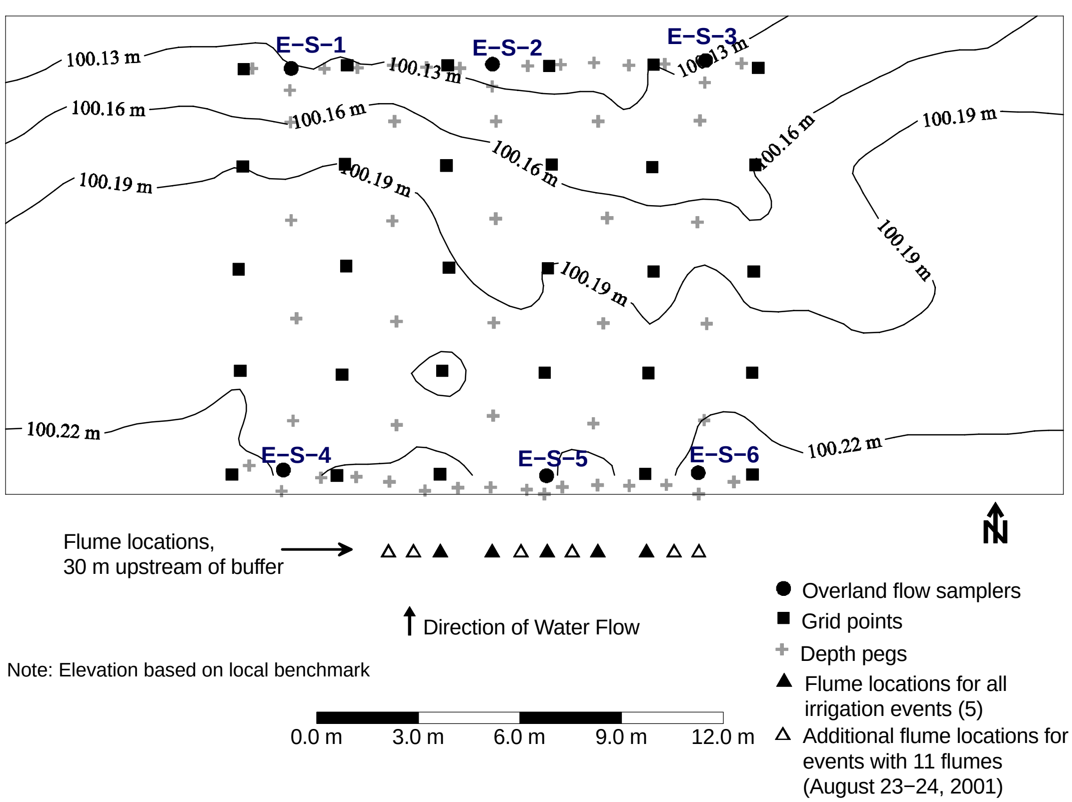

Figure 2. High-resolution east grid topography from 2001 survey.

MONITORING EQUIPMENT

Water and sediment inflow and outflow and maximum depth of flow were monitored at each grid area. Direction of flow was determined using dye tracer mapping. New overland flow samplers, which sample a 0.3 m wide section, have been developed during the course of this research project (Eisenhauer et al., 2002). Six samplers were installed in each grid area, three at both the upstream and downstream edges of the filter (fig. 2). The overland flow sampler has a capacity to sample a flow rate of 1.3 L s^{-1} and a total runoff volume of about 20,000 L. Wingwalls for minimizing flow divergence and convergence in the immediate area around the sampler extend 0.5 m upstream of the sump and are placed 0.3 m apart and approximately parallel with the flow direction. The sampler includes a 0.46 m diameter by 0.91 m long polyvinylchloride (PVC) sump that extends 0.76 m below grade. The wingwalls direct water into the sump. To remove coarse sediment and floating debris, a 0.15 m diameter PVC well-screen with 1.5 mm slotted openings is placed in the sump, and water entering the sump first encounters the well-screen. A sump pump, powered by a 12 V marine battery and triggered by electrodes spaced vertically 0.3 m apart, controls the water level in the sump. The time to fill the volume from when the pump shuts off to when it is triggered can be recorded to calculate the inflow rate to the sump. The water in the sump is pumped into three pairs of orifice-sample tube assemblies placed in series with each other. The discharge from the small orifice in each assembly flows into the next sampler tube. The discharge from the larger orifice in each assembly is discharged back to the vegetative filter. The sample tubes are designated as tube A, B, or C in sequence from the larger assembly to the smaller assembly. The sampler is designed to work as follows. For relatively small runoff events (<75 L), the split sample is retained in tube A. For larger runoff events (<943 L), the split samples are retained in tubes A and B. For runoff volume that exceeds the capacity of tubes A and B, a split of the runoff flows to tube C. Following a runoff event, a representative water sample is collected from each tube for use in estimating the mass of contaminant in the runoff water. This water sample is a flow-weighted sample.

Additional inflow measurements to each grid were determined using trapezoidal flumes (60° V-notch) installed 30 m up the furrow from each grid (fig. 2). The flumes were installed in this position to ensure free flow through the flumes. Flow in the furrows was bounded by the tillage ridges until the upstream edge of the vegetative filter. The flumes have a capacity of approximately 2 L s^{-1}. Replogle et al. (1990) stated that flumes of this type have a standard accuracy of 2% to 5%. The flow rate through the flumes was determined by manually recording the head in the flume. The head was recorded at approximately 1 min intervals during the first 10 min of flow, at 5 min intervals for the next 20 min of flow, every 10 min for the next 60 min of flow, and then every 30 min until the recession limb of the hydrograph, when readings were taken every 1 to 2 min. The readings were taken more frequently during the rising and recession limbs of the hydrograph, and since the water measured by the flumes was supplied by surface irrigation, the flow rate was relatively constant once the peak flow was reached until irrigation ceased and recession began. These head readings were used to determine the inflow hydrograph.

Within selected furrows, runoff was measured with a flume and with a sampler in the same furrow on the upstream edge of the VF. The runoff hydrograph obtained by the two methods (flume and overland flow sampler) produced essentially equal hydrographs (Eisenhauer et al., 2002).

During runoff experiments, maximum depth of flow was monitored at 51 locations in each grid area (fig. 2). The depth was monitored using small sections of PVC that fit over 1.27 cm diameter metal rod. A soluble paste (Kolor Kut) was applied to the PVC and was subsequently washed off the exterior of the PVC up to the maximum depth of water flow. Fifteen depth pegs were installed on the downstream edge of the filter, 16 depth pegs on the upstream edge, and 20 depth pegs on the interior of each grid area (fig. 2).

Dye tracer tests were performed by introducing fluorescent red dye (NSF certified for potable water) and monitoring the movement of the dye through the VF relative to the established grid locations (fig. 2). Approximately 250 mL of dye tracer was introduced as a slug at a point in the filter, and the movement of the dye tracer was visually monitored and mapped as it flowed through the filter. This information was used to evaluate the ability to predict the direction of overland flow in the filter using the topographic maps.

RUNOFF EXPERIMENTS

Five controlled runoff experiments using water supplied through furrow irrigation were conducted during the summers of 2001 and 2002 (table 2). Additionally, a natural rainfall-runoff event was monitored on 11 May 2002 (3.84 cm precipitation, 6.5 h approximate duration).

The event on 23 August 2001 was in the west grid with 11 irrigation gates open at the upstream end of the field. Within the furrows where water was applied, there were two furrows that were omitted, so 11 of the 13 contiguous furrows had water applied. The two omitted furrows were at the division between passes of 6-row farm equipment. The easternmost furrow that had water was the eastern edge of the west grid, 1.5 m east of sampler 6 (W-S-6). The event on 24 August 2001 was in the east grid. The easternmost furrow that was irrigated was the row where sampler 6 (E-S-6) was located.

The events on 18 July, 2 August, and 13 August 2001 and 1 July 2002 were typical irrigation events. Water was applied in every other furrow and only in non-wheel track furrows. The 23 and 24 August events were conducted to simulate greater flow rates and sediment loading than observed in the

Table 2. Irrigation runoff events at the Clear Creek Buffer.

Event Date	Approx. Set Time (h)	Approx. Inflow Rate to Furrow (upstream end of field) (L s^{-1})	Watered Furrow Spacing (m)	No. of Gates Open Upstream of Each Grid Area
18 July 2001	12	1.4	1.52	11
2 Aug. 2001	10	1.0	1.52	15 until 150 min prior to shutoff, and then 11
13 Aug. 2001	12	1.2	1.52	13
23 and 24 Aug. 2001	4	2.0	0.76 and 1.52	11
1 July 2002	12	1.4	1.52	11

irrigation events. The purpose of this was to try and achieve a flow rate and sediment mass flux consistent with a storm having a greater return period. The target flow rates and sediment injection rates were estimated using the UH utility in VFSMOD (Munoz-Carpena and Parsons, 2000). This utility uses the NRCS curve number method, unit hydrograph, and Modified Universal Soil Loss Equation (MUSLE) to compute runoff and sediment loading from a source area. A 1-hour duration, 10-year return period precipitation event was used to estimate loading.

Water was applied in 11 of 13 furrows rather than just the non-wheel track furrows, and soil was injected into the furrow to induce greater sediment loading. The soil injection rate was approximately 1500 g min^{-1} with an injection time of approximately 45 to 60 min. The soil was injected directly into the water stream approximately 4 to 5 m upstream of the flume locations in each of the 11 furrows using a 19 L, HDPE cylindrical tank with an orifice on the bottom to meter outflow at the desired injection rate. The sediment used was on-site soil, so the parent material was consistent with the eroded sediment from the other events. The sediment had been air-dried and sieved and was injected in the air-dried condition. A particle size distribution of the sediment at the flume location was determined from sediment collected in the water samples at the flume location. Based on sediment samples from the flume locations, the particle size distribution for the event where sediment was injected compared relatively well with the particle size distribution for natural irrigation events. The mean particle size (d_{50}) was 0.02 mm for the injection event and 0.01 mm for the natural events.

Inflow and outflow hydrographs were developed from the flume and overland flow sampler data. Ridges of soil were placed immediately upstream of each sampler at the VF entrance to direct flow from one furrow into the sampler. However, there is the possibility that some localized overtopping of furrows occurred during the 11 May 2002 rainfall-runoff event because the furrow ridges had been established the previous summer.

Suspended sediment concentration from runoff samples was determined by filtration of subsamples using a 1 µm filter for the 2001 events. The evaporation method for determining sediment concentration was used with a dissolved solids correction applied to the total solids concentration to obtain the suspended solids concentration for the events in 2002. The dissolved solids correction was determined based on the dissolved solids concentration from the five to eight samples for each event that were filtered. For the first three events in 2001 (18 July, 2 August, and 13 August) and the 1 July 2002 event, approximately five samples for water quality analysis were taken from each flume at approximately 10, 30, 60, 120, and 180 min after initialization of flow in the flume. These sampling times were used so that sediment concentration data were collected both at the beginning and during the runoff period while maintaining a reasonable number of samples for testing. For the 23 and 24 August 2001 events, additional samples were collected during the time when sediment was injected into the furrow. The sampling times for these events were approximately 15, 30, 40, 50, 60, 70, 80, 90, 120, and 165 min after initialization of flow in the furrow. Sediment injection started 30 min after flow began in the furrow and continued for 45 to 60 min.

The sediment concentration at each sampling time was multiplied by the corresponding water flow rate to determine the sediment mass flow rate. For times when samples were not collected but flow rates were measured, a linear interpolation in sediment concentration was used to estimate mass loading. For the runoff period after samples were collected, the final measured sediment concentration was usually used to estimate mass loading. There were a few cases where the final water sample had a greater sediment concentration than any of the other samples. In these isolated cases, sediment concentration was estimated by a linear interpolation from the time the sample was taken to the end of the event, with sediment concentration being zero at the end of the event. Total mass flow was determined by calculating the area under the mass loading rate curve. Total mass loading was used with the volume of water flow to determine an average sediment concentration.

As discussed previously, the overland flow samplers did not collect water quality samples at various times, but rather portions of the runoff were retained in each of three PVC tubes (tubes A, B, and C). For each experiment, a water sample was collected from each of these containers and analyzed for sediment concentration.

The average inflow of water and sediment to the filter was computed using runoff measurements from the flumes and samplers. The sediment load measured at the flume locations likely includes sediment that would be deposited prior to entering the VF due to backwater effects caused by the increased hydraulic roughness of the VF. The samplers were positioned at the upstream edge of the VF but had no vegetation upstream of the entrance to the filter, and water from adjacent furrows was prevented from entering the furrow with the overland flow sampler by berms placed upstream of the sampler. So, the backwater effects upstream of the overland flow sampler were expected to be reduced compared to a condition where flow is allowed to spread out prior to entering a sampler. As a result, the sediment loading computed from the overland flow samplers is estimated to be loading prior to significant deposition due to backwater effects. So, the inflow of sediment estimated for these tests includes some sediment that was likely deposited due to backwater effects directly upstream of the VF. For conditions where sampling is performed on the upstream edge of VF and flow is not confined within furrows to minimize backwater effects prior to entering the sampler, the sampling equipment should be placed farther upslope to prevent the sampler from acting like a drain (Eisenhauer et al., 2002).

Results

Water and Sediment Flow

Inflow and outflow volumes were computed using data from the flumes and overland flow samplers by determining the area under the corresponding hydrographs (table 3). The mean inflow to the filter was computed using seven monitored furrows (four flumes, two samplers, and one furrow with a flume and a sampler) in each grid area for all the events, except the 23 and 24 August 2001 events when eleven furrows (eleven flumes) were monitored. Inflow to the filter varied among furrows, so in preparing inflow hydrograph information, the mean inflow from the flumes and the upstream overland flow samplers is reported with 95% confidence interval error bars on the mean (figs. 3, 4, and 5). The inflow hydrographs represent a mean inflow over several

Table 3. Summary of inflow and outflow volumes for the west grid and east grid (bold indicates converging flow).

	18 July 2001	2 Aug. 2001	13 Aug. 2001	23 Aug. 2001	1 July 2002	11 May 2002
West grid inflow volume (L m^{-1})						
Average	7416	4090	7448	12600	12444	9587
Standard deviation	4928	3841	2273	6415	5381	1262
West grid outflow volume (L m^{-1})						
Sampler 1 (W-S-1)	1242[a]	259	839	1375	2253	1218
Sampler 2 (W-S-2)	**17268**	**10095**	**16329**	**16819**	**22443**	**16894**
Sampler 3 (W-S-3)	**11425**	**11451**	**9360**	**12827**	6636	**11879**
Average	9978	7268	8843	10340	10444	9997
West grid % reduction in volume	−35	−78	−19	18	16	−4
	18 July 2001	2 Aug. 2001	13 Aug. 2001	24 Aug. 2001	1 July 2002	11 May 2002
East grid inflow volume (L m^{-1})						
Average	17900	7120	14389	10397	9246	8457
Standard deviation	5391	3462	6817	3911	4913	4630
East grid outflow volume (L m^{-1})						
Sampler 1 (E-S-1)	12404	5490	10108	1866	4244	--[b]
Sampler 2 (E-S-2)	**24429**	**9894**	**19020**	9531	8493	4657
Sampler 3 (E-S-3)	9599	2089	7369	**13142**	2971	3326
Average	15477	5825	12166	8180	5236	3992
East grid % reduction in volume	14	18	15	21	43	53

[a] Value for volume of west grid sampler 1 on 18 July 2001 is an estimate.
[b] Sampler not operational.

flumes, but the outflow hydrographs were developed for each sampler on the downstream edge of the filter. Example hydrographs for the 13 August 2001 event show that the flow rate at the downstream edge of the VF varied with position, and the peak outflow rate was greater than the average peak inflow rate, indicating convergence of overland flow (figs. 3 and 4). The 23 and 24 August 2001 events had greater inflow rates, but similar to the other events, the flow rate at the downstream edge of the VF varied with position, and the peak outflow rate was greater than the average peak inflow rate (fig. 5).

If there was no infiltration and if overland flow was uniformly distributed in the VF, we would expect the same inflow as outflow volume (for a case with no rainfall), and if infiltration is considered with uniformly distributed flow, we would expect the outflow volume to be less than the inflow. However, the outflow volumes show that, for the west grid, there was a greater average outflow than average inflow at the locations monitored for four of the six events (table 3). For the east grid, there was an overall reduction in outflow volume, but there were individual samplers that had greater outflow than average inflow. Greater outflow than inflow indicates convergence of overland flow within the VF. For all events in the west grid, the peak outflow rate was greater than the average peak inflow rates (table 4). In the east grid, four of the six peak outflow rates were greater than the corresponding average peak inflow rate.

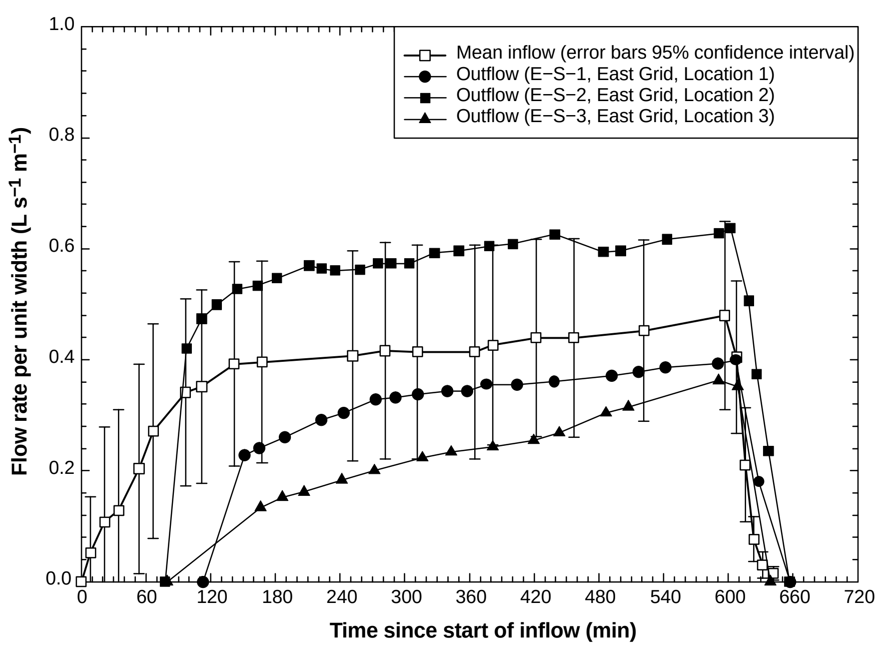

Figure 3. Hydrographs for east grid, 13 August 2001.

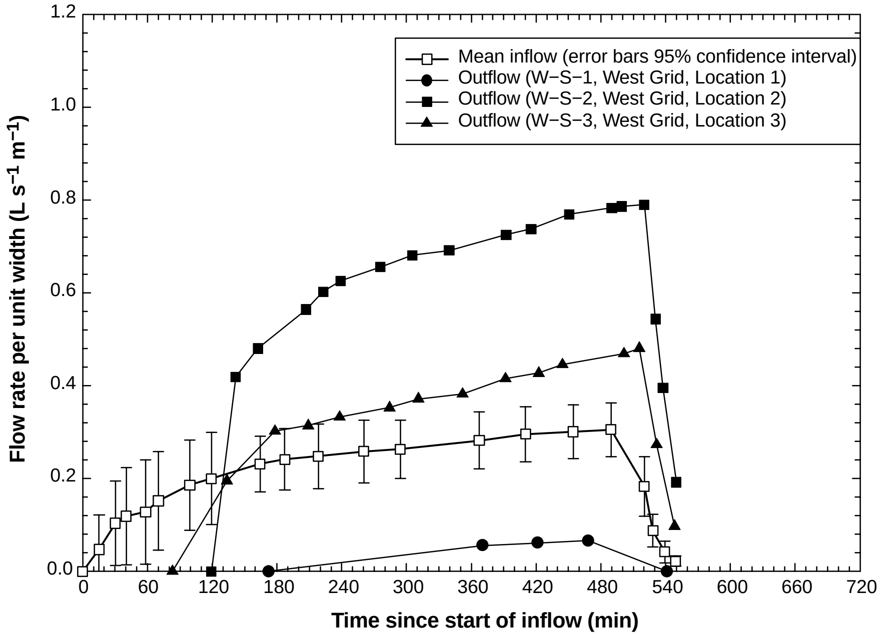

Figure 4. Hydrographs for west grid, 13 August 2001.

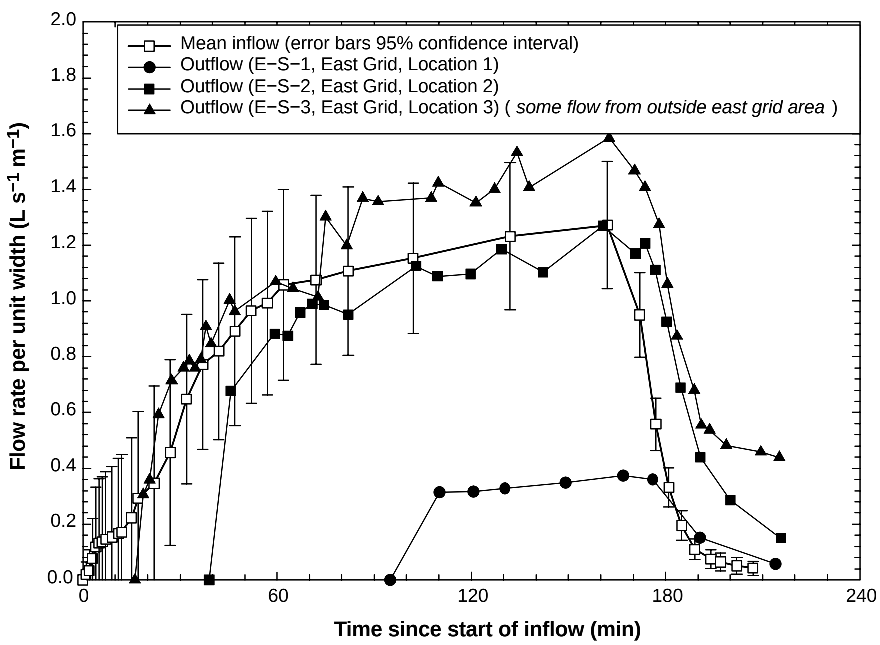

Figure 5. Hydrographs for east grid, 24 August 2001.

Table 4. Summary of peak inflow and outflow rates for the west grid and east grid.

	18 July 2001	2 Aug. 2001	13 Aug. 2001	23 Aug. 2001	1 July 2002	11 May 2002
West grid flow rates (L m^{-1} s^{-1})						
Mean peak inflow	0.26	0.40	0.30	1.32	0.56	1.23
Peak outflow	0.91	1.10	0.79	1.88	1.56	1.52
	18 July 2001	2 Aug. 2001	13 Aug. 2001	24 Aug. 2001	1 July 2002	11 May 2002
East grid flow rates (L m^{-1} s^{-1})						
Mean peak inflow	0.61	0.40	0.48	1.27	0.53	1.06
Peak outflow	0.77	0.63	0.64	1.27	0.57	0.50

Table 5. Summary of inflow and outflow sediment (suspended solids) mass flow for the west grid and east grid.

	18 July 2001	2 Aug. 2001	13 Aug. 2001	23 Aug. 2001	1 July 2002	11 May 2002
West grid inflow of sediment (g m^{-1})						
Average inflow	10154	973	1237	9628	35670	23716
Standard deviation	10239	1353	1003	6552	25069	10640
West grid outflow of sediment (g m^{-1})						
Sampler 1 (W-S-1)	234	158	133	319	1544	936
Sampler 2 (W-S-2)	1927	116	42	1787	15295	8606
Sampler 3 (W-S-3)	3197	306	154	3236	5151	8684
Average outflow	1786	193	110	1780	7330	6075
West grid % trapping efficiency	82	80	91	82	79	74
	18 July 2001	2 Aug. 2001	13 Aug. 2001	24 Aug. 2001	1 July 2002	11 May 2002
East grid inflow of sediment (g m^{-1})						
Average inflow	17832	1083	3344	9734	23127	10760
Standard deviation	9507	1657	3724	3560	20240	4462
East grid outflow of sediment (g m^{-1})						
Sampler 1 (E-S-1)	2379	90	228	169	4489	--[a]
Sampler 2 (E-S-2)	7800	88	1039	1432	7616	1583
Sampler 3 (E-S-3)	3964	79	197	551	2467	2066
Average outflow	4714	86	488	717	4857	1825
East grid % trapping efficiency	74	92	85	93	79	83

[a] Sampler not operational.

Sediment inflow per unit width varied from one event to the next (table 5). The sediment loading ranged from approximately 973 g m^{-1} to 35670 g m^{-1}. The sediment trapping efficiency ranged from 74% to 93%. If the events are considered cumulative, then the average sediment trapping was approximately 80%.

Dye Tracer Studies

Dye tracer flow paths were mapped onto both the low-resolution topography (6 cm contour interval) and the high-resolution topography (3 cm contour interval) (figs. 6 and 7). The water flow paths more closely follow the predicted path from the high-resolution survey than the predicted path from the low-resolution survey. In addition, even though there is little cross-slope at this site, the flow pathways were not directly perpendicular to the upstream and downstream edges of the filter. The ability to reasonably predict water flow pathways is important when positioning sampling equipment and when interpreting data. Topograph−

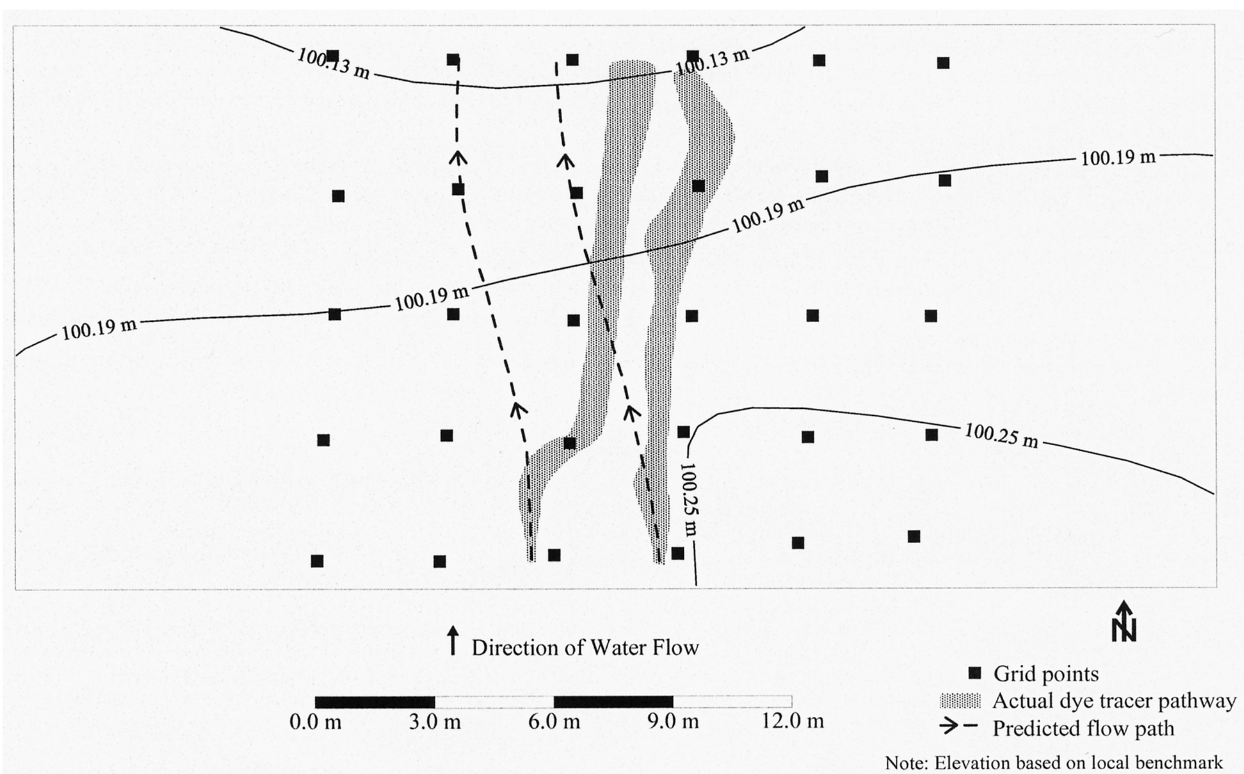

Figure 6. Low-resolution east grid survey with dye tracer pathway from 13 August 2001.

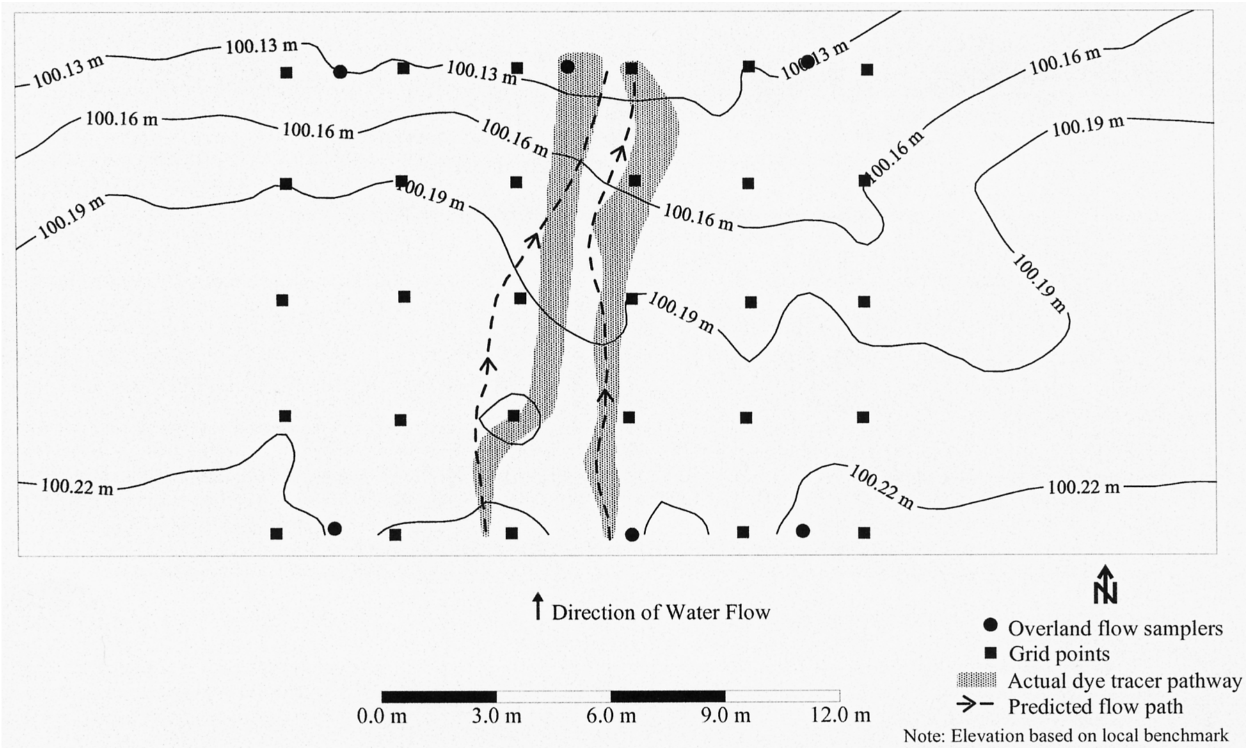

Figure 7. High-resolution east grid survey with dye tracer pathway from 13 August 2001.

ic data are critical for predicting the area contributing to a sampling location.

Using the high-resolution topographic map, the contributing area to a downstream width of 3 m was determined by drawing orthogonal lines to the contours and proceeding upstream. Orthogonal lines to the contours give approximate flow lines, and the area between adjacent flow lines are referred to as watershed facets (Bren, 1998). For both grid areas, Facet 2 (E2 and W2) has the smallest contributing upstream width of the five facets (figs. 8 and 9). Facet E5 has the largest upstream contributing width for both grid areas. The full impact of the contributing width of facet E5 is not completely reflected in the irrigation events since there was no inflow along the entire contributing width. The facets pro−

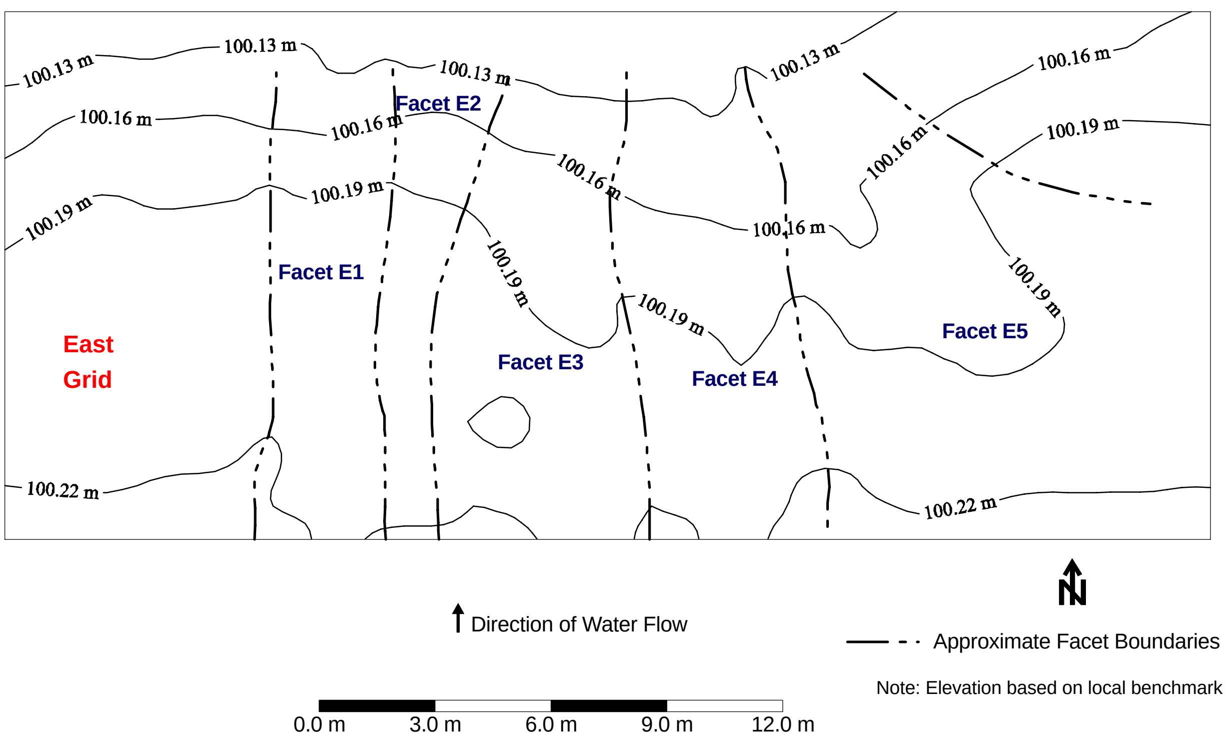

Figure 8. High-resolution east grid survey with facet boundaries.

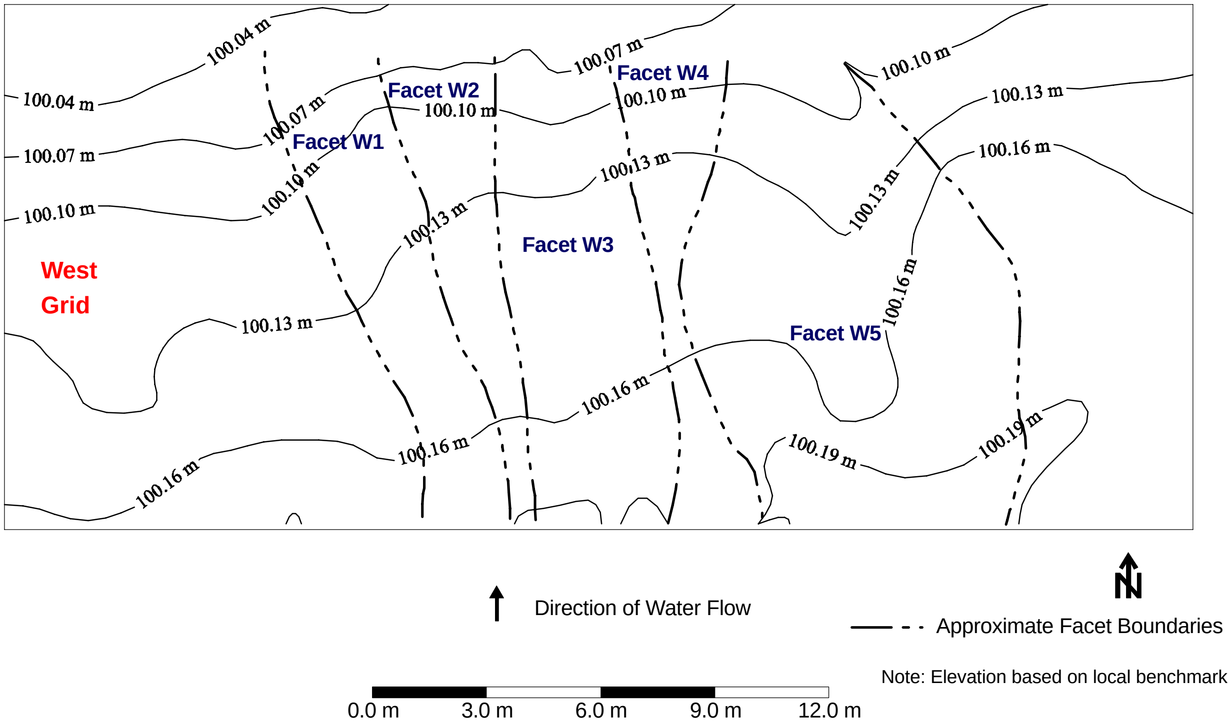

Figure 9. High-resolution west grid survey with facet boundaries.

vide further evidence that there are areas of converging and diverging overland flow in the VF. Using the high-resolution topography, it was possible to accurately predict water flow pathways in the VF. This method of obtaining high-resolution topography and defining watershed facets provides a tool for assessing convergence and divergence of overland flow in a VF.

Depth of Flow

The maximum depth of flow was measured at 51 locations in each grid for the irrigation events. Various transects were plotted for the maximum depth of flow for the 13 August 2001 irrigation event in the east grid (fig. 10). In these plots, a transect is a line running from west to east at a specific north-south location in the grid area. The trend in the depth of flow data was similar from one event to the next, giving confidence in the measurement equipment, especially since some of the events had similar flow conditions. The depth varied along a transect, indicating that flow is not uniformly distributed across the filter.

Discussion

It is apparent from the hydrograph and volumetric flow information that there is spatial variation in the flow rate along the downstream edge of the VF. The maximum outflow rate was greater than the average inflow rate for all events in the west grid and for four of the six events in the east grid, indicating convergence of overland flow. In addition, there appears to be evidence of diverging flow, especially shown by sampler 1 in the west grid (W−S−1). The flow rate at this location was much lower than the flow at the other measurement locations. For some events, the percent reduction in volumetric flow is less than zero (table 3), suggesting converging flow.

Runoff data from the experiments were compared to expectations of runoff from design storms. The volumetric inflow per unit width for a 1−hour duration, 10−year return period precipitation event is on the order of 11000 L m^{-1} using the NRCS (SCS) curve number method, assuming a 670 m field length contributing to the filter, an SCS runoff curve number of 75, and a field slope of 1.4%. The total inflow volumes for measured events ranged from 4090 to 17900 L m^{-1}, which brackets the volume expected for the 1−hour, 10−year return period precipitation event (11000 L m^{-1}). The peak flow rate for this 1−hour duration, 10−year return period precipitation event was estimated using HEC−HMS (USCE, 1998). The calculated peak flow rates for this event are approximately 2.8, 2.1, and 1.75 L m^{-1} s^{-1} for the 670, 400, and 300 m contributing field lengths, respectively. Measured peak flow rates, which ranged from 0.26 to 1.32 L

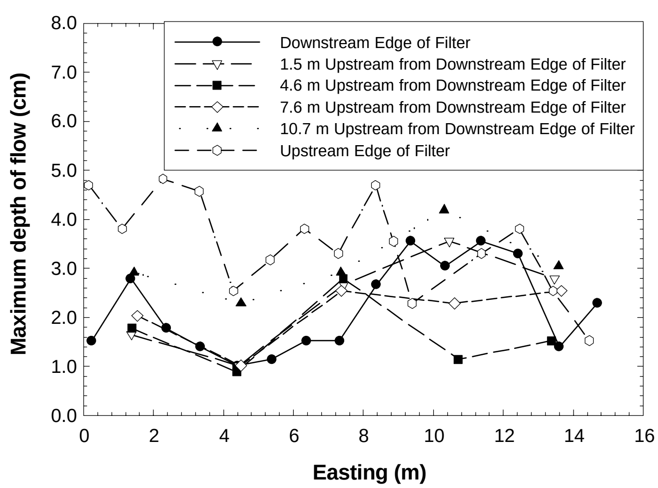

Figure 10. East grid, depth of flow at various transects, 13 August 2001 event.

m^{-1} s^{-1} for the events, were well below the peak flow rates expected for the 1−hour, 10−year return period precipitation event.

The area ratio for the Clear Creek Buffer is approximately 50. Reviewing the data from previous studies (fig. 1), for an area ratio of approximately 50:1, the range in sediment trapping efficiency is from 40% to 85%. This range is likely due to the differences in hydrologic, precipitation, runoff, and soil conditions for these various studies. A direct comparison of the existing data to our data is therefore difficult, but the comparison provides a frame of reference for the data from the Clear Creek Buffer. The efficiencies measured at the Clear Creek Buffer were 74% to 93%, slightly higher than the range determined in previous studies. Because the peak flow rates were relatively low and the site had a relatively low slope, it is understandable that the trapping efficiency of the Clear Creek Buffer is higher than the range reported in previous studies.

The dye tracer studies indicated that the flow pathways through the VF closely followed the pathways predicted by the high-resolution topographic map (fig. 7). The results provide confidence in our ability to predict the direction of overland flow, which is important for defining converging and diverging flow areas. High-resolution topographic maps provided a tool for assessing converging and diverging flow areas in a VF and the levels of convergence and divergence at the Clear Creek Buffer. In addition, being able to predict flow pathways would be important when modeling overland flow in a VF and when locating positions for samplers. The subareas of the Clear Creek Buffer had relatively little cross-slope and were relatively planar, with some subtle microtopographic features. Despite this, the overland flow did not cross the VF directly perpendicular to the upstream and downstream edges of the VF. The ability to predict the direction of water movement should be investigated on different filters and at different topographic resolutions.

The depth peg data indicate that the maximum depth of flow varies within the VF and along a transect perpendicular to the predominant flow direction. This information, along with the overland flow sampler data, provides evidence that flow converges and diverges and that flow is not uniformly distributed within the VF, despite the fact that the VF had been graded for furrow irrigation many years prior to this project.

Convergence and divergence of flow is also supported using the watershed facet concept (figs. 8 and 9). With areas of converging and diverging flow, the flow rate per unit width will vary within the VF. Areas of converging flow will have greater flow rate per unit width (Haan et al., 1994). The change in flow rate per unit width will likely impact the velocity of overland flow, which is an important factor in sediment transport (Tayfur et al., 1993). Depending on the level of convergence, flow convergence can reduce the ability of a filter to retain sediment (Helmers et al., 2005).

The watershed facets, defined using the high-resolution topographic map, were useful in highlighting areas of flow convergence and divergence in the VF where overland flow followed natural flow pathways. The area of the facets can be compared to the facet area assuming a constant width equal to the upstream width of the facet. From this assumption, a convergence ratio can be defined:

$$CR = 1 - \frac{FA_A}{FA_C} \tag{1}$$

where

CR = convergence ratio

FA_A = actual facet area

FA_C = facet area assuming constant width equal to upstream facet width.

Convergence ratios were calculated for all facets except E5, since the full facet area of E5 was not within the surveyed area (table 6). The ratios had a range of −1.55 to 0.34, where negative values indicate a diverging facet, positive values indicate a converging facet, and a convergence ratio of zero indicates uniform flow. The facets where overland flow samplers were located are noted in table 6. When reviewing the flow data shown in table 3, it is evident that the flows at samplers W-S-2 and W-S-3 indicate converging flow, while the convergence ratios for facet W3 and W5 indicate a diverging facet. Since the facet is defined by a 3 m width at the downstream edge of the VF and the sampler only samples a 0.3 m width, it is understandable that there is some difference between convergence ratios and flow at the samplers.

The tests performed at the Clear Creek Buffer site indicate that convergence and divergence of overland flow exist. However, a direct comparison of sediment trapping under these flow conditions compared to flow conditions with no convergence or divergence cannot be made. This study site has been modeled considering uniform, converging, and diverging flow conditions by Helmers et al. (2005), who found that while convergence and divergence of overland flow existed at this study site, there was negligible impact on sediment trapping. In this case, the convergence ratios ranged from −0.11 to 0.17 for the facets that were modeled and compared to measurements. Based on this, the overall sediment trapping performance of the VF is similar to a condition where the flow is uniformly distributed. Helmers et al. (2005) show that for the 24 August 2001 event for the east grid area, a convergence ratio of 0.46 was required to achieve a 10% reduction in the modeled sediment trapping efficiency (80% to 70%). The largest convergence ratio at the Clear Creek Buffer was for facet W4 (CR = 0.34). While this particular facet was not modeled, using curves developed by Helmers et al. (2005) for sediment trapping efficiency as a function of convergence ratio for the 24 August 2001 event, a sediment trapping efficiency of 73% would be estimated, compared to 80%

Table 6. Summary of watershed facet areas and convergence ratios.

Facet[a]	Sampler in Facet	Actual Facet Area (m^2)	Constant Width Facet Area (m^2)	Convergence Ratio
W1	W-S-1	33.2	29.8	−0.11
W2		21.5	8.4	−1.55
W3	W-S-2	47.7	45.3	−0.05
W4		21.5	32.4	0.34
W5	W-S-3	89.0	83.6	−0.06
E1	E-S-1	39.5	44.0	0.10
E2		22.5	18.1	−0.24
E3	E-S-2	58.4	70.0	0.17
E4		55.6	59.6	0.07

[a] Facet E5 is not included since its full facet area was not included in the surveyed area.

for CR = 0. From this modeling study, it was found that the effect of convergence ratio varied depending on the flow conditions in the vegetative filter. For example, the sediment trapping efficiency was more sensitive to convergence ratios at higher flow rates and shorter filter lengths.

The greatest area-based convergence ratio at the Clear Creek Buffer was only 0.34, but in many field conditions the ratio could be much greater. Dosskey et al. (2002) reported that the effective buffer area averaged 6%, 12%, 40%, and 80% of the gross buffer area (convergence ratios of 0.94, 0.88, 0.60, and 0.20, respectively) for four farms in eastern Nebraska, although some of the convergence reflected in the convergence ratios in their study occurred within the field before the flow reached the filter.

This study was conducted in part to investigate water movement through a VF with unconfined flow pathways. However, the study was performed on a relatively flat, planar VF with only subtle microtopographic features in the subareas. Despite this, the overland flow was not uniformly distributed, highlighting that it would be unlikely that shallow, completely uniformly distributed overland flow would exist in a VF under field settings. Since we had relatively low slope and low velocity conditions, the sediment trapping was relatively high even with some flow convergence. For these conditions, the impacts of flow convergence on sediment trapping caused by microtopography was probably minimal because of the low slope and low velocity.

While flow rate and flow volume varied with position along the downstream edge of the vegetative filter, the sediment concentration showed little variability. As such, there was likely minimal impact of converging or diverging flow on the sediment concentration. Previous VF research has shown that the majority of the sediment is deposited near the inlet portion of the vegetative filter. Robinson et al. (1996) found that sediment concentration decreased greatly in the first 3.0 m of the vegetative filter and that there was little change in sediment concentration beyond a length of 9.1 m. Schmitt et al. (1999) state that doubling the filter strip width from 7.5 to 15 m did not improve sediment settling. Since the flow at the Clear Creek Buffer was relatively uniformly distributed at the upstream edge of the filter, because the furrows did not allow flow to converge within the field, it is likely that the sediment concentration changed little after the initial portion of the vegetative filter. Thus, it is understandable that convergence and divergence of overland flow in the Clear Creek Buffer did not have a significant impact on sediment concentration in the outflow from the vegetative filter.

As mentioned above, the orientation of the furrows directed runoff into the buffer without in-field flow convergence. Helmers et al. (2005) found that both in-field and in-filter convergence are important in evaluating buffer performance. In our test conditions, the dominant convergence process observed was in-filter convergence. For cases where in-field convergence occurs, having a dense stand of vegetation in the VF in order to increase the hydraulic roughness will be important to diffuse some of the runoff prior to entering the VF. This impact of converging and diverging flow on sediment trapping should be considered in future investigations of VF performance, especially under conditions where topographic features may cause greater convergence than occurred at the Clear Creek Buffer.

Summary and Conclusions

The objectives of this study were to quantify performance of a VF with natural flow pathways and field-scale flow path lengths and to develop methods to detect and quantify overland flow convergence and divergence in a VF. The results of this field study showed that the volumetric outflow varied with position along the downstream edge of the filter. In addition, the outflow rate was greater than the average inflow rate for most of the monitored events, providing evidence that overland flow in the Clear Creek Buffer had areas of converging flow in the buffer. Even though this site had been graded for surface irrigation, overland flow was not uniformly distributed and there were areas of converging and diverging flow. From this, it is unlikely that shallow, completely uniformly distributed overland flow exists in a VF under field settings.

Water movement followed pathways predicted using a high-resolution topographic map (3 cm contour interval) more closely than it followed the pathways predicted by a low-resolution topographic map (6 cm contour interval). Dye tracer studies revealed that high-resolution maps more closely identified the actual flow pathways. Since flow pathways predicted by the high-resolution maps closely followed actual flow pathways, we used these maps to define and quantify converging and diverging flow areas using watershed facets. Watershed facets were defined using the high-resolution topographic maps by defining the contributing facet area to a uniform downstream width of 3 m. We concluded that it is possible to predict the direction of overland flow if the topographic map provides enough detail and that this method of developing high-resolution topography and watershed facets can be used to predict converging and diverging flow areas.

Convergence ratios were defined using the watershed facets. The ratios had a range of −1.55 to 0.34, where negative values indicate a diverging facet, positive values indicate a converging facet, and a convergence ratio of zero indicates uniform flow. Measured convergence ratios were generally less than values estimated by Dosskey et al. (2002) on four farms in eastern Nebraska (convergence ratios of 0.94, 0.88, 0.60, and 0.20).

Water flow and sediment mass flow varied by event and position along the downstream edge of the filter. The flow measured at the downstream overland flow sampler locations indicated converging flow at multiple sampling locations. The total mass inflow of sediment was approximately 73631 g m^{-1} for all the events in the two grid areas, and the mass outflow was approximately 14982 g m^{-1}, giving an average sediment trapping efficiency of 80%. This reasonable trapping efficiency was attained even though flow convergence occurred in the vegetative filter. When compared to modeling studies (Helmers et al., 2005) using data from the Clear Creek Buffer, the level of convergence at this site had little impact on the sediment trapping efficiency.

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