The effectiveness of grass strips for the control of sediment and associated pollutant transport in runoff

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Abstract Grass filter strips have been used widely for erosion control on agricultural lands, but the mechanism of such action is not fully understood. A series of experiments was conducted in a 6 × 1 m flume and rainfall–runoff simulator to investigate the effects of filter strips on runoff hydrology and sediment and chemical transport using real and artificial grass strips. Changes in flow configuration caused by the strips were recorded at regular intervals during the 45-min runs. For the range of slopes and flow rates investigated, sediment deposition occurs largely in the backwater region ahead of the strips, the length of which is inversely related to flume slope. There was some deposition on the downstream side of the strips, but no sediment deposition or trapping took place inside the strips and between the grass stands. In the experiments with non-consolidated soils, the soil inside the strips was eroded away by channelized flow. Filter strips did not effectively reduce the transport of the finer fractions of the sediment load. Size distribution analysis conducted on the deposited sediment before and after the strips suggests significant enrichment of fine particles, sorbed chemicals and organic matter as a result of runoff passing through the grass strips. In this study, grass strips 20 and 40 cm in width did not effectively reduce downslope transport of pollutants by surface runoff.

INTRODUCTION

The use of cross-slope vegetation strips has long been recognized as a soil conservation measure. Data from field and laboratory experiments indicate significant reduction in the sediment load of runoff when passed through an even quite narrow vegetated strip (Kemper *et al.*, 1992; Meyer *et al.*, 1995; Magette *et al.*, 1989; Raffaelle *et al.*, 1997). The effectiveness of grass strips in reducing runoff sediment load and soil erosion has been attributed to the filtering capacity of strips as well as their ability to slow down surface runoff and enhance deposition. Such attributes are based more on common sense than on the outcome of scientific investigations. However, there has been a renewed interest in recent years in understanding the mechanics of flow through porous barriers and their effectiveness in reducing the transport of sediment and pollutants down slopes, or into receiving waters, from agricultural lands (Landry & Thurow, 1997; Hairsine, 1996; Magette *et al.*, 1989). Because of the increasing interest in management of riparian lands to reduce the amount of nutrients and pollutants in runoff to streams, there is a need to study the effectiveness of grass strips in reducing downstream impact of intensive land use (Landry & Thurow, 1997; Hairsine, 1996; Magette *et al.*, 1989).

This paper reports on the results of a number of flume experiments carried out to determine the impact of different filter strips on overland flow and on the transport of sediment and their associated nutrients and pollutants, using both rigid (nail) and flexible (grass) buffer strips with a range of slopes, and strip densities.

MATERIALS AND METHODS

Flume and soil bed preparation

The experiments were carried out in a 1 × 6 m tilting flume with adjustable slope (0–45°) and instrumented with accurate inflow and outflow measuring equipment. The experiments covered two strip types (bed of nails and real grass), three strip densities (low, medium and high), two strip widths (20 and 40 cm), six flume slopes (between 0 and 8.76%), and two surface conditions (bare flume floor and soil). All experiments were carried out at a constant flow rate of $2.27 \times 10^3\ m^3\ m^{-1}\ s^{-1}$.

The first set of experiments was carried out on the bare wooden flume floor and no special flow bed preparation was required. Experiments with soil, however, required a detailed and exact bed preparation. The soil used in the experiments was passed through a large (1 × 1 m) 4 mm sieve before being transferred into the flume. It was then spread uniformly over the flume floor and checked for lack of side-slope using a spirit-level. A rectangular section of the bed, 20 × 50 cm, was then removed 1.5 m upstream of the flume exit and replaced with the nail or grass strips (Fig. 1). Soil level within the nail beds was kept at the same height as the rest of the flume. The soil bed was then put through two cycles of wetting and drying prior to starting the experiments.

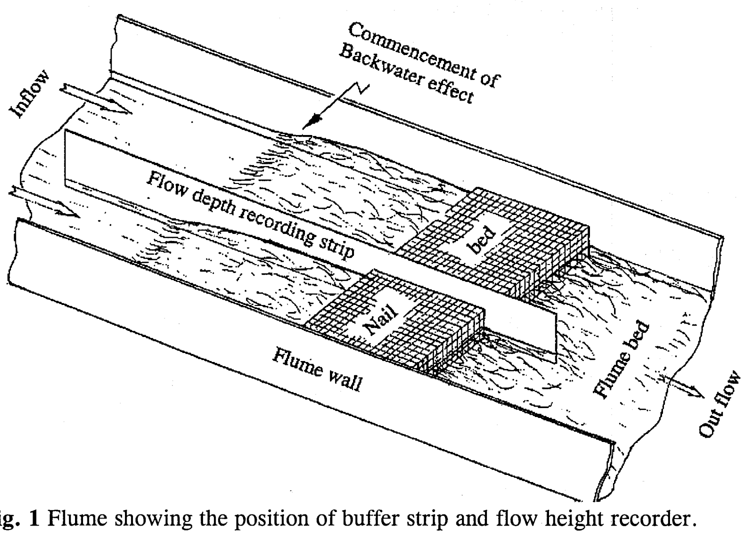

Fig. 1 Flume showing the position of buffer strip and flow height recorder.

As the strips of grass were grown over 30 days prior to the flume experiments, the soil under the grass became consolidated. In order to bring the soil bed in the flume to the same level of consolidation as the soil under the grass strip, it was compacted by a water drum roller. Soil compaction was measured inside and outside the grass strips with a portable fall-cone penetrometer. Compaction ceased when the two were similar. The soil used in these experiments was a silty clay and the final depth of the soil in the flume was about 5 cm.

Nail and grass strips preparation

A 1 × 1 cm grid of holes was drilled on a 20 × 50 cm piece of plywood, 1.2 cm thick. At the highest nail density (30% coverage), metal nails 2.76 mm thick and 10 cm long were inserted in every hole (Fig. 2(a)). For the medium density nail strip, every second nail in rows perpendicular to flow was removed and, for the low density configuration, every other nail in rows parallel to flow was also removed.

A number of wooden rectangular boxes of 20 × 50 cm, 5 cm high, with removable sides were made for growing grass strips. They were filled with soil and, after adding fertilizers, grass was grown at several densities, using lawn seeds. Three distinctly different grass densities of high, medium and low were later used for the experiments.

Flow height recording and measurement

PVC boards with the dimension 1 m long, 0.2 m wide, 2 mm thick and stained with potassium permanganate powder were inserted into the strips. The flow height and its variation was recorded from 60 cm before the strips to 20 cm after (Figs 1 and 2(a)). The recorded watermarks were photocopied and digitized using a specially developed computer program. The sketch and data file prepared for each experiment shows the variation in water height every 2 mm throughout the experiment with an accuracy of 1 μm. The recording started at some distance prior to the point where flow began to be affected by the presence of the nail or grass strips, and ended where water height stabilized after emerging from the strips (Fig. 1).

RESULTS AND DISCUSSION

Effects of buffer strips on flow hydrology

A clearly defined backwater region was formed in every experiment with nail or grass strips, the length of which varied with flume slope and strip density (Fig. 2(a)). The relationship between backwater length and slope is exponential for any given buffer strip density. Figure 3 shows one such exponential relationship for medium nail density with $R^2 = 0.996$ (R^2 values for other slopes were all more than 0.96). The maximum height to which backwater rises is fairly constant, about 2–3 times greater than the unaffected flow depth.

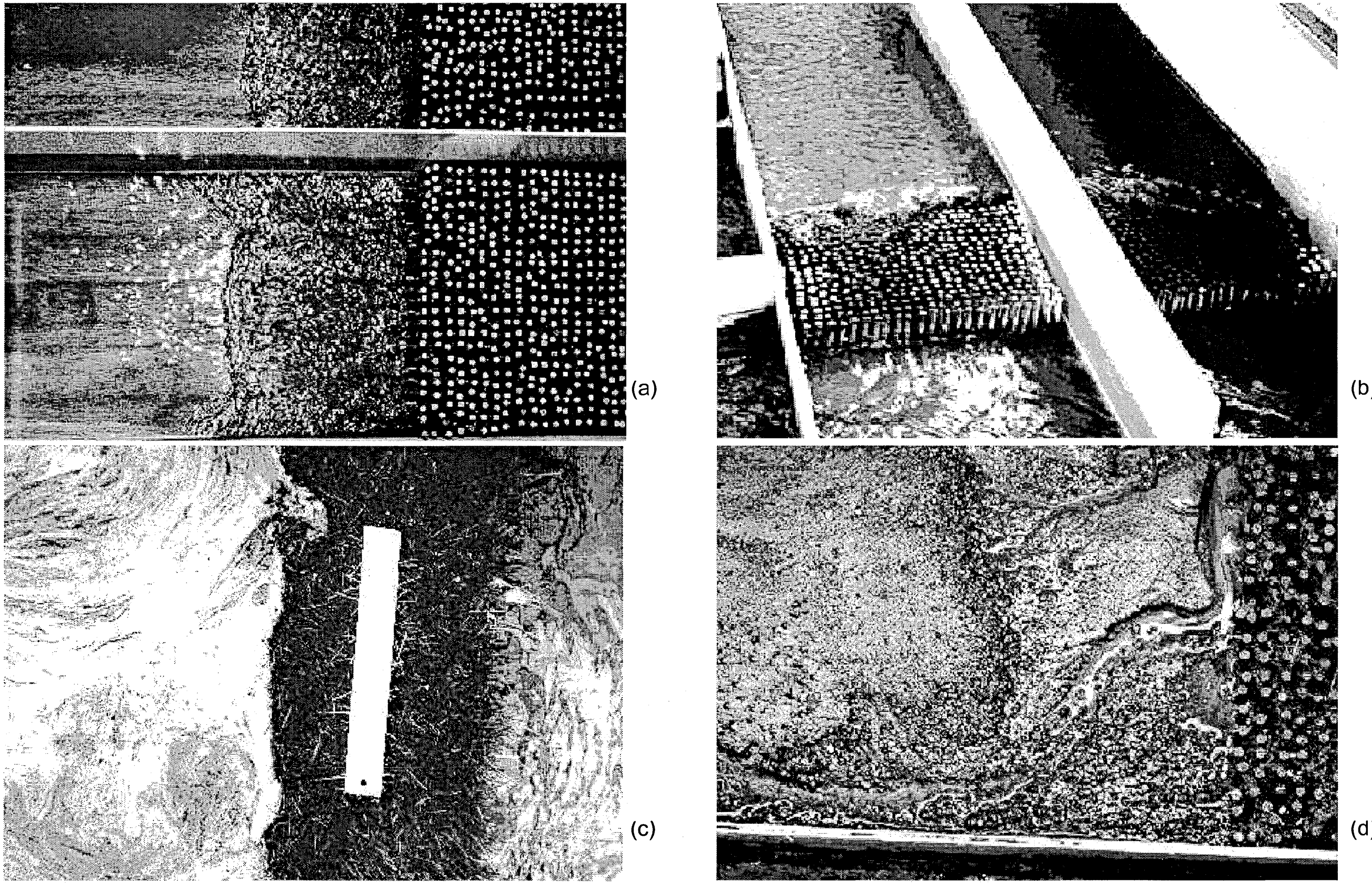

Fig. 2 (a) Backwater formed by water passing through a high density nail strip at slope 3.4% and flow rate 2.27×10^{3} m^3 m^{-1} s^{-1}. (b) Runoff passing through a high-density nail strip at 6.7% slope (deposited layer has reached the front edge of the strip and has piled up against it). (c) Runoff passing through a high-density grass strip at 6.7% slope (strip's resistance to flow has been broken in one point at the top of the picture). (d) Deposition front inside the backwater and about 15 cm from the front edge of a high density nail strip (photo taken after an experiment with a soil bed in the flume).

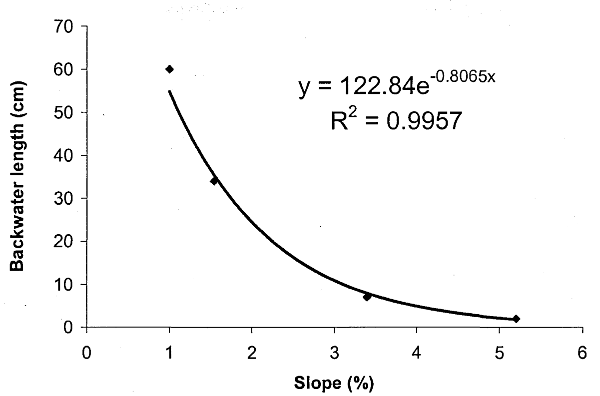

Fig. 3 Effect of slope on the length of backwater for medium nail density.

The relationship between backwater length and nail density appears to be linear for every slope within the range of nail densities studied (Fig. 4). The relationships of the type shown in Figs 3 and 4 can be used for predicting where most of the sediment load in runoff is likely to be deposited for given slope and buffer strip density. Such relationships have practical land management applications for assessing the effectiveness of buffer strips in erosion control and sediment associated pollutant transport.

The influence of grass and nail strips on flow behaviour was somewhat different once a soil bed was introduced into the flume. Unlike the bare board, flow over a soil bed did not quickly stabilize to give rise to a stable backwater with constant height and length for a given flume slope and strip density. Instead, the backwater grew in length as the experiments progressed. The reasons and the consequences of such behaviour are discussed in the next section.

The hydrological effects of grass and nail buffer strips were very much the same with and without a soil bed. The changes in the height and the length of backwater, caused by flow across the grass strips, followed the same patterns as in the nail strip experiments. The starting point of the elevated backwater moved nearer to the strips

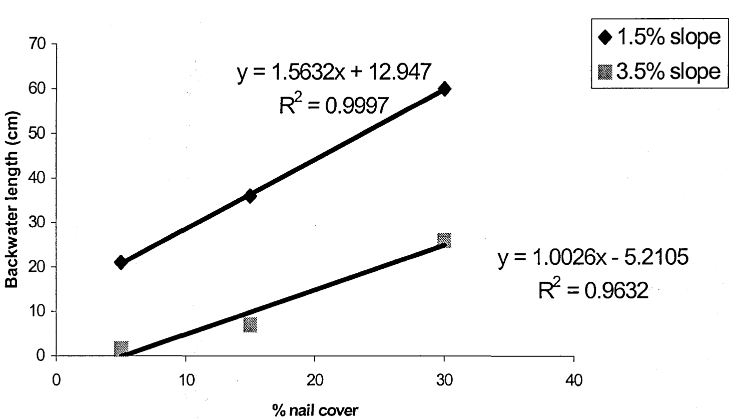

Fig. 4 Effect of nail density on the length of backwater on constant slopes.

with any increase in slope, for both grass and nail strips, reaching the front of the strips at the slope of around 6% (Fig. 2(b)). This is the same slope at which the length of backwater on bare flume floor was also reduced to zero. Although the length of the backwater was changing with time due to the increasing blockage by floating debris at the front edge of the strips, sediment deposition appeared to follow the hydrological pattern established at the early stages of the flow.

Grass stands were very thin at the base (0.5–0.8 mm) at the time of the flume experiments, providing very low surface coverage at all three densities (1–3%), when such coverage was calculated using stand diameter near the ground surface. However, the coverage was much higher some 3 cm above ground, where leaves appeared on the stands. Looking from above, the coverage for the high density grass was almost complete (Fig. 2(c)). This gave rise to a situation where, as the height of backwater increased, grass strips became more efficient in blocking the flow, which in turn contributed to an even higher build up of backwater and more deposition until the grass was no longer capable of resisting the pressure exerted by the swollen backwater and collapsed (Fig. 2(c)). However, a section of the flow which penetrated the strip, mostly near the surface, passed through the strip with its velocity undiminished, if not increased, not allowing any deposition of its sediment load to take place. Further deposition took place after the emergence of flow from the downstream end of the strips in the form of multi-layered fans.

The length of the strips (nail or grass), in the direction of flow, did not appear to have much effect on flow hydrology, as the characteristics of backwater and deposited sediment layer were similar for one (20 cm) and two (40 cm) strips beds in both nail and grass strips experiments.

Effect of buffer strips on sediment transport and deposition

The effect of grass and nail strips on the transport and deposition of sediment by overland flow was tested in a series of flume experiments where a soil bed was present in the flume. The bulk of the coarse sediment load was deposited at the front edge of the backwater creating a visible step (Fig. 2(d)), the height of which increased with increasing slope. The point of bulk sediment deposition was getting nearer to the strip with any increase in slope, reaching the front edge of the strips and pilling up against it at the slope of about 6% for the experiments with high nail and grass densities (Fig. 2(b)). This wall of deposited sediment, once it reached the front edge of the strips, did not move into the strips with further increase in slope. The sharp fall in the height of the accumulated sediment against the strips, shown in Fig. 5, suggest that flow may have speeded up inside the strips, moving with it any sediment entering the strip, to be deposited as fans downstream side of the strips or to stay in suspension and leave the flume. Dillaha *et al.* (1989) made similar observations in their field experiments with much wider grass strips. They observed that no deposition took place inside the strips and the deposited sediment moved forward only after burial of the front section of the strip occurred. The results of experiments on unconsolidated soil inside the strips, similar to the one shown in Fig. 5, suggest that not only is there no sediment deposition inside the strips, but also there is some erosion and soil loss from this region. Active erosion inside the buffer strips has also

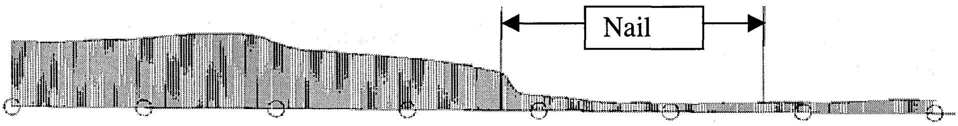

Fig. 5 Changes in the soil profile as a result of flow passing through a high density nail strip.

been reported by Jordan *et al.* (1993) and Smith (1992). However no such erosion took place inside the grass strips where the soil over which grass was grown had been consolidated. These results suggest that, under the experimental conditions used in this study, grass and nail strips have no filtering effect on the eroded sediment transported from the upper slopes regions. Their role in erosion control on slopes is confined to flow retardation and sediment deposition in the backwater of the strips.

The accumulation of floating debris against the nail and grass strips during these experiments caused the backwater to grow in length, and the buffer strips to become more efficient in slowing down the flow and in forcing it to drop its sediment load. Floating debris appears to play a much greater role in influencing the effectiveness of buffer strips than given the credit for (Fig. 2(c)). The effectiveness of a grass buffer strip in reducing sediment transport increased with slope up to the point where the grass strip failed and was run over by the flow. The point at which the grass strip fails depends on the rigidity and height of the individual grass stands, but not on the size or density of the strip. This finding is contrary to the results of several field studies. Further experiments are currently underway in our flume setting to clarify this point. The results presented in this paper show that, for the flow rate and grass and soil types used, 6% is probably the maximum slope over which 20 and 40 cm grass strips are capable of functioning effectively. The literature is also divided on the range of slopes over which grass strips are most effective as a soil conservation measure. FAO (1965) considers 15% to be the highest slope over which grass strips can be effectively used, but Lakew & Morgan (1996), Lidgi & Morgan (1995) and Boubakari & Morgan (1999) found their grass strips to be effective up to a slope of about 23%.

Effect of buffer strips on the concentration and transport of pollutants

Table 1 shows the results of sediment concentration measurements carried out with the high-density grass strip on four different slopes. Sediment transport capacity of the flow was highly sensitive to slope steepness, increasing by more than 60 fold as the slope increased from 1.5% to 5.2%. Most of the detached sediment at high slopes was deposited in the backwater, before reaching the strip. The deposited sediment in the backwater varied from 18% of total detached sediment at 1.5% slope to 77% at the highest slope of 5.2%. The efficiency of buffer strips in forcing runoff to drop its sediment load in the backwater region appeared to increase with slope up to the point at which strips gave in and were overrun by flow. For the selected flow rate and grass density, 5.2% was the highest slope that could safely be applied without the risk of the strip being overrun by the flow, a process which can be seen beginning to happen in Fig. 2(c). Table 1 also shows that sediment deposition inside

Table 1 The effect of high density grass strip on sediment concentration on different slopes.

Slope (%)	Sediment concentration ($g\ l^{-1}$): Unaffected flow	In the backwater	After grass strip	Sediment deposited (%): In the backwater	Inside grass strip
1.5	1.25	1.02	1.06	18	–4
2.0	4.30	3.11	3.20	28	+3
3.4	17.44	10.76	11.01	38	–2
5.2	78.63	18.15	16.81	77	+7

the strip is negligible, which is in agreement with the visual and photographic evidences provided and discussed above.

Sediment passing though the strips was significantly finer than that initially dislodged by the flow. The Mean Weight Diameter (MWD) of sediment that passed through the strip was 0.8 mm while that of the suspended sediment in unaffected flow, prior to sensing the strip, was 2.1 mm for the experiment whose results are given in Table 1. Measurement of organic matter, nitrogen and phosphorus for different size classes of soil particles showed that the concentration of these chemicals increased as the particle sizes decreased. The ratio of organic matter concentration in each particle size fraction, C, to that of the original soil, C_0, has an inverse log-linear relation with particle diameter, d (in μm), as shown in the following equation:

$$C/C_0 = 5.5 - 0.6 \ln d \qquad (1)$$

As a result of the settlement of mostly large particles in the backwater, finer particles were preferentially eroded and transported in the runoff that flowed across the grass strips. This in turn led to the enrichment of sorbed nutrients, agricultural chemicals and organic matter in the suspended sediment, which was either deposited downslope of the strips or stayed in suspension until it entered the receiving waters. Grass strips are therefore less effective in reducing overland transport of solids-associated chemicals than in reducing sediment loading. Since some of the suspended sediment which has passed through the buffer strip gets deposited as fans downstream side of the strips, grass strips may in fact contribute to the accumulation of some sorbed chemicals in this region. Grass strips are more effective in preventing pollutant transport if such pollutants are evenly distributed over the entire range of the soil particles sizes, a situation which can develop in a well aggregated clay soil, as reported by Ghadiri & Rose (1993).

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