

VETIVER BUFFER STRIPS: MODELLING THEIR EFFECT ON SEDIMENT AND NUTRIENT REDUCTION FROM SURFACE FLOW

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ABSTRACT

Vetiver buffer strips are widely employed to reduce fluxes of eroding soil and associated nutrients and pollutants from catchments into waterways. The physical processes involved in sediment reduction by buffer strips have been examined in a number of studies and various models have been developed to describe some of these processes. However, the sediment-removal efficiency is complex as it is time-dependent and changes as deposition builds up and existing models do not allow for this, amongst other limitations. A new model, the Griffith University Soil Erosion & Deposition — Vegetative Buffer Strip Model (GUSED-VBS), has therefore been developed which couples the hydraulics, sediment deposition and subsequent adjustment to bed topography, to simulate the build-up of sediments in the backwater zone and its effect on flow conditions. The model can be used to predict sediment retention by buffers as well as sediment concentrations, size distributions and nutrient enrichment ratios of runoff. Experiments to characterize sediment and nutrient retention by a vetiver strip were carried out using surface flow in the Griffith University Tilting-Flume Simulated Rainfall facility and were later used to test the model. Replicate experiments were conducted at three slopes using a dense vetiver strip inserted into the flume. Water profiles were recorded, then sediment comprising either a sandy soil (Podzol), a red clay (Ferralsol) or a black clay (Vertisol) was introduced into flow upstream of the buffer and sediment deposition and outflow characteristics were measured for each soil. Total carbon, nitrogen and phosphorous levels were determined in different size fractions of each sediment, to characterize nutrient enrichment. Sediment loads in the outflow increased slightly with time for the Vertisol due to sediment movement into the buffer but were static for the other two soils. The buffering action of the vetiver was efficient, reducing sediment in the outflow to 3.2, 6.0 and 11.3 % of the inflow concentration for the Podzol, Ferralsol and Vertisol respectively, with a significant differences ($P < 0.01$) between soils. Sediments in the runoff were primarily in the 0.002 – 0.2 mm size range and the greatest enrichment of fines (silt size or smaller) occurred in the Ferralsol and Vertisol. Particulate-carbon, -nitrogen and -phosphorous levels in the outflow were reduced by more than 60% compared to the inflow. Measured data from the flume experiments were compared to simulated data from GUSED-VBS. Water profiles and total sediment deposition were simulated well with low root mean square errors and coefficients of efficiency approaching 1. Reductions of the inflow nutrient loads were fairly well simulated. Further work is underway to test the model using field data.

1.0 INTRODUCTION

Vegetative buffer strips are used world-wide to reduce sediment and pollutant fluxes from moving off site and into waterways. A variety of buffer types are employed, ranging from trees along riparian zones, short grass filters in urban storm-water drains to stiff grass hedges at field edges or along waterways. Buffers are often more cost effective to install and maintain than mechanical works and have the advantages of being more aesthetically pleasing, as well as providing habitat for wild-life. These buffers remove sediments/pollutants through a combination of settlement, filtration and adhesion (Newham, 2005). Our research concentrates on stiff grass hedges (or barriers) that are very effective in causing settling-out of sediments, together with particulate-sorbed nutrients and pollutants. Vetiver grass is typically employed for these hedges, as it has an erect, stiff growth and a strong rooting system. Even a single row of vetiver often less than 0.5 m wide will substantially reduce of sediment fluxes (Dabney et al., 1995, McKergow et al., a,b 2004; Truong, 1999) and vetiver has been shown to outperform other grasses under fast flow conditions (Sobey, 2006)

The vetiver strip retards surface flow, causing a backwater (ponded area) immediately upslope of the strip (Fig 1), with a corresponding reduction in flow velocity. As sediment-laden flow reaches this ponded area, the coarser material with higher settling velocity is deposited. Very fine material may remain in suspension and move through the buffer. The outflow from buffers may thus contain soluble components and fine particles with preferentially-adsorbed chemicals (Ghadiri and Rose, 1991). Whilst overall pollutant loads are thus reduced by buffers, this preferential movement of fines through vetiver strips could have implications on the type and extent of pollutant movement to streams. McKergow et al. (2004a) noted that typically 40 to 90 % of the sediment load is reduced by buffer strips but the trapping of particulate or sediment -associated nutrients is generally lower.

The hydrology and the reduction of particulate and dissolved material occurring in or before the barrier strips have been examined in a number of studies (Dabney et al., 1995; Deletic 2005; Dillaha et al., 1989; Ghadiri et al., 2001; Rose et al., 2003) and various models have been developed to describe some of these processes (Deletic, 2001; Flanagan and Nearing, 2000; Munoz-Carpena et al., 1999; Newham et al., 2005). The WEPP model (Flanagan and Nearing , 2000) is able to predict the pattern of enriched sediment size distribution but only simulates the reduced sediment transport capacity in the hydraulically rough areas of the strip without simulating the significant deposition in the ponded area. The model also over-predicts the medium size fractions and under-predicts the fine size fractions. The Kentucky model incorporated into a dynamic model by Munuz-Carpena et al.(1999) and the TRAVA model of Deletic (2001, 2005) have limitations in dealing with sediment of a wide variety of sizes and sediment concentrations and in the model of Newham et al. (2005), the settling process is not explicitly modelled in the backwater and the trapping capacity of the buffer is computed from the volume of the backwater. Because of the settling process and flow adjustment in response to sedimentation, the buffer strip efficiency is time-dependent and changes as deposition builds up in the backwater region, adding to the complexity of the situation. As the change in the backwater region during deposition is actually unknown, this paper tests a new modelling approach based on the work of Rose et al. (2003) to couple the hydraulics, sediment deposition and subsequent adjustment to bed topography to simulate the built-up of sediments in the backwater zone and its effect on flow conditions.

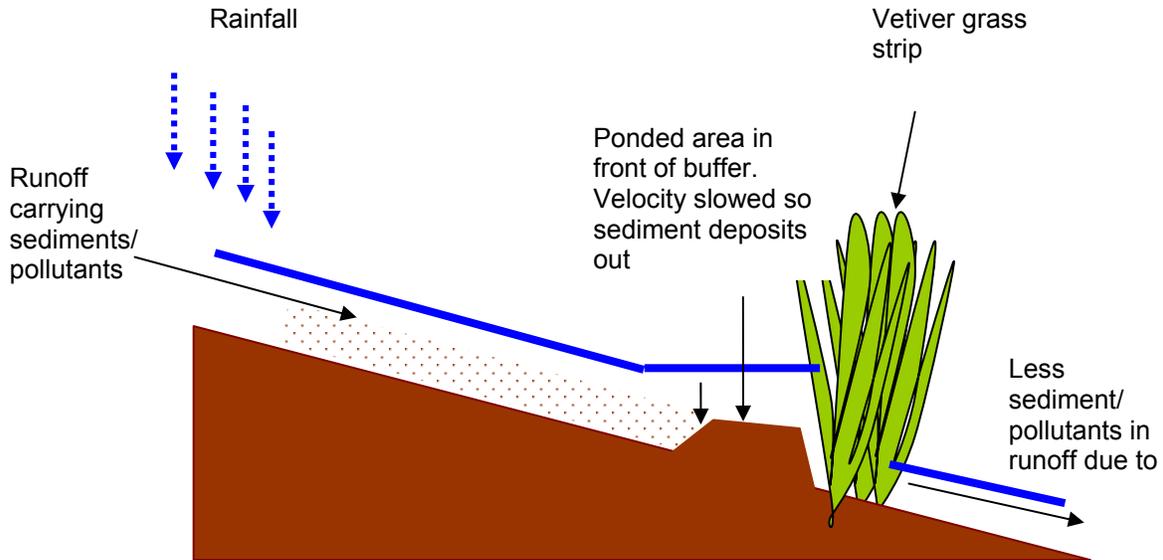


Fig.1. Processes involved in sediment reduction by a vetiver grass strip

However, the quantification of the sediment-trapping ability of vetiver and its effect on reducing diffuse sources of pollution has been extremely difficult, due to all the complexities involved including rainfall and runoff characteristics, sediment type, slope, buffer properties etc. We introduce a new model called GUSED-VBS (Griffith University Soil Erosion & Deposition model – Vegetative Buffer Strip) that has the ability to predict sediment retention (through particle settling) by various buffers, including vetiver, and is also able to predict sediment concentration and sediment size in runoff.

Our objective was to measure sequential water and sediment profiles before and after a vetiver buffer strip and to compare these to simulated data from the newly-developed GUSED-VBS Model. Surface flow experiments were therefore carried out in the Griffith University Tilting-flume Simulated Rainfall facility (GUTSR) at 1, 3 and 5 % slopes using a black clay soil, and at 5% slope for a sandy and a red clay soil. Further work is underway to complete field testing of this model but initial results at flume scale suggest that it can be effectively used to predict sediment and nutrient reduction. After further testing, we anticipate that the model will therefore be used to improve the design of buffer systems for different landscapes, so that erosion losses are decreased. This should not only reduce the consequences of these losses environmentally, but will also lower input losses by farmers and reduce the cost to tax payers for the clean-up of diffuse pollution,

2.0 METHODS AND MATERIALS

2.1 Soils

Three Australian soils of contrasting texture were used for this study: a brown sandy loam soil, classified as a Podzol; a red clay classified as a Ferralsol and a self-mulching black clay classified as a Vertisol (FAO, 1998). Standard soil textural and chemical analyses (Table 1) were carried out on the soil according to the Australian Standards (1995) and Rayment and

Higginson (1992) respectively. The settling velocities were calculated from size class data (wet sieving) employing the equation of Cheng (Cheng, 1997), using wet aggregate densities (Loch and Rosewell, 1992) of 2500, 1600 and 1500 kg m⁻³ for the Podzol, Ferralsol and Vertisol respectively. Soils were sieved into different size fractions and total N and C were measured in the different fractions by an Elemental Analyser (Euroe A) using Dumas combustion, whilst total P was measured colourimetrically from kjeldahl digests.

Table 1. Analytical data for three soils used in experiments

Property	Podzol	Ferralsol	Vertisol
Sand (2.00-0.02 mm) (%)	90	36	13
Silt (0.02- 0.002 mm) (%)	4	21	23
Clay (<0.002 mm) (%)	6	43	64
Soil textural class	Sand	Clay	Clay
Mean settling velocity of inflow sediment (m s ⁻¹)	0.043888	0.03654	0.00966
Wet density of sediment (kg m ⁻³)	2500	1600	1500
1:5 pH in CaCl ₂	5.2	5.3	7.3
Electrical conductivity of 1:5 suspension (dS m ⁻¹)	0.051	0.064	0.191
Cation Exchange Capacity (mmoles _c kg ⁻¹)	97	157	643
Exchangeable Sodium Percentage	2.0	1.3	0.5

The Podzol is the coarsest of the three soils, consisting primarily of coarse sand-size particles with little aggregation. The Vertisol and Ferralsol are both classified as clay textured when fully dispersed but the Vertisol has a larger clay fraction (Table 1), consisting primarily of smectites. The settling velocities of the inflow sediments (<4.76 mm sieved soils) were in the order of Podzol >Ferralsol >>Vertisol. The Ferralsol had an unexpectedly high settling velocity due to the preponderance of large stable aggregates in the soil. These have formed as a result of the inert clay fraction and high iron oxide content of the soil (14% dithionite extractable, Black and Waring, 1976).

2.2 Flume Experiments

The GUTSR consists of a 5.8 m long, 1 m wide flume, of adjustable slope (Ghadiri et al., 2001). Experiments were carried out in a 3.5 by 0.3 m section constructed within the flume. For the flume experiments, dense vetiver (*Vetiveria zizanioides* L., sterile cultivar Monto) strips (0.3 m wide) were grown in planting boxes. Prior to transferring a strip to the flume, the entire root system was dipped into a Plaster of Paris mixture to prevent sediment washoff from the root bed and to give firm anchorage to the plants, similar to that experienced by deeply rooted vetiver in the field. The completed strip was thus 0.3 m in width (to fit across the flume) and 0.3 m in length (along the flow path of the flume) with a stem/culm density of 4300 stems m⁻². Average stem/culm width was 9 mm at 30 mm height. The completed length was similar to that of a vetiver hedge in arable fields after ~1 year of growth (Dalton, 1997). The block was inserted in the flume and a raised flume surface was constructed level with the base of the plants, and on either side of the buffer, using impermeable boards. As the floor of the GUTSR is impermeable, sediments were removed from flow by settling alone. Three replicate

experiments were conducted for each soil at 5 % slope and additionally for the Vertisol at 1 and 3% slopes using the flow conditions shown in Table 2.

Table 2: Flow conditions in the GUTSR flume

Slope (%)	1	3	5
Unit flow rate ($\text{m}^2 \text{s}^{-1}$)	0.00033	0.00067	0.001
Upstream flow depth (mm)	<-----8----->		

After stabilization of flow, the water surface elevations upstream and downstream of the vetiver strip were recorded using thin rigid PVC strips with dye (Ghadiri et al., 2001; Rose et al., 2003). The soils were then introduced as slurry into the surface flow through the dispenser (Fig.1). The flow was maintained at the same total flow rate as previously by adjusting the inflow rate. The loose slurry was prepared by adding 200 mL of water to 90 g air dry sieved soil (<4.76 mm) in each of 40 beakers for the Ferralsol and Podzol. For the Vertisol, a separate set of experiments was done at 1, 3 and 5% slopes. For the Vertisol, slurry was prepared by wetting 180 g air dry soil (<4.76 mm) in each of 20 buckets. Wetting was done two hours prior to each run, followed by stirring, to ensure full saturation/swelling of the soil. The slurry was then added to the dispenser from the containers, every minute over a 40 min period (for the Podzol and Ferralsol) and over a 20 min period for the Vertisol. Although more slurry was added per minute over a shorter period for the Vertisol, the total added slurry amounts were the same for all three soils. The sediment was continuously agitated in the dispenser with an electric mixer, to ensure an even distribution of sediment into the flow.

Four samples were collected from the dispenser (inflow) for each soil and analysed for particle size distribution and total sediment concentration by wet sieving, using the method described in Ghadiri et al.(2001). Sieves of mesh size 2.00, 1.00, 0.50, 0.25, 0.106 and 0.054 mm were used. Sediment <0.054 mm was collected during the wet sieving process and later analysed by sedimentation in a 1 litre cylinder using a pipette. Outflow samples were collected in 600 mL beakers at 2 min intervals during each run, and sediment concentrations (g L^{-1}) determined by oven drying. Larger outflow samples were collected in buckets over a 20 s period, at 4 minute intervals, to yield outflow rates together with sediment whose components were analysed for particle size distribution. The rate of sediment deposition was estimated using small zinc tags (20 x 20 x 1 mm) introduced into the flow on top of depositing sediment at different distances, and times, upstream of the buffer. At the end of the sediment addition, the elevation of the new water surface was again measured, using dyed PVC strips. After flow ceased, the surface elevation of the sediment both across and along the flume was photographed, then measured using dyed PVC strips. Depths to the tags imbedded in the sediment were also recorded, and then samples of the sediment were taken from different distances upstream of the vetiver strip. The deposited sediment samples were analysed for particle size distribution by wet sieving and pipette analysis. Mean weight diameters (*MWD*) of the sediments were calculated according to Van Bavel (1950).

2.3 Statistics

Statistical t tests (at the 5% level) were used to test the hypothesis that there was no difference between mean data values measured for the Podzol and Ferralsol. We did not conduct t tests to compare the results from the Vertisol to the other two soils, as it was applied at a different rate.

2.4 GUSED-VBS Model

GUSED is designed to generate hillslope runoff, sediments and nutrient/chemical generation. The VBS component of GUSED has been developed to predict the hydrological and sediment deposition profiles that occur when sediment-laden flow passes through buffers (Hussein et al., 2006; Rose et al., 2003). GUSED attempts to solve a set of coupled ordinary differential equations including the governing equation for steady gradually varied flow, namely the backwater equation (Chow, 1959). The coupled ordinary differential equations are solved for each time step using the Runge–Kutta method with adaptive step-size control. A routine is implemented using Cash–Karp parameters for the embedded Runge–Kutta method (Cash and Karp, 1990; Press et al., 1992). The bed profile is updated at the end of each time step. This in essence assumes a series of steady state solutions of flow and sediment transport and deposition. The output of GUSED -VBS includes water surface and bed profiles at different distances upstream of the buffer at the end of each time step, as well as the sediment concentrations in the flow for each size class, at the upstream end of the buffer.

We used the following input variables to GUSED -VBS to simulate deposition upslope of buffer strips for the three soils as follows: distance increments of 0.05 m, giving a total simulation distance of 1.5 m upstream of the vetiver strip; time intervals of 1 minute for a total of 20 minutes for the Vertisol and forty minutes for the Podzol and Ferralsol; slope and unit discharge as shown in Table 2, water density 1000 kg m^{-3} ; wet density of sediments as shown in Table 1, Manning $n = 0.05$; threshold stream power 0.008 kg m^{-3} ; fraction of stream power effective in entrainment or re-entrainment 0.1 ; initial water depths adjacent to upstream end of buffer of 23, 28 and 30 mm at 1, 3, and 5% slopes, and the fractions of the incoming sediment in nine size classes.

Simulations were run using the input data. Coefficients of model efficiency Ec (Nash and Sutcliffe, 1970) were computed from the measured and simulated data. An Ec value of 1 indicates a perfect fit and as values tend to 0 or to negative values, this indicates increasingly poor fit. The root mean square errors ($RMSE$) for the data were also calculated and percentage of the mean observed value ($RMSE * 100 / Om$) where Om = mean of the measured values, to indicate the relative magnitude of errors (Hussein et al., 2006).

3.0 RESULTS AND DISCUSSION

3.1 Water and Sediment Profiles

Flows in the flume upstream of the vetiver strip, were subcritical, with Froude numbers of 0.59 ± 0.04 . The digitized data relating to flow/deposited sediment depths were recorded, as illustrated in Fig. 2 for one of the Podzol replicates at 5% slope. Upslope distances from the start of the vetiver strip are presented as negative values. Flow depths were corrected relative to 0 mm elevation, at the start of the vetiver strip. Flow depths inside the vetiver strip could not be reliably recorded due to the thick foliage of the grass. The ‘water start’ line in Fig.2 shows the water profile depths at the start of this particular experiment and indicates that the grass retarded flow, causing a backwater area with an increased flow depth upslope of the vetiver strip. A maximum flow depth of 0.025 m (25 mm) was recorded for this replicate just upstream of the vetiver strip and the backwater zone extended -0.40 m (upstream) of the vetiver strip. Upon the addition of the Podzol sediment, deposition occurred in the ponded zone due to reduced flow velocity. Larger particles/aggregates with high settling velocities

therefore deposited in the backwater region. After 40 minutes, the sediment ('sediment end' in Fig.2) reached a final maximum height of ~12 mm at -0.5 m in front of the vetiver strip and extended upstream to -0.8 m. The backwater zone thus grew in length and height due to net deposition, extending upstream to a final value of ~0.85 m ('water end' Fig. 2) and flow depth over this sediment reached a maximum height of 57 mm at the start of the vetiver strip.

Water and sediment profiles were thus recorded for all replicates and results were analysed. Backwater lengths varied between 0.3 to >1.5 m, increasing with decreasing slope and maximum backwater depths (measured at the start of the vetiver strip) ranged from 21 to 60 mm, increasing with slope (Hussein et al.,2006). Sediments were primarily deposited in front of the vetiver strip in a low mound, as illustrated by the sediment deposit trace in Fig. 2, with very little deposition in, or after, the strip. The Podzol and Ferralsol were deposited further upstream of the vetiver strip, in contrast to the Vertisol which was deposited close to, and into, the vetiver strip. This is to be expected, as the finer sediment of the Vertisol has a lower settling velocity (Table 1) and is carried further towards the strip by the flow, before being deposited. The settling velocity of the Ferralsol is slightly lower than that of the Podzol and so it is deposited further downstream than the Podzol. Sediment deposition also varied with slope for the Vertisol, with the zone of maximum deposition moving downstream as slope increased (Hussein et al.,2006). Similarly shaped hydrology profiles with vetiver strip or barrier strips have been recorded in flumes by Ghadiri et al. (2001); Dabney et al. (1995) and Meyer et al. (1995) for supercritical flows.

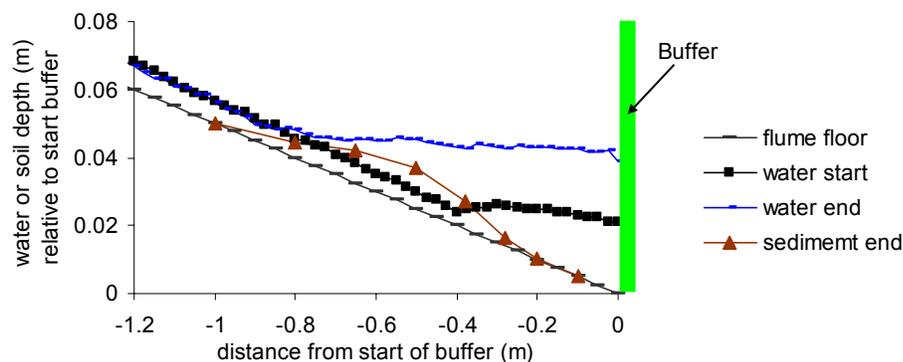


Fig. 2. Water and sediment profiles for the Podzol. Distances and depths are measured upstream from the start of the buffer

3.2 Sediment Concentration in the Outflow

Mean sediment concentrations in the outflow are shown as a percentage of the inflow concentration in Table 3. Overall sediment loads were effectively reduced to between 3.2 to 11.6 % by the vetiver strip, indicating that ~97 to 88 % of the inflow sediment were deposited. Trapping efficiency was therefore high under these subcritical flow rates. The greatest reduction was measured for the coarse Podzol and there was a significant difference in sediment load between the Podzol and Ferralsol ($p < 0.01$). For the Vertisol, sediment load increased with increasing slope (Table 3) and there were significant differences ($p < 0.01$) in sediment reduction between slopes. This increase in load (decreased sediment trapping efficiency) is probably due to the decreasing backwater length, which thus allowed less length (and therefore time) for the suspended particles to settle. Buffer systems incorporating these

strips should thus be designed more conservatively for steeply sloping land. This efficiency may also be reduced at higher, subcritical, flow rates. For comparison, Meyer et al. (1995) reported decreased trapping efficiencies of 78 to 49% for 20 cm vetiver strips in a flume at 5% slope, at flow rates of 0.011 to 0.043 m² s⁻¹, which were considerably higher than those used in our study. However, subcritical flow rates are more typical for overland or sheet flow in the field particularly when there is good surface cover (Emmett, 1978) suggesting that sediment trapping for this type of flow is probably efficient. This has been confirmed in a number of field studies on grass buffer strips which show high sediment removal efficiencies at moderate slopes and flows (Blanco-Canqui et al. (2004a, b) As the tests were conducted on relatively young vetiver grass, it is expected that sediment trapping efficiency of the buffer strip would increase as the strip thickened with age. Similarly, the proportion of finer particles trapped by the strip will also increase as the hedges mature.

Table 3: Relative sediment concentrations in the outflow for the three soils. Standard errors are shown in parenthesis.

Soil	Ferralsol	Podzol	<-----Vertisol----->		
Slope %	5	5	5	3	1
Outflow as a % of the inflow concentration	6.0 (0.44)	3.2 (0.40)	11.6 (0.5)	10.2 (0.8)	5.9 (0.2)

3.3 Sediment Size in the Outflow (runoff)

Fig.3 presents a comparison of the particle sizes in the outflow for the three soils. Despite the differences between the inflow sediment for all three soils (Table 1), sediment in the outflow is primarily in the 0.002-0.2 mm size range, with some clay (<0.002 mm) in Ferralsol and Podzol outflow. Thus most of the coarse material (>0.2 mm) was deposited out, upstream of the buffer. A t test comparing size class means showed no significant differences between the Podzol and Ferralsol outflow, apart from the clay fraction (p<0.01), where the Podzol had a greater fraction of clay. Chemicals are generally preferentially sorbed to the finer fractions in soil (Ghadiri and Rose, 1991) or may be sorbed on the outer layers of larger aggregates. These outer layers can be transformed into fine particles by mechanical breakdown or raindrop stripping (Ghairi and Rose, 1991). Thus while the overall sediment loads are reduced by buffers, this preferential movement of fines through vetiver strips suggests that pollutants adsorbed to fine particles may still move through buffers.

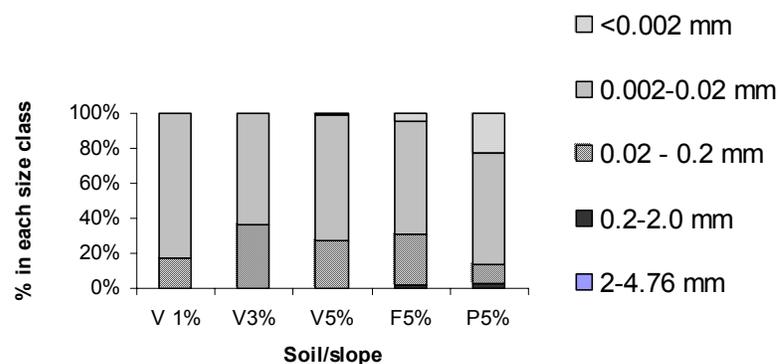


Fig 3. Particle size distribution in the outflow for three soils
V = Vertisol, F = Ferralsol, P = Podzol

3.4 Nitrogen, Phosphorous and Carbon Retention

The vetiver strip caused deposition of a large percentage of the particulate-held total N, P and C (Fig. 4). High trapping rates were produced where particulate-held N, P and C were associated with coarser soil fractions and/or where the incoming sediment was itself coarse, as the deposited sediments primarily consisted of coarse 0.02-4.76 mm sized particles (Hussein et al., 2006). P levels were reduced by >63% of the inflow concentration with the greatest % reduction occurring for the Ferralsol (95%) at 5% slope and the least reduction for the Vertisol (63%) at 5% slope. As slope decreased for the Vertisol, the P trapping efficiency increased, probably due to the greater sediment trapping (Table 3). For particulate-N, >68% was reduced whilst >65% of the C was reduced, with the Vertisol at 5% again showing the lowest trapping. Total-C reduction was particularly high for the Podzol. This was due to the fact that of the C contents measured in the different size fractions of this soil, the highest levels were found in the coarse fraction (2.0-4.76 mm), possibly due to the high levels of decomposing leaf litter present at the collection site. As the coarser fractions were effectively trapped for the Podzol, this resulted in the highest overall C-trapping efficiency.

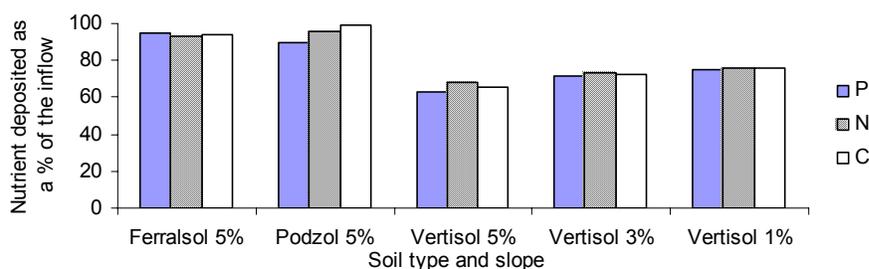


Fig.4. Deposition of particulate-held nutrients and carbon for different soils and slopes

Field research has likewise found that grass barriers effectively trap nutrients (Dorioz et al., 2006; McKergow et al. 2004 a,b). Blanco-Canqui et al. (2004b) found that a 0.7 m switchgrass barrier reduced sediment load by 91%, particulate N and P by 53 to 67 % and soluble N and P by 50 to 68%. When combined with a 8 m fescue filter strip in which infiltration losses rather than settling losses of sediment were encouraged, sediment loads were only marginally reduced (<5%) but particulate and soluble loads decreased by a further 5 to 50 %. Strips that combine erect grass hedges such as vetiver to promote settling with wide (> 5m) filter strips covered by lower, less erect grass to promote settling and infiltration are thus more effective than those with just one type of grass. However, if space is limited, even a single vetiver hedge has the ability to greatly reduce sediment loads and partially remove pollutants.

3.5 Modelling

The GUSED-VBS model was used to simulate the water and sediment profiles for the given experimental conditions and these were compared to measured data. Examples of measured versus simulated profiles are presented for the Vertisol at 5% slope in Fig 5a and b respectively. Goodness of fit parameters were assessed from a comparison of measured versus simulated water and sediment profiles (Table 4). Parameters are defined in the Methods and Materials section. Simulations were run at 1, 3 and 5% slopes for the Vertisol and at 5% slope for the Ferralsol and Podzol and values were averaged from the 5 simulations..

Simulated water profiles (e.g. Fig. 5a) matched measured values fairly closely for all slopes although simulated profiles were considerably smoother than the measured data. The mean Ec value for all the simulated water profiles was 0.70, approaching the value of 1 which indicates a perfect fit, whilst the average $RMSE$ and magnitude of error were low, indicating close agreement between simulated and measured data. The simulated sediment profiles were similar in overall shape to the measured data for all the Vertisol runs, such as the example shown in Fig.5b, but indicated deposition closer to the grass strip than was measured for the Podzol and Ferralsol. The mean Ec value for the sediment profiles again approached 1 (Table 4) but the $RMSE$ and magnitude of errors were larger, indicating greater differences between observed and simulated data. The simulated sediment profiles are therefore not as good a fit as the water profiles, but are within an acceptable range.

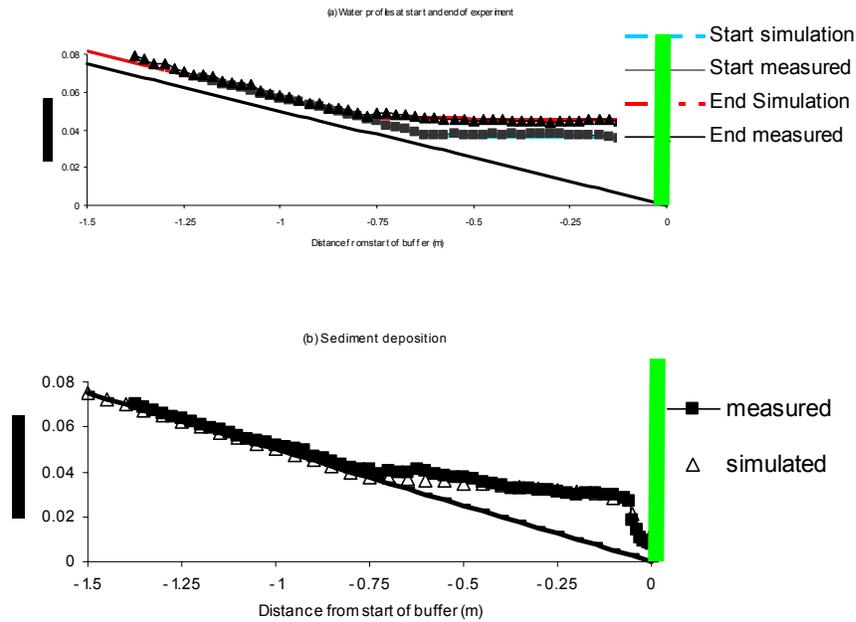


Fig.5. Measured and simulated (a) water and (b) sediment profiles for the Vertisol at 5 % slope. Experiment duration is 20 minutes.

The total mass of sediment deposited from the flume experiments within the area of 1.5 m x 0.3 m upstream of the grass strip (kg sediment per 0.45 m² area) was compared to the simulated data (calculated by difference between the inflow and outflow sediment loads). The Ec value was again close to 1 and $RMSE$ was low, with relative magnitude of errors of ~7%, indicating close agreement. Therefore overall the model successfully simulated the changing hydrology during deposition and also simulated total sediment deposition, but was less successful at simulating the location of the deposition for the coarser sediments.

Table 4: Assessment of goodness of fit for the GUSED-VBS model

Type of simulation	Ec	$RMSE$	Relative magnitude of error (%)
Water profile(mm)	0.70	0.0018	4.4
Sediment profile (mm)	0.68	0.1489	28.6
Total sediment deposited upstream of grass strip (kg per 0.45 m ²)	0.87	0.0072	7.3

3.6 Simulated Versus Measured Particle Size of Deposited Sediment

Fig. 6 presents the comparison between simulated and measured sizes of deposited sediment. The simulated data usually underestimated finer particles and overestimated coarser particles in the deposits.

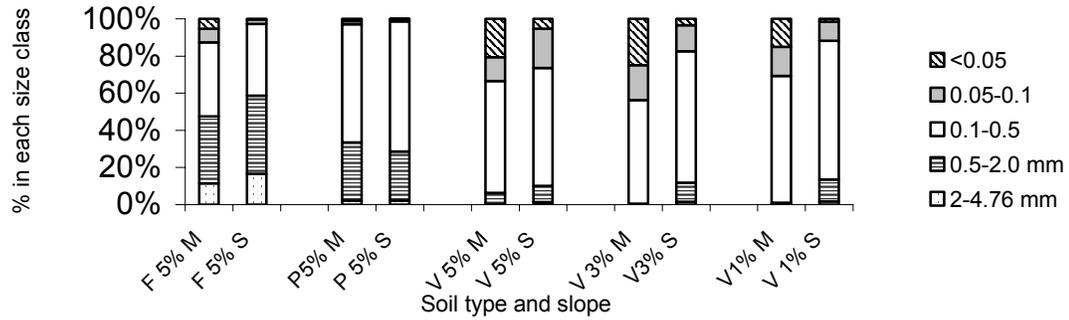


Fig.6. Comparison of the size distribution of deposited sediment for different soils and slopes
F = Ferralsol, P = Podzol, V = Vertisol, M= measured data, S = simulated data

3.7 Simulated Versus Measured Nutrient Removal

Fig.7 shows an example of simulated versus measured nutrient removal for particulate-sorbed P. The simulated data follows a similar trend to the measured data but simulated values were 5-10 % lower for all soils, except for the Vertisol at 1% slope. The N and C simulations (not presented) were somewhat similar. The model thus slightly generally under-predicts the nutrient retention by the vetiver buffer. This is probably due to slight under-prediction of sediment deposition by the model (Hussein et al., 2006) combined with differences between simulated and measured particle sizes (Fig.6). Further work is underway to examine and explain these differences and to test the model with field data. The simulation of nutrient reduction by this process-based model is however an important first step towards the examination of spatial and temporal dynamics of nutrients in buffers and possible incorporation into the kind of conceptual model proposed by Dorioz et al. (2006)

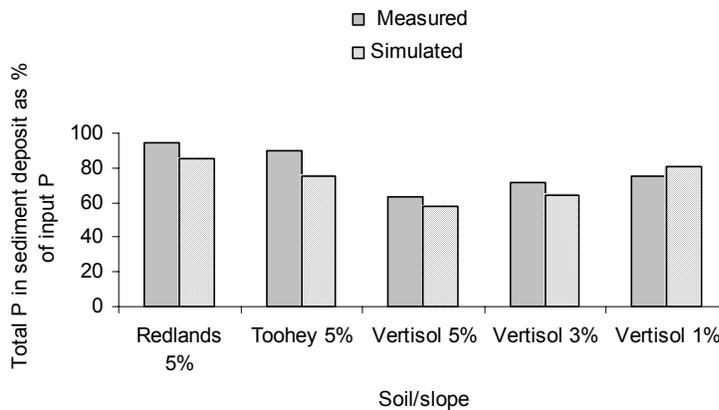


Fig. 7. Comparison of simulated versus measured % of total P in deposited sediment

4.0 CONCLUSION

At low slopes and subcritical flow rates, a vetiver hedge retarded flow and effectively reduced sediment loads in the outflow for three soil types to less than 12 % of the inflow concentration. Sediment reduction increased with increasing coarseness of the input sediment. The vetiver strip was less effective in trapping sediment as slope increased for the Vertisol. A newly developed erosion and deposition model (GUSED-VBS) was introduced, which predicts time-dependent changes in sediment retention by buffers. The inputs for the model are readily obtainable from many field and laboratory studies. The model predicted water profiles and total mass reduction well, with a reasonable fit for sediment profiles and nutrient reduction. Overall the model appears to provide a very useful start for estimating sediment retention by grass strips but further testing using both laboratory and field data is desirable.

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6.0 REFERENCES

- Australian Standards 1995. AS 12898.3.6.2-1995. Method 3.6.2 Soil classification tests- determination of the particle size distribution of a soil - analysis by sieving in combination with hydrometer analysis (subsidiary method). Government of Australia.
- Black, A.S. and Waring, S.A. 1976. Nitrate leaching and adsorption in a Krasnozem from Redland Bay, Queensland. *Aust. J. Soil Res.* 14, 171-180.
- Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H. and Alberts, E.E. 2004a. Grass barriers for reduced concentrated flow induced soil and nutrient loss. *Soil Sci. Soc. of America J.* 68, 1963-1972.
- Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H., Alberts, E.E. and Thompson, A.L. 2004b. Grass barriers and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen and phosphorus loss. *Soil Sci. Soc. of America J.* 68, 1670-1678.
- Cash, J.R. and Karp, A.H. 1990. A variable order Runge-Kutta method for initial value problems with rapidly varying right hand sides. *ACM Transactions on Mathematical Software* 16, 201-222.
- Cheng, N.S. 1997. Simplified settling velocity formula for sediment particles. *J. of Hyd. Eng., American Soc. of Civil Engineers* 123, 149-152.
- Chow, V.T. 1959. *Open channel hydraulics*. McGraw Hill New York. 680 pp.
- Dabney, S.M., Meyer, L.D., Harmon, W.C, Alonso, C.V. and Foster, G.R., 1995. Depositional patterns of sediment trapped by grass hedges. *Transactions of the ASAE* 38, 1719-1729.
- Dalton, P.A. 1997. Application of vetiver grass hedges to erosion control on the cropped flood plain of the Darling Downs. M.Eng. Thesis, Faculty of Engineering & Surveying, University of S. Q., Australia.
- Deletic, A., 2001. Modelling of water and sediment transport over grassed areas. *J. of Hydrology* 248, 168-182
- Deletic, A., 2005. Sediment behaviour in runoff over grassed surfaces. *J. of Hydrology* 301, 108-122.
- Dillaha, T.A., Reneau, R.B., Mostaghimi, S., Lee, D., 1989. Vegetative filter strips for agricultural nonpoint source pollution control. *Transactions of the ASAE* 32 (2), 513-519.
- Dorioz, J.M., Wang, D., Poulenard, J. and Trevisan, D. 2006. The effect of grass buffer strips on phosphorus dynamics – a critical review and synthesis as a basis for application in agricultural landscapes in France. *Agric. Ecosystems & Envir.,* 117.
- Emmett, W.W. 1978. Overland flow. Chapter 5. In: Kirkby, M.J.(ed.) *Hillslope hydrology*. Wiley, NY., pp.145-176.
- FAO 1998. *World Reference Base for Soil Resources*. World Soil Resources Report 84. FAO Rome 88 pp.
- Flanagan, D.C., Nearing, M.A., 2000. Sediment particle sorting on hillslope profiles in the WEPP Model. *Transactions of the ASAE* 43, 573-583.
- Ghadiri, H. and Rose, C.W. 1991. Sorbed Chemical transport in overland flow: I. A nutrient and pesticide enrichment mechanism. *J. Environ. Quality* 20, 628-633.
- Ghadiri, H., Rose, C.W. and Hogarth, W.L., 2001. The influence of grass and porous barrier strips on runoff hydrology and sediment transport. *Transactions of the ASAE* 44, 259-268.

- Hussein, J., Yu, B., Ghadiri, H. and Rose, C.W. 2006. Prediction of surface flow hydrology and sediment retention upstream of a vetiver buffer strip for a Vertisol at three slopes. *J. of Hydrology*..... (submitted...)
- Loch, R.J. and Rosewell, C.J. 1992. Laboratory methods for measurement of soil erodibilities (K factors) for the Universal Soil Loss Equation. *Aust. J. of Soil Res.* 30, 233-248.
- McKergow, L.A., Prosser, I.P., Grayson, R.B. and Heiner, D. 2004a. Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 2. Water quality. *Aust. J. of Soil Res* 42, 485-499.
- McKergow, L.A., Prosser, I.P., Grayson, R.B. and Heiner, D., 2004b. Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 1. Riparian Hydrology. *Aust. J. of Soil Res* 42, 473-484.
- Meyer, L.M., Dabney, S.M. and Harmon, W.C. 1995. Sediment trapping effectiveness of stiff grass hedges. *Transactions of the ASAE* 38, 809-815.
- Munoz-Carpena, R., Parsons, J.E., Gilliam, J.W., 1999. Modelling hydrology and sediment transport in vegetative filter strips. *J. of Hydrology* 214, 111-129.
- Nash, J.E. and Sutcliffe, J.V. 1970. River flow through conceptual models, part 1 – a discussion of principles. *J. of Hydrology* 10, 282-290.
- Newham, L.T.H., Rutherford, J.C. and Croke, B.F.W. 2005. A conceptual model of particulate trapping in riparian buffers. CSIRO Land & Water Technical Report 21/05. CSIRO Land & Water Canberra, Australia.
- Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. 1992. *Numerical Recipes in Fortran*, Cambridge University Press, Cambridge, pp. 963.
- Rose, C.W., Yu, B., Hogarth, W.L., Okom, A.E.A. and Ghadiri, H. 2003. Sediment deposition from flow at low gradients into a buffer strip – a critical test of re-entrainment theory. *J. of Hydrology* 280, 33-51
- Rayment, G.E. and Higginson, F.R. 1992. *Australian laboratory handbook of soil and water chemical methods*. Australian Soil and Land Survey Handbook. Series 3. 330pp.
- Sobey, I. 2006. Utilisation of Vetiver System in Disaster Mitigation in Central Vietnam. *Vetiver System: Disaster Mitigation and Environmental Protection in Vietnam*. Proceedings of the. Regional Vetiver Conference, Cantho City, Vietnam January 2006.
- Truong, P.N.V. 1999. Vetiver grass technology for flood and stream bank erosion control. Proceedings of the International Vetiver Workshop Nanchang, China, October 1999.
- Van Bavel, C.H.M. 1950. Mean weight diameter of soil aggregates as a statistical index of aggregation. *Soil Sci. Soc. of America Proceedings* 14, 20-23.

A Brief Introduction to the First Author

Dr Janet Hussein is a soil scientist, formerly from Zimbabwe. She is currently working as a Research Fellow in the Centre for Riverine Landscapes based in the Faculty of Environmental Sciences at Griffith University, Brisbane, Australia, evaluating the role of vetiver buffer strips in reducing sediments and associated pollutants to water bodies. The authors received funding from the Australian Research Council for this project.