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Quantitative evaluation of strategies for erosion control on a railway embankment batter

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Abstract:

Strategies for erosion control on a railway embankment batter (side slope) are quantitatively evaluated in this paper. The strategies were centred on control ('do nothing' treatment), grass seeding, gypsum application, jute mat (an erosion control blanket) placement and planting hedgerows of Monto vetiver grass. Rainfall and runoff were monitored at 1 min intervals on 10 m wide embankment batter plots during 1998 and 1999. Total bedload and suspended sediment eroded from the plots were also measured but only for a group of storm events within sampling intervals. It has been demonstrated that vetiver grass is not cost-effective in controlling erosion on railway batters within Central Queensland region. Seeding alone could cause 60% reduction in the erosion rate compared with the control treatment. Applying gypsum to the calcium-deficient soil before seeding yielded an additional 25% reduction in the erosion rate. This is the result, primarily, of 100% grass cover establishment within seven months of sowing. Therefore, for railway embankment batter erosion control, the emphasis needs to be on rapid establishment of 100% grass cover. For rapid establishment of grass cover, irrigation is necessary during the initial stages of growth as the rainfall is unpredictable and the potential evaporation exceeds rainfall in the study region. The risk of seeds and fertilizers being washed out by short-duration and high-intensity rainfall events during the establishment phase may be reduced by the use of erosion control blankets on sections of the batters. Accidental burning of grasses on some plots caused serious erosion problems, resulting in very slow recovery of grass growth. It is therefore recommended that controlled burning of grasses on railway batters should be avoided to protect batters from being exposed to severe erosion. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS erosion; embankment; batter; railway; plot experiment; runoff; vetiver grass; gypsum; grass seeding

INTRODUCTION

Erosion and sedimentation problems on railway track formation within Central Queensland cause increased maintenance costs, risks of outages (power failure) and derailments, interruptions of normal train operations, and environmental degradation. The Central Queensland railway network covers an approximate area of 100 000 km^2 with a total route length of 1357 km. A survey conducted by Nissen (1997) indicated that 10% of the total route length, consisting of 60% cuttings and 40% embankments, require some form of erosion-damaged remediation works. Continuous sections needing repair works vary between 50 m and 2000 m in route length. Routine remediation works are undertaken solely to maintain train operations, with emphasis placed on fast implementation. The remediation works do not permanently correct the erosion damage, and are unsuitable for sustained erosion control.

Unfamiliar terminologies in railway industry need to be introduced before proceeding. Figure 1 depicts a typical cross-section of a railway embankment. The outer verge is the section around the junction between the top of the embankment and the batter (side slope). The mid-point of the rail track is the drainage divide, the

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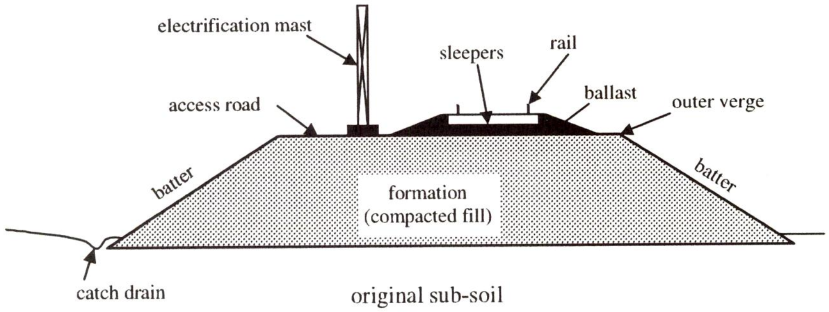

Figure 1. Typical cross-section of a railway embankment (not drawn to scale)

top of the embankment being the area between the divide and the junction with the batter. The section between the outer verge and ballast is normally used as an access road for routine maintenance operations. Ballast consists of crushed aggregate and its depth is generally between 200 mm and 250 mm. The minimum bulk density of the ballast is 2·5 tons/m^3 (Plunket, 2000). The ballast provides acceptable resilience and sufficient energy absorption for the track structure. It also distributes the imposed loading, thus reducing stresses at the formation level. Efficient drainage of water from the track, retardation of vegetation growth, and ease of maintenance following construction are additional benefits of the ballast.

The need for cost-effective remediation practices was identified by the Infrastructure Services Group of QR (formerly Queensland Rail) in 1997. Research into the problems of erosion has been undertaken in association with Central Queensland University (Gyasi-Agyei and Sibley, 1998, 1999, 2000; Gyasi-Agyei *et al.*, 1998, 2000). The research project involved characterizing the erosion problem and setting up of field trials to demonstrate various techniques of minimizing erosion problems. The field trials involved implementing selected bioengineering erosion and sediment control strategies on sections of railway formation batters, and monitoring the erosion rates of the field trial sections over time. The track formation soils within Central Queensland vary considerably and so does the rainfall distribution. It is, therefore, clear that a cost-effective way to develop strategies for prevention and control of track formation erosion that will have wide applicability is to model the processes involved. However, the computer model has to be calibrated with monitored rainfall, runoff and soil loss data from field trial sites. Once the computer model is operational, it could be used to predict on-site and off-site losses of sediment from a particular embankment and cutting design and surface treatment. This paper presents the results of the field trials established on the Gregory railway line embankment batter to monitor rainfall, runoff and soil loss. This demonstration site was selected for the following reasons:

1. the formation soil (subsoil) properties and the geometrical characteristics are typical of other embankment erosion problem sites;
2. presence of extensive rills on batters;
3. lack of vegetation cover for erosion control on the batters;
4. the site is not visible from the access road thereby minimizing the risk of the installed equipment being stolen or vandalized.

The selected site was a good choice for demonstration of current techniques of batter erosion control, and it offered a high possibility of transfer of the research outcomes to other sites.

Although many useful experimental studies have been conducted on runoff and erosion in the literature, there remains a lack of knowledge concerning the erosion of railway formation, especially in regions such as Central Queensland. Steep slopes, subsurface soil types, and adverse rainfall patterns within the region are some of the distinguishing features necessitating this research. The need for reliable data and information on runoff and erosion of railway formation cannot be overemphasized.

EXPERIMENTAL SITE DESCRIPTION

Location and climate

The Gregory railway line embankment field trial site is 300 m long and is located approximately 25 km west of Blackwater, in Central Queensland, Australia (Figure 2). It is centred at the 8·6 km route distance mark from Burngrove. This line, opened in February 1980, forms part of the Blackwater system. The respective mean minimum and mean maximum daily temperatures are 7 °C and 22 °C in July, and 22 °C and 35 °C in January. Mean monthly rainfall varies between 21 mm in August and 104 mm in January, with an annual average value of 639 mm. Rainfall generally is characterized by short-duration and high-intensity storm events. Some values of the rainfall intensity–frequency–duration for Blackwater are provided in Table I (AUS-IFD, 1998). Class A pan mean annual evaporation for the study region is estimated as 2400 mm. Hence annual potential evaporation exceeds annual rainfall within the study region.

Soil properties

Table II presents the summary of the chemical properties of the formation soil relevant to erosion control. The formation soil is likely to exhibit structural problems, manifested by hard setting or surface crusting, as a result of very low organic carbon content. Also, the formation soil pH is slightly alkaline and its salinity is moderate, as indicated by the electrical conductivity and chloride content. The exchangeable sodium percentage (ESP) indicates that the formation soil is strongly sodic and is thus liable to exhibit dispersibility and erodibility. These interpretations are made according to Witheridge and Walker (1996) and Queensland

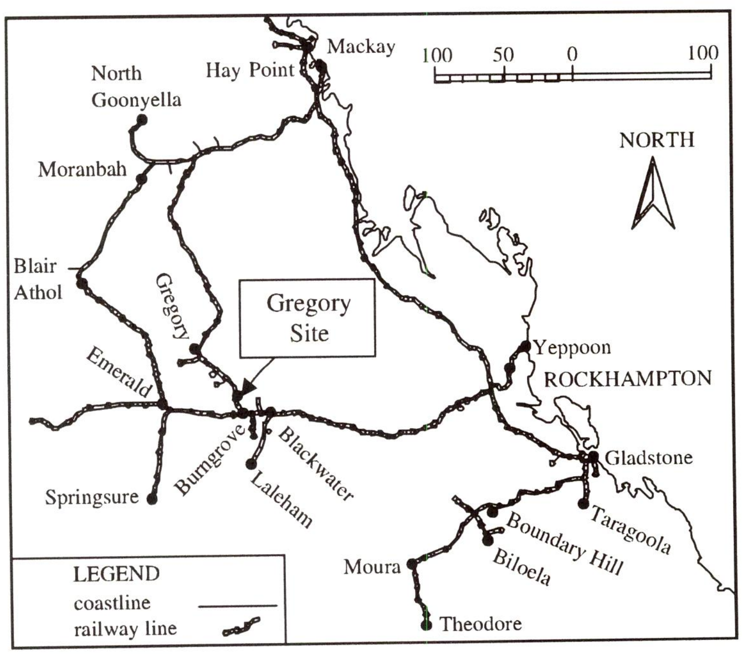

Figure 2. Location of Gregory field trial site

Table I. Rainfall intensity–frequency–duration data for Blackwater (mm/h)

Duration (minutes)	Frequency (years)						
	1	2	5	10	20	50	100
5	102·0	131·0	169·0	192·0	222·0	264·0	297·0
15	67·0	86·0	110·0	125·0	145·0	172·0	192·0
30	48·5	63·0	80·0	90·0	104·0	123·0	138·0
60	33·9	43·6	55·0	62·0	72·0	85·0	95·0
120	20·0	25·8	33·0	37·4	43·3	51·0	58·0
360	8·4	11·0	14·2	16·3	19·0	22·7	25·6
720	4·9	6·4	8·4	9·7	11·3	13·6	15·4
1440	3·0	4·0	5·3	6·1	7·2	8·7	9·9

Table II. Summary of soil chemical properties

Parameter	Value
pH (1 : 5 water)	8·5
Organic carbon (%)	0·2
Chloride (mg/kg)	475·0
Electrical conductivity (se) (dS/m)	4·2
Electrical conductivity (1 : 5water) (dS/m)	0·5
Cation exchange capacity (meq/100 g)	18·7
Exchangeable sodium percentage (ESP)	23·9
Calcium : magnesium ratio	1·1

Department of Minerals and Energy (1995). Emerson crumb test results place the soil into Class 2, indicating that it slakes with some dispersion when saturated.

The soil, consisting of 25% clay, 18% silt and 57% sand, is classified as a sandy clay loam according to the USDA soil classification system (Marshall *et al*., 1996). The median diameter, d_{50}, is 80 μm. The average dry bulk density and particle density of the soil were determined as 1·73 Mg/m^3 and 2·62 Mg/m^3, respectively. Infiltration tests were carried out at two locations at the top of the embankment using a CSIRO disc permeameter. The average saturated hydraulic conductivity was estimated at 5·3 mm/h. The saturated hydraulic conductivity was also measured using the falling head permeability test. This method gave a saturated hydraulic conductivity value of 7·3 mm/h, which is comparable to the value obtained from the CSIRO disc permeameter.

MEASURING EQUIPMENT

The equipment installed at the Gregory railway line field trial site is used to monitor rainfall and runoff, at 1 min intervals, for individual storm events, and total bedload and suspended sediment for a group of storm events within the sampling intervals. A sampling interval (SI) is defined as the time between two successive soil loss data collection dates. Such fine-scale data are required to calibrate an event-based runoff-erosion model.

Equipment set up

A trough was placed along the lower border of every plot, extending across the plot width. The 10 m plot width is considered sufficiently large enough to minimize edge or border effects. The troughs are made from 1 mm zinc annealed steel sheets and are 9600 mm long, 360 mm wide and 250 mm deep. The trough collects the runoff and sediment from the plot. It then releases the water and suspended sediment through an overflow slot (220 mm × 30 mm) in the attached manifold into a welded PVC tipping bucket. The frame of the overflow slot extends 20 mm above and below the bottom of the trough. It reduces the velocity of runoff encouraging deposition of sediments. The troughs were placed at a slight slope to ensure that the bedload sediment is well drained of water before sampling.

Two Monitor RGD-04 (200 mm diameter) tipping bucket pluviometers were installed. The runoff tipping bucket is a design of Queensland Department of Natural Resources (Ciesiolka *et al.*, 1995). A flow splitter at the outlet of the tipping bucket allows for the collection of water samples, using a short diversion pipe to a 5 L plastic container. The flow splitter samples approximately 1/1000 of the tipping bucket volume. These water samples are used to determine the suspended sediment in the runoff. Figure 3 shows a sketch of the runoff and sediment measuring system. Sediment filter baskets (7500 mm long, 120 mm wide and 180 mm deep), with Silt Fence2000 (commercial name) around the inlet sections, were placed in the sediment troughs to trap most of the eroded sediments. The tipping mechanism of the pluviometer and the runoff tipping buckets are transmitted electronically to a Monitor GLX-128D data logger. The data stored are accessed on-site with an IBM compatible laptop computer via an RS232 interface.

Design of the erosion study plots

The plots, extending up to the centre of the rail track, were laid out as shown in Figure 4. On a flat surface, the plots usually are partitioned with earthen bunds, steel or wooden barriers. However, this was considered unnecessary here as the small slope angle of the top section enables runoff generally to run fairly straight down the batter of the embankment. The data logger has eight channels. Only seven plots representing different treatments were therefore prepared. The last channel was devoted to a pluviometer (Figure 4). Table III provides the geometrical characteristics of individual plots. The plots are identical in terms of aspect and soil properties.

Tipping bucket calibration

The runoff tipping buckets are identical in material, size and shape, and therefore are expected to have the same calibration (rating) curve. Static calibration, involving pouring water slowly into one side of a tipping bucket until it tips, indicated that the average volume per tip was 3·74 L. The volume per tip is expected to

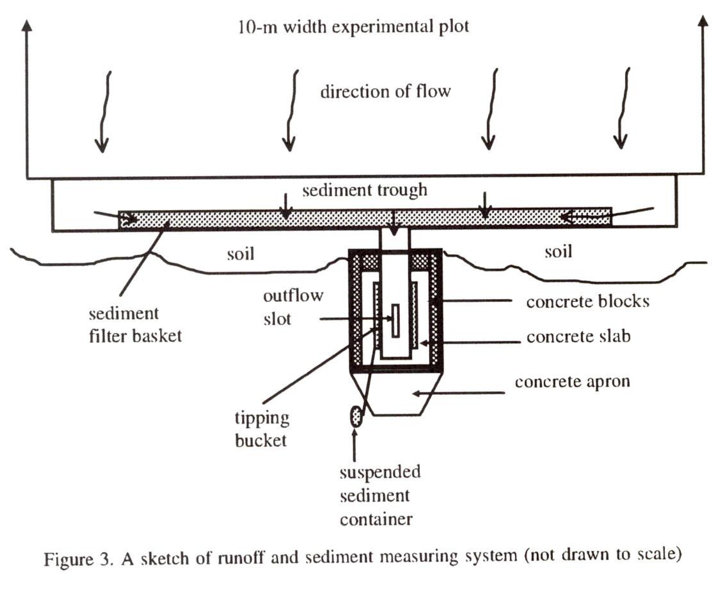

Figure 3. A sketch of runoff and sediment measuring system (not drawn to scale)

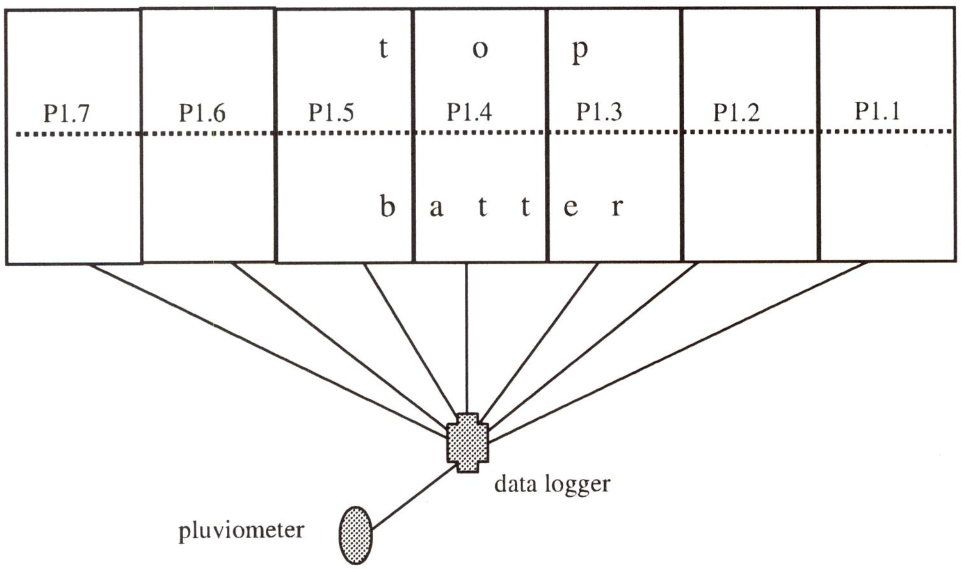

Figure 4. Layout of the first replication consisting of seven plots connected to the data logger

Table III. Geometrical characteristics and treatments of the field trial plots

Replication	Plot number	Top section		Batter section		Treatment
		Length (m)	Slope (°)	Length (m)	Slope (°)	
1	1·1	5·0	4·0	6·7	30	T7
	1·2	4·8	3·5	6·5	30	T5
	1·3	5·0	4·5	6·2	27	T2
	1·4	4·9	4·0	6·3	25	T4
	1·5	4·9	4·5	6·5	30	T1
	1·6	5·3	4·0	6·1	29	T3
	1·7	5·3	4·0	6·1	30	T6
2	2·1	5·2	4·0	6·0	28	T1
	2·2	5·3	3·0	5·8	31	T7
	2·3	5·2	3·0	5·6	31	T3
	2·4	5·2	3·0	5·5	31	T5
	2·5	5·2	4·0	5·9	29	T2
	2·6	5·1	4·0	5·9	28	T4
	2·7	5·1	4·5	5·7	29	T6

increase with the number of tips per minute (tipping rate). Two main reasons for this are that water splashes out of the bucket before tipping and there is water loss when the buckets are switching over. These losses increase with the flow, or tipping, rate. Thus, the use of static volume per tip to estimate runoff for all ranges of tipping rate will result in an underestimation of the runoff volume. A dynamic calibration therefore was carried out for one runoff tipping bucket at the Central Queensland University Fluid Mechanics Laboratory. A 1·2 m long replica of the manifold was used. The calibration was carried out for two different distances (317 mm and 337 mm) between the bottom of the bucket and the bottom of the manifold. This was necessary

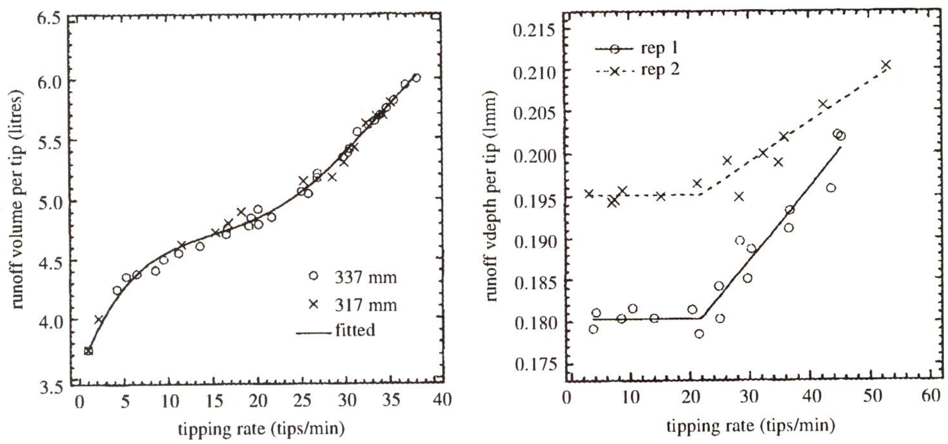

Figure 5. Tipping bucket calibration: runoff (left) and rain gauge (right)

because the distance at the field trial site varies between 315 mm and 330 mm. The rating curves for the two settings were similar, so one curve was fitted. It can be seen in Figure 5 that the volume per tip Y_r (L/tip) increases with tipping rate X_r (tips/min). Using the static volume per tip could result in underestimation of runoff volumes by up to 60%. So far, the maximum recorded tipping rate at the field trial site has been 33 tips/min. A maximum tipping rate of 38 tips/min was used for establishing the rating curve (Equation 1).

$$Y_r = 3{\cdot}5605 + 0{\cdot}1931X_r - 0{\cdot}01299X_r^2 + 0{\cdot}0004099X_r^3 - 0{\cdot}000004138X_r^4, \quad R^2 = 0{\cdot}993 \tag{1}$$

Owing to the small size of the pluviometer tipping bucket, very low flow rates, ranging between 0·003 and 0·3 L/min, were required for calibration. This was achieved by using a constant-head apparatus at the Geomechanics Laboratory of Central Queensland University. The flow volume was estimated from the weight of water, and the density at 25 °C. For both pluviometers, the rainfall depth per tip Y_p (mm/tip) is constant up to a tipping rate X_p of 22 tips/min, and then increases linearly (Figure 5). The rainfall depth per tip of the replication 1 (first) pluviometer, Equation (2), is slightly smaller than that of the replication 2 (second) pluviometer, Equation (3). However, the values of both pluviometers are slightly lower than that specified by the manufacturer (0·2 mm/tip for all ranges). This work stresses the need for independent calibration of pluviometers before being installed. So far, the maximum recorded tipping rate at the field trial site has been 18 tips/min, whereas the maximum used for the calibration was 50 tips/min.

$$\text{Rep 1:} \quad Y_p = 0{\cdot}18032 + 0{\cdot}000866\{\max[0, (X_p - 22)]\}, \quad R^2 = 0{\cdot}943 \tag{2}$$

$$\text{Rep 2:} \quad Y_p = 0{\cdot}19515 + 0{\cdot}000467\{\max[0, (X_p - 22)]\}, \quad R^2 = 0{\cdot}911 \tag{3}$$

BATTER EROSION CONTROL STRATEGIES

The research project aims at developing cost-effective bioengineering options, particularly the establishment of grasses, to control railway formation batter erosion. Grass cover plays vital roles in controlling soil erosion. The roles include (e.g. Goldman *et al.*, 1986, p. 6.1; Gray and Sotir, 1996, p. 55):

1. reduction in raindrop impact by the shielding effect of foliage and plant residues, thereby reducing raindrop splash detachment rates;

2. increase in infiltration rates in upper soil layers caused by root systems and holes where roots have decayed, yielding less runoff to detach and transport sediment;
3. prevention of surface crusting/sealing and increase in surface roughness, thereby slowing runoff, which delays rill development and reduces the efficiency of runoff to detach and transport sediment;
4. the embedded rooting systems of grasses increase soil cohesion, thus increasing resistance to erosion and rill development;
5. stems and foliage filter out sediment from runoff;
6. protection of soil from wind.

Most of the formation soils within the study area are sodic and/or saline. Sodic soils are dispersive and require a calcium-rich soil ameliorant. Gypsum was selected because of its low cost, availability, pH neutrality and ease of handling. It is a naturally occurring soft crystalline mineral that is the hydrated form of calcium sulphate. Application of gypsum to calcium-deficient soils will increase soil porosity, structural stability, soil infiltration and hydraulic conductivity, and reduce soil crusting, soil swelling and shrinkage. Gypsum application also improves root penetration and seedling emergence rates (Witheridge and Walker, 1996).

Grass species

A seed mixture indicated in Table IV was used in the field trial. Vetiver grass has gained international attention as being effective for controlling erosion on steep slopes (National Research Council, 1993). An Australian cultivar, 'Monto', was used in the field trial. This cultivar is sterile (i.e. bears unviable seeds) and does not produce spreading rhizomes, so it will not spread but limits its growth to the point of planting. This cultivar is known to survive and grow well on many soil types with only minimal limitations to soil fertility, pH, or salinity (Truong and Hengchaovanich, 1997). It is also reported to be capable of growing in a wide range of climatic conditions (Gray and Sotir, 1996, p. 184–5). Vetiver grass works best when planted in hedges or hedgerows along contour lines, with the plants spaced at approximately 15 cm. The hedgerow becomes a living porous barrier that slows and spreads runoff water and traps sediment, thereby contributing to a significant reduction in erosion (Truong and Hengchaovanich, 1997). The details of the grass establishment procedures are presented in Gyasi-Agyei and Sibley (1998) and Gyasi-Agyei *et al.* (1998).

Initial surface protection

Extreme site conditions such as highly erodible soils and steep slopes require immediate and effective protection against erosion. In particular, initial protection is required where rainfall intensities may be high to avoid washout of seeds and fertilizer before vegetation is established. Biodegradable soil stabilization blankets/nets, and/or mulch, are used to protect ground surface against intense rainfall events prior to vegetation establishment. These blankets also provide microhabitat conditions favourable for vegetation establishment before the vegetation begins to protects the soil. In addition, the erosion control mat protect the young seedlings against desiccation and wind as well as controlling erosion and retaining moisture. Jute mat was used in the field trial, and there are other products on the market within the same price range.

Table IV. Seed mixture

Species	Common name	Quantity (kg/ha)
Urochloa mozambicensis cv. Saraji	Sabi grass	24·3
Chloris gayana cv. Pioneer	Rhodes grass	2·4
Bothriochloa pertusa cv. Emerald	Indian blue grass	0·83
Stylosanthes scabra cv. Unica and Primar	Stylo legume	0·95
Clitoria sp. cv. Milgara	Butterfly pea legume	13·0

Batter erosion control treatments

Owing to the limited number of channels on the data logger system, only seven different treatments could be used in the field trial at the Gregory site. The treatments are: T1, control ('do nothing' treatment); T2, grass seeding; T3, gypsum + grass seeding; T4, grass seeding + jute mat; T5, four hedgerows of vetiver grass; T6, two hedgerows of vetiver grass; T7, two hedgerows of vetiver grass + grass seeding.

The initial batter surface showed extensive rills and scattered growth of buffel grass. An excavator therefore was used to smooth out the rills and scarify the surface. The outer verge of the formation top surface was rounded using a Bobcat. Treatment T1 is a control where nothing was done to the plot after the surface was scarified. In treatment T3, gypsum (application rate of 15 tons/ha) was uniformly spread on the batter and mixed with the top 100 mm of the soil using an excavator. In treatment T4 the jute mat was placed on the smoothed and scarified surface and stapled at 1 m intervals to ensure that it remained well seated over the seeded soil. Clumps of vetiver grass (2–3 slips/clump) were planted in hedgerows at a spacing of 10 cm between the clumps, and 1·2 m between the hedgerows in treatment T5, and 2 m between the hedgerows in treatments T6 and T7. Fertilizer Q5 was applied at a rate of 1000 kg/ha. This fertilizer contained N, P, K, S and Ca at 5·3, 5·8, 5·0, 13·3, and 12·8 percentage, respectively. The seven treatments were imposed randomly within a replication and four replications were used. Only the two replications that were instrumented are reported in this paper. Table III provides the treatment imposed on each plot.

As the rainfall occurrence is highly unpredictable, and the annual potential evaporation exceeds annual rainfall, in this region, provision of irrigation was considered essential for establishment of grasses. The plots were irrigated using an impact-type sprinkler system. A 15 000-L water truck supplied water to the system. Figure 6 shows the irrigation days and daily rainfall during the irrigation period.

DATA SAMPLING AND PROCESSING

Soil loss data for a given SI represent contributions of all rainfall events within it. The rainfall and runoff data were obtained at a 1-min time-scale but only the totals within the SIs are presented in this paper. Table V provides the SI in which soil loss data were collected from the field trial site during 1998 and 1999. The troughs were thoroughly cleaned towards the end of the irrigation period and before SI01 began. This ensured non-inclusion of soil loss from sources such as gravity rolling and sliding resulting from disturbance caused by humans during plot preparation, seeding and matting, and the installation and operation of the irrigation system.

The fieldwork involved the following tasks:

1. downloading rainfall and runoff data from the data loggers;
2. weighing the bedload soil trapped in the troughs;
3. bedload soil sampling from each trough for moisture content determination;

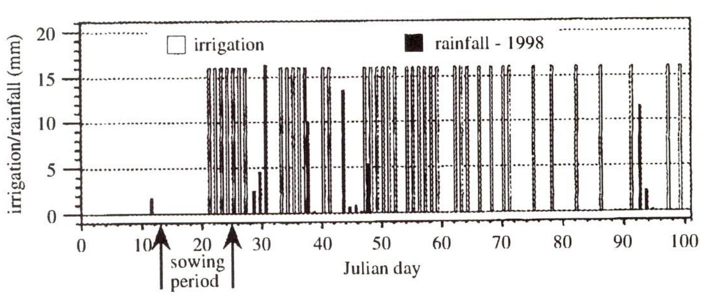

Figure 6. Irrigation and daily rainfall during the irrigation period

Table V. Sampling interval dates and the corresponding rainfall depth

Sampling interval (SI)		Rainfall depth		
Interval number	Period	Replication 1 (mm)	Replication 2 (mm)	Average (mm)
SI01	25-03-1998 to 16-05-1998	230·3	229·2	229·8
SI02	16-05-1998 to 15-07-1998	47·6	49·8	48·7
SI03	15-07-1998 to 21-08-1998	39·3	41·2	40·3
SI04	02-08-1998 to 18-09-1998	133·5	136·7	135·1
SI05	18-09-1998 to 02-10-1998	60·6	62·1	61·3
SI06	02-10-1998 to 16-10-1998	34·8	36·5	35·7
SI07	16-10-1998 to 04-11-1998	170·6	184·3	177·5
SI08	04-11-1998 to 20-11-1998	38·8	41·6	40·2
SI09	20-11-1998 to 10-12-1998	68·0	72·2	70·1
SI10	10-12-1998 to 15-01-1999	139·6	146·4	143·0
SI11	15-01-1999 to 16-03-1999	122·1	122·2	122·2
SI12	16-03-1999 to 05-08-1999	95·6	97·2	96·4
SI13	05-08-1999 to 06-12-1999	127·3	121·6	124·5

4. sampling 600 mL of sediment-laden runoff from the splitter sample drums, following shaking, for determination of runoff sediment concentration;
5. estimating grass cover on each plot and taking photographs of the plots;
6. inspecting the plots for any damage or anomalies such as water leakage, the positions and dimensions of rills present, and any other features of interest.

The total soil loss (kg) from the field plots was determined as the sum of the bedload soil collected from the troughs and the suspended sediment transported by the runoff water passing through the tipping bucket. These weights were calculated back to oven dry (105 °C) weights. The total dry weight of the bedload soil (kg) was calculated as: total weight of the bedload soil measured at the field trial site (kg) × oven dry weight of the bedload soil sample (g)/weight of the bedload soil sample (g). The dry weight of suspended sediment (g) was calculated as: total runoff volume (L) × the sediment concentration of the splitter water sample (g/L). The rating curves, Equation (1) through Equation (3), were used to convert the data logger data into rainfall (mm) and runoff (L). The total runoff volume estimates were corrected for the rainfall entering directly into the sediment troughs.

Percentage grass cover is defined as the percentage of the horizontal projected area covered by grasses. This was estimated by both visual inspections of the plots and photographic analysis. Photographs were taken using a camera mounted on a 4 m long pole, the pole being extended manually to position the camera. For SI12, three people estimated the grass cover independently by visual inspection. Their estimates of the grass cover were similar, with the values for few plots showing variations within 5%.

RESULTS AND DISCUSSION

Rainfall

It is observed in Figure 5 that the tipping bucket calibration curve was different for the pluviometers. Replication 1 pluviometer has smaller tipping volume than replication 2 pluviometer. This implies that, for the same amount of rainfall, replication 1 pluviometer will register a higher tipping rate than replication 2 pluviometer. This observation from the initial data motivated the calibration exercise. However, the difference in rainfall depths recorded by the pluviometers is small, as indicated in Table V for the total amount per SI.

The year 1998 was exceptionally wet (987 mm) although little rain fell in the first three months, with no rainfall in March. By comparison, in 1999 there was over 70 mm rainfall in January and in February. However, the yearly total (395 mm) for this year was about half the long-term average value of 639 mm recorded at Emerald Post Office (a representative rainfall station of the region), and 60% lower than the amount recorded in 1999. Figure 7 depicts the daily rainfall distribution of 1998 and 1999 for the field trial site, with the days falling within the SIs indicated. Evidently, the rainfall distribution over the 2-year period is highly variable.

The timing of grass seeding and vetiver grass planting during the period 13/01/98 to 25/01/98 was fortuitous because the grasses had developed deeper roots, as a result of irrigation, before the heavy rainfall events occurred in April 1998.

Rill development

Several forms of erosion (splash, sheet or interrill, and rill) are occurring on the railway embankment batter plots. However, rill erosion deserves a special mention. Rills are visible channels, small enough to be obliterated by normal tillage and grading operations. Once rills start to develop, shallow sheet flow tends to concentrate in them, aggravating the erosion process. It is difficult for grasses to establish naturally in rills to combat the erosion problems. Monitoring rill development is time consuming and requires regular visits to the site. However, one observation was that the rills appeared during the first few storm events, and the subsequent storm events only enlarged and deepened the rills. The rills start at the outer verge of the

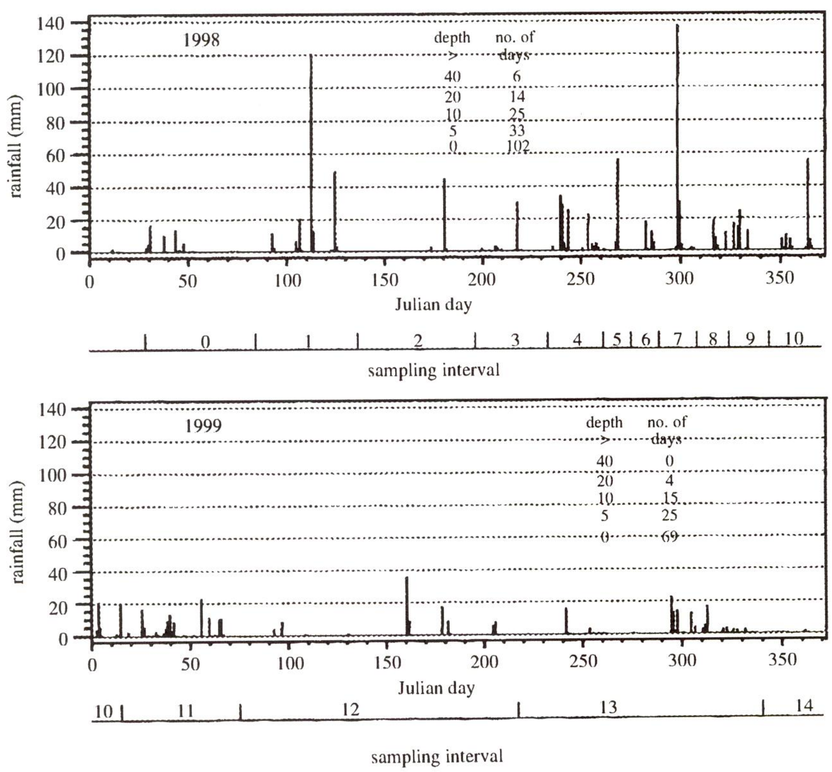

Figure 7. Daily rainfall distribution for 1998 and 1999 at the field trial site (average of the pluviometers)

formation crown (Figure 1) and propagate downwards. An account of surface features observed on 16 May 1998 include: extensive deep rills developing on the T1 plots; few minor rills developing on the T2 plots; no rills on T3, T4 and T7 plots; and numerous rills developing behind vetiver grass on T5 and T6 plots. The full extent of rill development will be revealed after burning the established grasses on the field trial plots.

Grass cover

Table VIa presents average grass cover levels, grouped by treatment option and for each SI. The T3 (gypsum + seeding) plots were the first to reach 100% cover. Gypsum application improved soil properties significantly, thus promoting quick establishment of the grasses. Closely following were the T4 (jute mat + seeding) plots. The T7 (two hedgerows vetiver + seeding) and T2 (seeding) plots also became well vegetated, with maximum grass cover levels in excess of 85%. Natural grass establishment rates on the remaining plots (those without seeding) were very slow. The control plots (T1) were encroached on by grasses from adjacent plots, increasing their percentage cover substantially. The grasses on the control plots were slashed on 20 November 1998 and on 28 October 1999, decreasing the percentage cover levels observed at the SI09 and SI13. A point worth nothing is that without grass establishment on the adjacent plots there could be no such significant grass cover on the control plots. Also slashing the grasses on the control plots helped to obtain more data on the lower tail of the percentage grass cover, information required for the event-based runoff-erosion computer model calibration. Slashing did not alter the grass root density, a controlling factor of infiltration, but it slightly decreased the resistance to flow. It should be noted that the cut foliage was removed from the plots after slashing. A fire outbreak in February 1999 (SI11) burned grasses on a small section of plot 1·2, but completely denuded plot 1·3 and plot 1·4. Grass growth recovery on the burned plots has been very slow. Variation of grass cover levels on plots of the same treatment could be attributed to non-uniformity of irrigation, seeding application and germination rates, and washout of seeds during the initial storms.

Runoff

Runoff generation on the railway embankment is by the Horton infiltration excess mechanism. Table VIb provides values of runoff generated on individual plots and grouped by treatment option. The runoff in millimetres was obtained by dividing the total runoff in litres by the horizontal projected area of the plot in square metres.

In general, the variation of runoff generated by plots of the same treatment is as a result of the differences in percentage grass cover the higher the grass cover level the lower the runoff amount generated. For example, control plot 2·1 generated more runoff compared with control plot 1·5 until the grass cover level switched at SI08, plot 1·5 now having lower grass cover levels. Thereafter control plot 1·5 generated more runoff than control plot 2·1. Part of the jute mat on plot 2·6 was destroyed by runoff during SI01. Plot 2·6 therefore experienced a significantly high runoff response compared with its counterpart plot 1·4. Although the grass cover on plot 1·4 was burned during SI11, the runoff response was slow, still generating lower runoff amounts compared with plot 2·6. It needs to be mentioned that, after complete burning of grasses on plot 1·4, extensive surface cracking developed and this may have increased infiltration, offsetting the effect of burning on runoff. However, immediate response in runoff generation after burning is exemplified by plot 1·3. Before burning, during SI11, plot 1·3 generated more runoff compared with plot 2·5 of the same treatment (T2). It is observed that plot 1·3 produced more runoff than plot 2·5 during SI12 and SI13. As the grass cover on the gypsum (T3) plots established at a similar growth rate, the difference in their runoff generation amounts is small.

Figure 8 shows the variation of runoff production with grass cover for a given SI (the treatments are not distinguished). A well-defined decreasing trend of runoff production with grass cover is observed. Calibration of the event-based runoff-erosion model will reveal trends of grass cover levels with model parameters relating to runoff production.

Table VI. Results of the field trial per sampling interval (SI)

(a) Average grass cover (%)

Treatment	Plot	SI01	SI02	SI03	SI04	SI05	SI06	SI07	SI08	SI09	SI10	SI11	SI12	SI13
1	1·5	7·5	10·0	12·5	20·0	27·5	30·0	32·5	37·5	20·0	22·5	30·0	37·5	20·0
	2·1	2·5	5·0	5·0	7·5	12·5	15·0	27·5	45·0	40·0	52·5	67·5	80·0	30·0
2	1·3	37·5	47·5	52·5	57·5	60·0	60·0	62·5	67·5	70·0	70·0	5·0	5·0	5·0
	2·5	42·5	75·0	80·0	82·5	85·0	87·5	90·0	92·5	95·0	95·0	95·0	95·0	95·0
3	1·6	80·0	92·5	95·0	97·5	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0
	2·3	65·0	85·0	92·5	97·5	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0
4	1·4	70·0	85·0	90·0	92·5	97·5	100·0	100·0	100·0	100·0	100·0	5·0	7·5	10·0
	2·6	55·0	75·0	82·5	87·5	90·0	92·5	97·5	100·0	100·0	100·0	100·0	100·0	100·0
5	1·2	15·0	25·0	27·5	35·0	40·0	40·0	45·0	52·5	57·5	62·5	40·0	40·0	42·5
	2·4	25·0	37·5	42·5	50·0	57·5	60·0	62·5	67·5	70·0	72·5	77·5	80·0	80·0
6	1·7	7·5	10·0	12·5	20·0	27·5	30·0	32·5	37·5	40·0	42·5	47·5	52·5	55·0
	2·7	10·0	17·5	22·5	30·0	37·5	40·0	40·0	42·5	45·0	45·0	47·5	50·0	50·0
7	1·1	25·0	45·0	52·5	60·0	67·5	72·5	77·5	80·0	80·0	82·5	85·0	87·5	90·0
	2·2	50·0	75·0	82·5	87·5	90·0	90·0	90·0	92·5	95·0	97·5	100·0	100·0	100·0

(b) Runoff (mm)

Treatment	Plot	SI01	SI02	SI03	SI04	SI05	SI06	SI07	SI08	SI09	SI10	SI11	SI12	SI13
1	1·5	133·4	15·0	9·5	37·9	23·5	7·9	33·7	4·9	33·0	40·2	16·5	17·1	22·7
	2·1	152·3	15·3	10·3	47·2	30·7	9·5	65·9	4·9	31·5	31·0	3·7	6·3	11·7
2	1·3	99·1	6·0	7·5	40·1	25·2	3·7	72·3	0·4	11·7	9·3	6·6	18·0	22·5
	2·5	112·9	5·1	5·0	45·5	30·4	4·0	74·3	2·8	19·7	23·9	7·4	10·1	14·0
3	1·6	130·8	0·4	0·5	11·6	10·5	0·2	84·5	0·1	3·7	3·3	1·1	1·0	0·9
	2·3	80·5	0·4	0·5	7·0	4·8	0·1	63·4	0·0	3·6	3·9	0·9	2·2	1·4
4	1·4	53·3	0·2	0·1	1·9	3·2	0·4	14·6	0·3	1·1	2·4	1·2	2·9	7·9
	2·6	77·2	2·3	2·0	22·5	16·1	3·4	66·1	2·1	16·1	20·9	5·3	10·9	14·3
5	1·2	101·2	14·5	11·5	44·7	31·4	8·3	37·4	6·6	40·2	54·7	21·1	20·5	22·8
	2·4	101·2	4·8	6·6	23·2	23·6	3·6	35·9	1·9	13·9	18·4	9·8	10·9	12·9
6	1·7	158·5	21·0	12·0	57·8	49·8	7·0	68·1	5·6	30·9	41·5	13·3	14·2	16·7
	2·7	134·1	10·3	8·6	60·3	34·0	9·4	123·4	6·7	35·2	47·5	16·9	22·2	29·6
7	1·1	113·2	11·9	10·1	43·8	36·5	5·5	32·6	3·2	15·2	39·3	13·6	13·0	16·4
	2·2	94·9	2·7	1·8	31·2	30·2	2·5	84·9	1·4	16·4	22·5	5·3	7·9	9·8

(continued overleaf)

Table VI. (*continued*)

(c) Sediment concentration (tons/ha-mm)

Treatment	Plot	SI01	SI02	SI03	SI04	SI05	SI06	SI07	SI08	SI09	SI10	SI11	SI12	SI13
1	1·5	0·711	0·459	1·303	0·810	0·648	0·500	1·631	0·236	0·139	0·312	0·248	0·230	0·202
	2·1	0·698	0·541	1·589	0·758	0·886	0·709	1·343	0·398	0·196	0·253	0·589	0·336	0·269
2	1·3	0·550	0·229	0·413	0·205	0·169	0·244	0·359	0·699	0·248	0·114	0·124	0·313	0·351
	2·5	0·470	0·290	0·425	0·247	0·229	0·161	0·346	0·131	0·076	0·146	0·089	0·134	0·116
3	1·6	0·302	0·319	0·219	0·118	0·086	0·016	0·080	1·032	0·032	0·000	0·035	0·060	0·004
	2·3	0·396	0·188	0·009	0·090	0·142	0·058	0·041	0·001	0·171	0·164	0·148	0·035	0·006
4	1·4	0·140	1·382	0·009	0·112	0·142	0·019	0·020	0·913	0·079	0·078	0·055	0·154	0·344
	2·6	0·419	0·217	0·239	0·194	0·288	0·179	0·243	0·164	0·154	0·122	0·075	0·113	0·143
5	1·2	1·063	0·437	1·206	0·698	0·542	0·603	1·923	0·171	0·285	0·238	0·164	0·149	0·174
	2·4	1·123	0·544	1·088	1·043	0·363	0·585	1·022	0·220	0·279	0·184	0·107	0·149	0·116
6	1·7	0·587	0·251	0·861	0·376	0·198	0·500	0·802	0·111	0·165	0·106	0·104	0·168	0·161
	2·7	0·643	0·615	1·464	0·692	0·551	0·651	0·566	0·328	0·384	0·265	0·207	0·309	0·224
7	1·1	0·779	0·328	0·854	0·332	0·368	0·365	1·060	0·231	0·346	0·100	0·128	0·113	0·116
	2·2	0·503	0·340	0·462	0·167	0·179	0·270	0·235	0·206	0·148	0·137	0·095	0·128	0·126

(d) Soil loss (tons/ha)

Treatment	Plot	SI01	SI02	SI03	SI04	SI05	SI06	SI07	SI08	SI09	SI10	SI11	SI12	SI13
1	1·5	94·80	6·90	12·37	30·68	15·23	3·95	54·95	1·15	4·60	12·53	4·10	3·93	4·59
	2·1	106·24	8·30	16·34	35·73	27·22	6·74	88·41	1·95	6·17	7·83	2·17	2·13	3·14
2	1·3	54·54	1·37	3·08	8·20	4·27	0·91	25·97	0·31	2·89	1·05	0·82	5·64	7·90
	2·5	53·13	1·47	2·12	11·23	6·96	0·64	25·74	0·37	1·50	3·50	0·66	1·36	1·63
3	1·6	39·50	0·12	0·11	1·37	0·90	0·00	6·77	0·11	0·12	0·00	0·04	0·06	0·00
	2·3	31·87	0·07	0·00	0·62	0·68	0·00	2·58	0·00	0·61	0·63	0·13	0·08	0·01
4	1·4	7·47	0·21	0·00	0·22	0·46	0·01	0·29	0·25	0·08	0·19	0·07	0·44	2·73
	2·6	32·37	0·49	0·48	4·37	4·65	0·61	16·08	0·35	2·47	2·55	0·40	1·23	2·05
5	1·2	107·56	6·32	13·86	31·23	17·03	4·99	71·99	1·13	11·48	13·04	3·45	3·06	3·98
	2·4	113·59	2·62	7·19	24·15	8·57	2·13	36·69	0·42	3·88	3·39	1·04	1·61	1·49
6	1·7	93·03	5·28	10·31	21·77	9·84	3·51	54·63	0·61	5·10	4·40	1·39	2·39	2·69
	2·7	86·16	6·31	12·59	41·76	18·70	6·12	69·89	2·20	13·53	12·58	3·51	6·86	6·61
7	1·1	88·19	3·89	8·60	14·55	13·42	2·02	34·55	0·73	5·27	3·93	1·74	1·47	1·90
	2·2	47·73	0·92	0·82	5·22	5·40	0·67	19·91	0·29	2·42	3·10	0·50	1·01	1·24

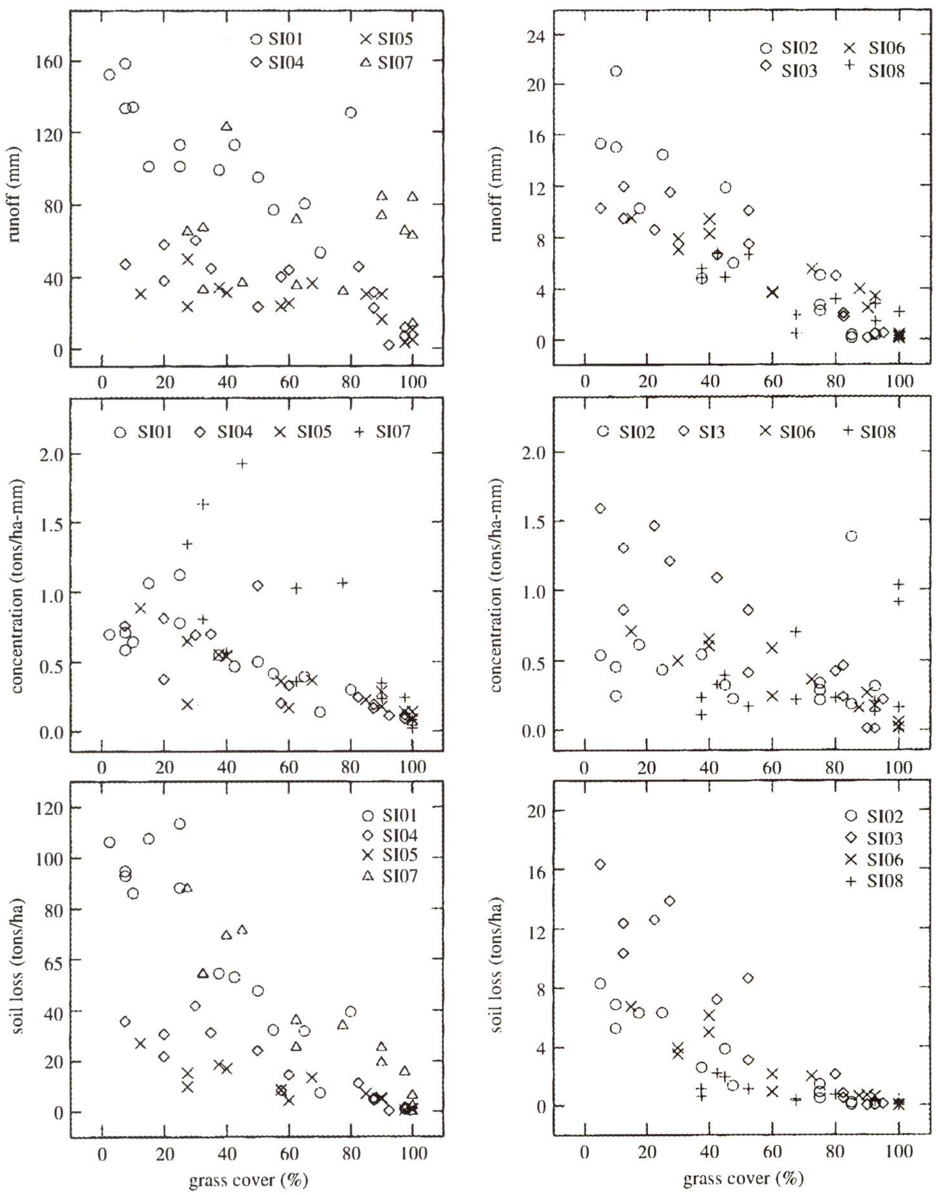

Figure 8. Effect of grass cover on runoff production, sediment concentration and soil loss for a given sampling interval

A comparison of the performance of the various treatments in terms of cumulative runoff generated at the end of the 2-year study period is depicted in Figure 9, for individual plots and for the average of the two plots of the same treatment. The highest runoff was generated on T6 plots, which consisted of two hedgerows of vetiver grass. This treatment generated cumulative runoff 27% in excess of that of the control

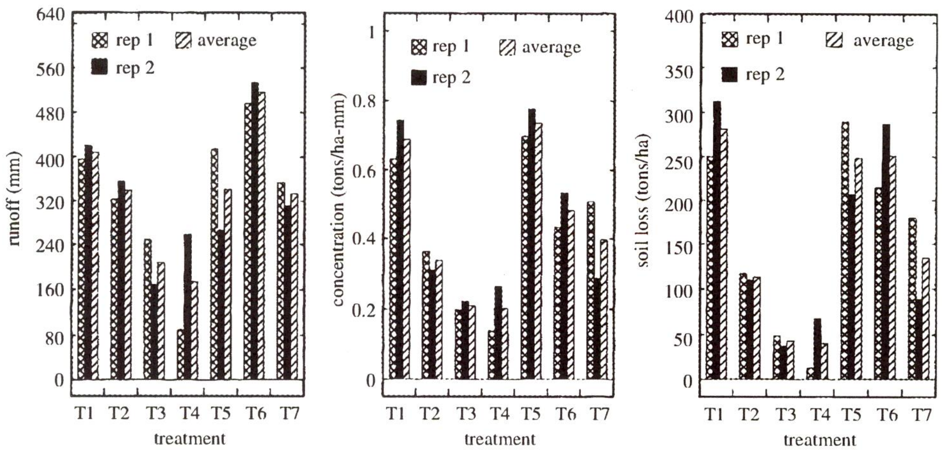

Figure 9. Cumulative runoff, sediment concentration and soil loss variation with the treatment options

plots. These plots have the least grass cover of all treated plots. The numerous small rills that developed behind the vetiver grass hedgerows provided an efficient transport system to discharge runoff quickly, thereby minimizing infiltration rates. This effect offsets the expected increase in infiltration rates by the deep root penetration of vetiver grass on these plots. However, a comparable runoff volume was observed on the control plots (T1) during the first three SIs.

Third in ranking, in terms of runoff production, is the T2 (seeding) plots, where a 17% reduction in runoff was observed relative to runoff on the control plots. This was closely followed by the T7 plots, where 18% reduction in runoff was observed. Thus, addition of two hedgerows of vetiver grass to seeding (T7) marginally (1%) reduced the cumulative runoff production further. However, doubling the number of hedgerows to four (T5) without seeding, that is, halving the hedgerow spacing, greatly decreased the cumulative runoff production, with a cumulative runoff reduction of 16% compared with the control. This could be explained partly by the increased root density, increased surface resistance by the stems, and increased deposition of soil in front of the hedgerows, partially obliterating rills developed behind upstream hedgerows. The flow-path length also decreased, making rill formation far less effective. It is interesting to note that during the highest daily rainfall intensity (SI07), T5 plots generated the least average runoff volume.

The least runoff was generated on T3 (49% cumulative runoff reduction) and T4 (57% cumulative runoff reduction) plots. Grasses on these plots established quickly, reaching cover levels of 100% within seven months, and significantly increasing infiltration rates. Also no rills developed on these plots owing to quick establishment of the grasses. However, runoff generated on the T4 plots was slightly below that of the T3 plots, in particular during heavy rainfall events. Jute mat increases the storage capacity and the surface resistance thereby encouraging infiltration.

Sediment concentration

Sediment concentration values are given in Table VIc. On average, it is observed that grass cover has a similar effect on sediment concentration as on the runoff production. The higher the grass cover level, the lower the sediment concentration. This is demonstrated in Figure 8, where sediment concentration and grass cover levels within the SIs are depicted.

Figure 9 compares the cumulative sediment concentration of the various treatments at the end of the 2-year study period, for individual plots and for the average of the two plots of the same treatment. Four hedgerows of vetiver (T5) produced the highest sediment concentration, 7% in excess of that of the control plots. Treatment T2 (seeding only) caused 51% reduction in sediment concentration in relation to the control. Treatments T2 and T7 generated comparable runoff volume, but T7 plots produced a lower sediment concentration reduction (42%). The gypsum application plots (T3) and the jute mat plots (T4) yielded a similar sediment concentration reduction of about 70%. Treatment T6 plots produced 30% sediment concentration reduction.

In general, the presence of hedgerows of vetiver grass increases the sediment concentration. Some of the eroded sediment is normally trapped in front of the hedgerows, creating miniature drop structures (in excess of 5 cm high) behind them. Runoff over the drop structures, therefore, has a high eroding potential owing to increased velocity caused by the hydraulic head that triggers rill development. These rills enlarge and deepen as more soil is eroded during subsequent rainfall events. Although some deposition occurs in front of the hedgerows, the erosion behind them negates the effect of deposition on sediment concentration. Decreasing the spacing between the hedgerows (from 2 m to 1·2 m) increased the sediment concentration levels, although there was an increase in percentage grass cover, with a decrease in raindrop splash erosion, as the number of hedgerows increased. This merit is small compared with rill erosion triggered by the hedgerows. Moreover, the efficient transport system of the rills developed by the hedgerows increases the potential of the soil particles detached by raindrop impact to be transported out of the batter during the storm event. At some sections, about 10 cm of vetiver grass roots have been exposed by erosion.

Soil loss

Table VId gives the soil loss for individual plots for a given SI. There is a strong decreasing trend of soil loss with increasing grass cover. This results from the multiplicative effect of grass cover levels on runoff production and sediment concentration. The trend is depicted in Figure 8 for some SIs. Clearly the higher the runoff produced the higher the soil loss. The observed decreasing trend of soil loss with cover is expected where runoff, and soil loss, is dominantly driven by overland flow. Rose *et al.* (1997) reported similar results on experiments conducted on agricultural plots within Australia and South-east Asia.

Figure 9 shows the cumulative soil loss generated from the plots during the 2-year study period. The performance of vetiver grass in terms of percentage soil loss reduction is nearly identical for two (T6) and four (T5) hedgerows, being 11% and 12%, respectively. Treatment T6 generated higher runoff than T5, but contributed to a lower sediment concentration leading to similar soil loss. The addition of two hedgerows of vetiver grass to the seeded plots (T7) decreased the soil loss reduction by 8% compared with seeding alone (T2). Seeding alone caused 60% reduction in soil loss compared with the control, and a remarkable additional 25% soil loss reduction was achieved by applying gypsum before seeding (T3). The jute mat plots (T4), which yielded the least soil loss over the 2-year study period, achieved 86% soil loss reduction.

An important observation is the soil loss for plot 1·3 and plot 1·4 during SI12 and SI13 (Table VId). The grasses on these plots were burned during S11. Before burning, plot 1·3 was generating similar amount of soil loss as plot 2·5 of the same treatment. However, the soil loss from plot 1·3 was over four times that of plot 2·5 after burning. Plot 1·4 generated far less soil loss compared with plot 2·6 of the same treatment. As explained earlier, part of the jute mat on plot 2·6 was destroyed by runoff during the initial storms. However, after burning, plot 1·4 generated half the amount of plot 2·6 in SI12 and more than that of plot 2·6 in SI13. These observations suggest that controlled burning, or accidental burning, could be a disaster for erosion control on railway embankment batters.

SUMMARY AND RECOMMENDATIONS

The results of an erosion control field trial on a railway embankment batter are presented in this paper. The field trial consists of two replications of seven treatments on 10-m wide plots. Rainfall, runoff and soil loss were monitored during 1998 and 1999. The results have been presented over sampling intervals that represent a number of rainfall events occurring within the sampling interval. The summary of the findings during the 2-year study period is as follows.

1. Erosion rate decreases with increasing grass cover level, demonstrated by plots of the same and different treatment.
2. Seeding alone caused 60% reduction in the erosion rate.
3. Applying gypsum to the calcium-deficient formation soil before seeding yielded an additional 25% reduction in the erosion rate, making a total of 85% reduction.
4. Laying jute mat over seeded plot provided only marginal (1%) reduction in erosion rate compared with gypsum application and seeding.
5. Planting two hedgerows of vetiver grass increased runoff by 27% and decreased sediment concentration by 30%, which resulted in a decrease in erosion rate by 11% compared with the control treatment.
6. Doubling the number of hedgerows, i.e. halving the spacing between the hedgerows, changed the runoff production and sediment concentration regime remarkably. The overall runoff decreased by 16%, but the sediment concentration increased by 7%, with only 12% reduction in the erosion rates compared with the control treatment.
7. Surprisingly, the addition of two hedgerows to seeded plots marginally decreased the runoff by a further 1% and increased the sediment concentration by a further 9%, with a net increase in erosion rate of 8% compared with the seeding-only treatment.
8. Accidental burning of 100% grass cover on some plots immediately increased erosion rate, on one plot by more than four times. Grass growth recovery on the burned plots has been very slow.

Note that the soil type and rainfall patterns during the field trial could influence the performance of the various treatments. Hence the research needs to be repeated at different sites and over a period of several years. The soil loss reported for the control treatment is actually less than the potential maximum soil loss corresponding to zero grass cover, as extrapolated in Figure 8.

Current practice of minimizing erosion-related interruption of train operations by QR involves widening of eroded embankment, cleaning of cutting track sections, filling of rills and erosion pipes with soil on access roads, culvert cleaning and replacement of sediment fouled ballast. These remediation measures do not solve the problems but only move the problems further away from the track section. Past maintenance records indicate that these remediation measures need to be carried out at the same site at least 1 in every 10 years. The above routine maintenance measures cost on average A$ 11·73/m^2 of eroded batter (Gyasi-Agyei, HEFRAIL Research Proposal, 2000). Other non-quantified, but substantial, costs associated with erosion on the batters include interruptions of normal train operations, the risks of moisture and erosion induced formation failures and associated outages and derailments, and inundation of ground-level railway signalling systems. There is also the environmental degradation issue and the risk of lawsuits resulting from sediment delivery from QR easements to nearby water courses (e.g. creeks, stock ponds).

Table VII presents a conservative estimate of unit cost saving (A$ 11·73 times the fraction of soil loss reduction) for imposing the various treatments. The costs of imposing the treatments are also provided in

Table VII. Cost and benefit analysis of imposing the treatments

Treatment (Tx)	T1	T2	T3	T4	T5	T6	T7
Soil loss reduction ($1 - Tx/T1$) 100%	—	60	85	86	12	11	52
Cost savings (A$)	−11·73	7·04	9·97	10·09	1·41	1·29	6·10
Unit cost without irrigation (A$/m^2)	—	3·00	3·10	8·00	8·00	4·00	7·00
Unit cost with irrigation (A$/m^2)	—	8·00	8·10	13·00	13·00	9·00	12·00
Benefit/cost ratio—without irrigation	—	2·35	3·22	1·26	0·18	0·32	0·87
Benefit/cost ratio—with irrigation	—	0·88	1·23	0·78	0·11	0·14	0·51

Table VII. Cost saving of treatment T1 is entered as a negative value because it indicates the actual cost for the 'doing nothing option'. The benefit/cost ratio indicates that, without irrigation, treatments T2, T3 and T4 are cost-effective options. When the current irrigation cost of A$ 5 is taken into account, the gypsum + seeding is the only cost-effective treatment option at least within a 10-year period. Vetiver grass treatments, even without irrigation, are not a cost-effective batter erosion control option to consider within the region of study. Current research (HEFRAIL Project) is looking into a range of options with a target batter erosion control cost of A$ 5·5 (including irrigation where applicable) with a very low risk of remediation failure. A great emphasis is placed on the development of a low-cost irrigation system that is transferable from one site to the other as soon as the grasses are established. Meanwhile, the following recommendations are made.

1. The cost of applying gypsum to calcium-deficient soil is very small, yet the results in terms of erosion control are remarkable. It is therefore recommended to apply gypsum to all sodic soils (ESP > 10) of railway formation before seeding. Other sources of calcium, such as lime (only if the soil pH is below 6·0), could be used in lieu of gypsum and the application rate must vary according to the chemical properties of the formation soil.
2. Vetiver grass is expensive to establish, and there is little indication that it is going to survive after two years of establishment. The use of vetiver grass to control erosion on railway batters within Central Queensland therefore is not recommended, except for coastal regions where annual rainfall is in excess of 600 mm. However, the potential use of vetiver as vegetation barrier strip around culvert inlets to filter sediment from runoff looks promising and is currently under investigation within the HEFRAIL project.
3. Seeding alone has been demonstrated to be effective in controlling erosion given favourable rainfall patterns during the first three months following seeding. The risk of seeds and fertilizer being washed out by high-intensity rainfall events during the initial phase is very high. This risk needs to be reduced by limited use of low-cost biodegradable erosion control blankets. It would be expensive to cover the entire area of the batters with an erosion control blanket. An effective compromise solution could therefore be to cover only portions of the batter, for example the top and bottom 1 m sections that are highly susceptible to erosion. An erosion control blanket placed on the lower part of an eroding hillslope would not only help protect the area from erosion but would also induce deposition of the material eroded from above.
4. Controlled burning of grasses on railway batters is not recommended. Destruction of established grasses by burning could cause serious erosion problems, owing to very slow growth of grass following burning. It needs to be underlined that unintentional fires within the railway corridors in Central Queensland are rare.
5. Natural rainfall cannot be relied upon for the establishment of grasses on steep railway formation batters within Central Queensland, in particular when planted between March and November. Therefore, irrigation needs to be an integral part of grass establishment on railway formation batters to ensure that adequate grass cover is established for erosion mitigation. The goal should be 100% grass cover established as quickly as the resources allow.

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REFERENCES

AUS-IFD. 1998. Software developed by Urban Water Systems Group, School of Civil Engineering, Queensland University of Technology, Australia.

Ciesiolka CA, Coughlan KJ, Rose CW, Escalante MC, Hashim GM, Paningbatan EP, Sombatpanit S. 1995. Methodology for a multi-country study of soil erosion management. *Soil Technology* **8**: 179–192.

Goldman SJ, Jackson K, Bursztynsky TA. 1986. *Erosion and Sedimentation Control Handbook*. McGraw-Hill: New York, USA.

Gray HG, Sotir RB. 1996. *Biotechnical and Soil Bioengineering Slope Stabilization, 1996. A Practical Guide for Erosion Control*. Wiley: New York, USA; 378.

Gyasi-Agyei Y, Sibley J. 1998. *Development of Strategies for Prevention and Control of Rail Track Formation Erosion in Central Queensland*. Research Report CRE R 41 ERO-S1-1/98, Central Queensland University: Rockhampton, Australia.

Gyasi-Agyei Y, Sibley J. 1999. *Strategies for the Mitigation of Erosion Problems in a Railway Cutting and Easement: Boundary Hill Balloon Field Trials*. Research Report CRE R 44 ERO-S2-1/99, Central Queensland University: Rockhampton, Australia.

Gyasi-Agyei Y, Sibley J. 2000. *Hydrology and Erosion Studies of a Railway Embankment*. Research Report CRE R 45 ERO-S1-2/2000, Central Queensland University: Rockhampton, Australia.

Gyasi-Agyei Y, Sibley J, Ashwath N, Nissen D, Griffin T. 1998. A biotechnical approach to the remediation of erosion damage to rail track formations in Central Queensland. In *Proceedings, Conference on Railway Engineering* CORE1998, Rockhampton, Australia, 6–9 September; 33–40.

Gyasi-Agyei Y, Sibley J, Truong P, Nissen D. 2000. A catchment-based approach to the mitigation of erosion problems in a railway cutting. In Proceedings, Conference on Railway Engineering CORE2000, Adelaide, Australia, 22–23 May; 22.1–22.13.

Marshall TJ, Holmes JW, Rose CW. 1996. *Soil Physics*. Cambridge University Press: Cambridge.

National Research Council. 1993. *Vetiver Grass—a Thin Green Line against Erosion*. National Academy Press: Washington, DC.

Nissen D. 1997. *A field-based study of erosion characteristics of rail embankments and cuttings in Central Queensland*. Undergraduate Thesis, Central Queensland University: Rockhampton, Australia.

Plunket CF. 2000. Track infrastructure for high speed passenger operation on a meter gauge network. In *Proceedings, Conference on Railway Engineering* CORE2000, Adelaide, Australia, 22–23 May, 15.1–15.12.

Queensland Department of Minerals and Energy. 1995. *Technical Guidelines for the Environmental Management of Exploration and Mining in Queensland*. Brisbane, Australia.

Rose CW, Coughlan KJ, Ciesiolka CAA, Fente B. 1997. The role of cover in soil conservation. In A New Soil Conservation Methodology and Application to Cropping Systems in Tropical Steeplands. Australia Centre for International Agricultural Research: Canberra, Australia. Tech. Rep. 40; 59–78.

Truong P, Hengchaovanich D. 1997. Application of the vetiver grass system in land stabilization, erosion and sediment control in civil construction. Paper presented at the Queensland Main Roads Southern Region Symposium, Toowoomba, Australia, 20–22 November.

Witheridge G, Walker R. 1996. Soil Erosion and Sediment Control, Engineering Guidelines for Queensland Construction Sites. The Institution of Engineers: Brisbane, Australia.

