Water Erosion Prediction for a Tailings Surface Using the WEPP Model

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WATER EROSION PREDICTION FOR A TAILINGS SURFACE USING THE WEPP MODEL

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ABSTRACT

A two-year sediment monitoring program was undertaken to measure sediment yield at various locations on a mine disposal area. The purpose of monitoring was to provide data for calibration of a numerical model to simulate long-term sediment yield. Falconbridge Ltd. commissioned the study to characterize the erosion characteristics of a tailings cone at their Kidd Creek mine near Timmins, Ontario. This information is required to develop a reclamation plan and sediment handling system.

The Water Erosion Prediction Project (WEPP) model was calibrated using the field data. It was then used to simulate a 24 year period of historical weather data. The model simulations indicated a mean annual areal average erosion of 2.75 mm and a 1 in 100 year annual erosion of 10.7 mm.

The sediment data was also used to compare the sediment yield of three alternative sediment yield models. The other models included two variations of the Universal Soil Loss model and a simplified runoff volume correlation model. Of the three, the Modified Universal Soil Loss Equation (MUSLE) model provided the best predictions.

INTRODUCTION

Falconbridge Limited operates the Kidd Creek mine near Timmins, Ontario, located 550 km north of Toronto. Tailings from the mine are stored using the Thickened Tailings Disposal system. Under this system, the tailings are pumped to the tailings area in the form of a slurry at 18 to 20 % solids. The slurry is separated into a thickened tailings (approximately 61% solids), and thickener overflow (relatively clear water). Thickened tailings are released at the centre of the tailings impoundment, where the solids settle out to form a concave cone with slopes of up to 5% near the top and 1% or flatter at the perimeter. A plan of the tailings area is shown on Figure 1.

The surface area of the tailings cone is approximately 1020 ha and is unvegetated. The tailings material consists primarily of silt-size particles. Natural runoff from rainfall or snowmelt runs down the cone slopes, causing erosion of the surface material. Some sediment is deposited on the lower slopes of the cone. The remaining sediment is carried to the perimeter stream. The stream conveys some of the sediment to the settling ponds.

As part of their planning for mine closure and reclamation, Falconbridge Ltd. commissioned a study to characterize the erosion characteristics of the tailing cone. The long-term sediment yield from the cone is of particular interest because it affects the selection of the type of reclamation surface required for the tailings area. It also affects the type and cost of a permanent sediment handling system. The erosion and sediment yield study described in this paper was undertaken by AGRA Earth & Environmental Limited (AEE).

The approach adopted for the sediment component of the study was to measure sediment yield at various locations on the tailings cone over a relatively short period of two years, and to calibrate a numerical model for predicting sediment yield over a longer period. The numerical model would provide the basis for estimating long-term sediment yield characteristics including mean annual sediment yield and the annual variation of sediment yield.

FIELD MONITORING

Erosion and sediment yield were monitored systematically in 1992 and 1993 at the following locations, as shown on Figure 1:

- Five sediment traps on the tailings surface. Two traps (G1, G2) measured sediment yield from established gullies which had relatively large drainage areas. Three sediment traps (S1, S2, S3) measured sheet erosion from relatively small drainage areas.
- Three sampling locations in the perimeter stream: the thickener overflow (TO), the flume (A-A), and the northwest measurement site (B-B).

Additional grab samples were collected from runoff in gullies on the tailings cone and from the perimeter stream.

The catchments which were of greatest value for model calibration, G1 and A-A, are described below.

SITE G1

The catchment area above G1 is 2.2 ha. The catchment profile is concave, with a slope of 2.8% near the top and 1.5% near the sediment trap at the bottom. The overall slope is 2.0%.

The G1 sediment trap was a 1.2 m wide by 2.4 m long by 1.0 m deep plywood box buried in the tailings material at a gully. The trap was equipped with a staff gauge and a V-notch weir at the outlet for manual flow measurement. During the second year of monitoring, a larger trap (2.4 m wide by 6.1 m long by 1.2 m deep) was connected to the original trap to provide more sediment storage capacity. In addition, a water level recorder and automatic sediment sampler were installed to monitor discharge and sediment concentrations more closely during an intensive monitoring period in the second summer. Water levels were recorded at 10 minute intervals and sediment samples were collected at the trap outlet at 30 or 60 minute intervals whenever there was flow through the trap.

SITE A-A

The catchment area above A-A is 86.0 ha. It has a concave slope ranging from 0.6% to 3.0%. The overall slope is 1.8%. The perimeter stream which forms the lower boundary of the catchment has a relatively constant base flow of approximately 0.4 m^3/s from the thickener overflow (TO).

The discharge at A-A was measured at 60 minute increments during the first year and 5 minute increments during the second year . Samples were collected for suspended sediment analysis at TO (approximately once per day) and at A-A (every 4 - 6 hours during and after runoff events; less often during dry periods). Sediment yield from the catchment was computed as the difference between the incoming sediment load from TO and the sediment load measured at A-A. Surveys of the perimeter stream in the reach between TO and A-A confirmed that there was negligible net change in streambed sediment storage during the monitored period.

The results of the 2 year field monitoring program are summarized in Table 1. Detailed results for site G1 are presented in Table 2

MODELLING

Model Selection

A numerical erosion model with the following characteristics was needed. The model should be:

- physically-based to facilitate calibration;
- capable of modelling snowmelt, which contributes significantly to annual erosion; and
- applicable to the unvegetated conditions at Kidd Creek.

The Water Erosion Prediction Project (WEPP) model (Flanagan, 1994a), was developed for agricultural purposes and was found to be the most suitable model available for the project. WEPP is a physically-based simulation model with a daily time step. It is a comprehensive model, including both hydrologic (runoff) and erosion processes. The hydrologic processes include a winter component dealing with frozen soils and snow accumulation and melt. If runoff is predicted to occur, the model computes soil detachment, transport, and deposition at frequently-spaced points along a profile. At the time of the study, the most recent version of the model was the hillslope version, WEPP 94.3.

Hydrologic Calibration

The model was calibrated using climate data from the two year field monitoring program and the previous year to reduce the influence of the initial condition settings. The climate input file was prepared from weather data recorded at the site, supplemented by records at nearby Atmospheric Environment Services (AES) stations at Porcupine and Timmins.

The hydrologic component of WEPP was calibrated by adjusting soil albedo, the effective hydraulic conductivity, and the cation exchange capacity. The modelled runoff proved to be insensitive to changes in any of these parameters, resulting in an imperfect but acceptable simulation of the runoff response to snowmelt and rainfall, as shown on Figures 2 and 3. Observed and modelled daily runoff for the catchment above G1 during the intensive monitoring period is shown on Figure 2. Observed and modelled monthly runoff for the catchment above A-A for year 1 and year 2 is shown on Figure 3.

The model underestimated snowmelt runoff volumes in both years. During the summer, some rainfall events were overpredicted in some cases and underpredicted or missed in other cases. Model results for the second year were better than for the first year. The observed differences between modelled and observed runoff are not unexpected because of the very small and variable catchment areas and because of the difficulty of measuring local climate conditions and small quantities of runoff.

Sediment Yield Calibration

Three soil parameters were used to calibrate the WEPP model for erosion and sediment yield. The parameters are the baseline rill erodibility, the baseline interrill erodibility, and the critical shear stress. Three modifications were made to make the hillslope version of the WEPP model more applicable to the Kidd Creek tailings area.

- The hillslope version of the model predicts erosion and sediment transport in rills but not in gullies. Many of the channels on the tailing cone are large enough to be considered gullies. To account for the presence of gullies, it was assumed that all detached sediment would be transported to the toe of the slope. Deposition which occurs on the lower portion of the slope in the model is ignored.

- The model adjusts effective erodibility values with time to account for soil crusting. The inorganic tailings material did not display the crusting phenomenon which is typical of agricultural soils. Therefore regular tillage was specified in the model to maintain high erodibility values representative of the tailings surface and of freshly tilled agricultural soil.

- WEPP consistently underpredicted the snowmelt runoff and erosion, as discussed below. To account for the weakness of snowmelt erosion prediction, annual sediment yields predicted by the model were adjusted by a factor of 1.65. The adjustment factor was selected based on the comparison of modelled and measured sediment yield. The adjustment factor is not included in the calibration data presented on Figures 4, 5, and 6.

The accuracy of the sediment yield calibration can be assessed by comparing modelled and observed sediment yield. During the intensive monitoring period, the calibration was very good, as shown on Figure 4. The erodibility parameters were selected so that the total modelled erosion during the period was equal to the observed erosion. The large difference between modelled and observed erosion for June 9 and 10 is believed to be due to a problem with the rainfall data. During that event, the precipitation records on site were missing and AES considered their records at Porcupine to be in error. The Porcupine records were used since nothing else was available. It is likely that the actual rainfall intensities experienced at the site were much greater than the model data file indicates.

When the entire second year (1993) monitoring season was considered (including the snowmelt before the intensive monitoring period), the calibration at G1 was much poorer, as shown on Figure 5. Modelled erosion early in the year was much less than the observed erosion. There is some uncertainty in the observed sediment yields during the snowmelt because of variable trap efficiencies. However, the WEPP model clearly underestimated the snowmelt erosion. The computed erosion for the total season in 1993 at G1 is 50% of the observed erosion.

Modelled and observed sediment yields at A-A for the second year (1993) are compared on Figure 6. The modelled sediment yield was slightly less than the observed yield, but the general quality of the calibration was quite good. Differences between the modelled and observed values arose during the snowmelt period when the WEPP model again underestimated the sediment yield.

MODEL RESULTS

Long-term erosion rates were estimated using the WEPP model and historical weather data. The period 1970-93 was selected based on the availability of detailed weather data at the nearby Porcupine AES station. Computed annual sediment yield from the tailings cone, including the adjustment for snowmelt erosion, ranged from 0.44 mm to 10.4 mm. The resulting mean annual yield was 2.75 mm. For a total cone area of 1020 ha, the mean annual yield was 48 000 T (28 000 m^3). This is the sediment which is expected to be eroded from the cone and delivered to the perimeter stream under current conditions, with the existing cone slopes.

A frequency analysis of the annual yields was conducted to predict sediment yields for various return periods. A Log Pearson Type III distribution fit the data well and yielded the results given in Table 3.

COMPARISON OF OTHER MODELS

Three alternative sediment yield models were compared with the results of the WEPP model. The first is a simple correlation of daily sediment yield with daily runoff, and the other two are variations of the USLE. WEPP output includes both runoff and sediment yield; the three alternative models compute only sediment yield.

Simple Runoff - Yield Model

The first model used for comparison with WEPP is a simple correlation of daily runoff volume and daily sediment yield:

$$A_n = k(Q_D)^x \qquad [1]$$

where: A_D = daily sediment yield (T)
Q_D = daily runoff volume (mm)
k, x = empirically-determined parameters

The simplified model was tested by examining the correlation between daily runoff and daily sediment yield. The results on Figure 7 show a reasonable correlation for most events ($r^2 = 0.75$).

USLE

The USLE (Wischmeier and Smith, 1978) is an empirically-derived model. It takes the form:

[2] $$A = RKLSCP$$

where:

A = computed soil loss per unit area
R = rainfall and runoff factor
K = soil erodibility factor
L = slope-length factor
S = slope-steepness factor
C = cover and management factor
P = support practice factor

Each of the terms on the right hand side of the equation, except R, is a constant for a given catchment. Therefore, if the USLE is applicable to the Kidd Creek tailings cone, there should be a good correlation between the sediment yield (A) and the rainfall-runoff factor (R). R is a funcition of the 30-minute rainfall intensities during the storm. As rainfall data for the Kidd Creek site was collected at only one-hour intervals, R was computed from the one-hour intensities to test the correlation between the soil loss per unit area (A) and the rainfall-runoff factor (R). The results on Figure 8 show no better correlation ($r^2 = 0.75$) than the simple runoff-yield model. This result is believed to be due to the inapplicability of the USLE to the non-agricultural conditions on the tailings cone.

MUSLE

The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) is a variation of the USLE which replaces the rainfall energy term R in the USLE with a modified runoff factor R_q involving the total runoff volume and the peak runoff rate. An advantage of the modification is that the MUSLE can be applied to snowmelt events.

The applicability of MUSLE was tested by examining the correlation between R_q and sediment yield. The results shown on Figure 9 indicate a better correlation ($r^2 = 0.93$) than for the USLE or the simplified model. However, the sediment yield values shown as "estimated" on Figure 8 are estimated on the basis of runoff volume, so these points reflect some auto-correlation.

CONCLUSIONS

1. The WEPP model, although designed for agriculture purposes, was applied to the case of an unvegetated, non-agricultural, non-organic tailings surface. After calibration with field data, WEPP provided very good estimates of summer (rainfall) runoff and erosion.

2. WEPP 94.3 underpredicted the snowmelt runoff and erosion from the Kidd Creek tailings cone. (A subsequent version, WEPP 94.7 [Flanagan, 1994b], released after the study was completed, incorporates updated snowmelt routines which may improve the accuracy of snowmelt runoff and erosion prediction.) Nevertheless, the overall predictive capability of WEPP was good, considering the highly variable nature of erosion processes and the difficulty of monitoring actual rainfall, runoff and sediment yield at very small catchments.

3. The MUSLE modified runoff factor correlated very well with observed sediment yields at Kidd Creek. The USLE demonstrated no advantage over a simple correlation between daily runoff volumes and daily sediment yield.

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TABLE 1
Measured Sediment Yield on the Tailings Cone

Period	Unit Sediment Yield At:					
	S1 (mm)	S2 (mm)	S3 (mm)	G1 (mm)	G2 (mm)	A-A (mm)
1992	–	–	–	–	1.01	3.0
1993	+1.39	+0.38	–	3.45	1.89	5.3

TABLE 2
Sediment Yield at Box G1 - May 20 - Sept. 30, 1993

Date	Rainfall	Peak Runoff	Peak Runoff	Sediment Transport Through the Trap	Sediment Captured	Sediment Yield		Comment
	(mm)	(m³)	(l/s)	(kg)	(kg)	(kg)	(mm)	
93.05/24 to 25	2.4.4	148.0	35.6	1620	3180	4810	0.12	
93/05/27 to 28	6.4	5.6	0.7	0.1		0		
93/05/30 to 31	17.0	99.7	5.0	78	1420	1500	0.038	Total capture from May 27 to May 30
93/06/09 am	10.0	22.3	18.4	100		100	0.003	
93/06/09 pm	missing	97.9	85.1	1660		1660	0.042	
93/06/10	4.4	62.3	57.9	1130	4030	5160	0.13	Total capture for June 9-10
93/06/17	12.4	1.6	2.5	0.1				
93/06/25	10.9	1.2	3.3	0				
93/07/05 to 06	39.4	337.0	171.0	9570	4120	13700	0.34	Total capture from June 17 to July 6
93/07/09	19.8	96.0	39.1	236	3200	3440	0.087	
93/07/1	8.6	21.3	20.8	83.3	467	550	0.014	
93/07/28 to 29	20.3	72.2	36.3	381.1	2301	2682	0.068	
93/08/11	12.4	110.0	141.0	2420	1180	3590	0.091	
93/08/23 to 24	9.2	11.3	14.5	13	848	861	0.022	
93/09/09	19.3	37.4	9.7	154	727	881	0.022	
93/09/13	4.0	0.7	0.69	0		0		
93/09/14 am	25.4	337.0	49.1	3000		3000	0.076	
93/09/14 pm	16.4	94.5	14.0	210	5000	5210	0.131	Total capture for Sept 13-14
TOTALS		1560	–	20600	26500	47100	1.19	

TABLE 3
Frequency Analysis of Sediment Yields

Return Period (years)	Annual Sediment Yield	
	(mm)	(T)
2	2.2	39 000
5	3.9	69 000
10	5.3	93 000
20	6.8	120 000
50	8.9	160 000
100	10.7	190 000

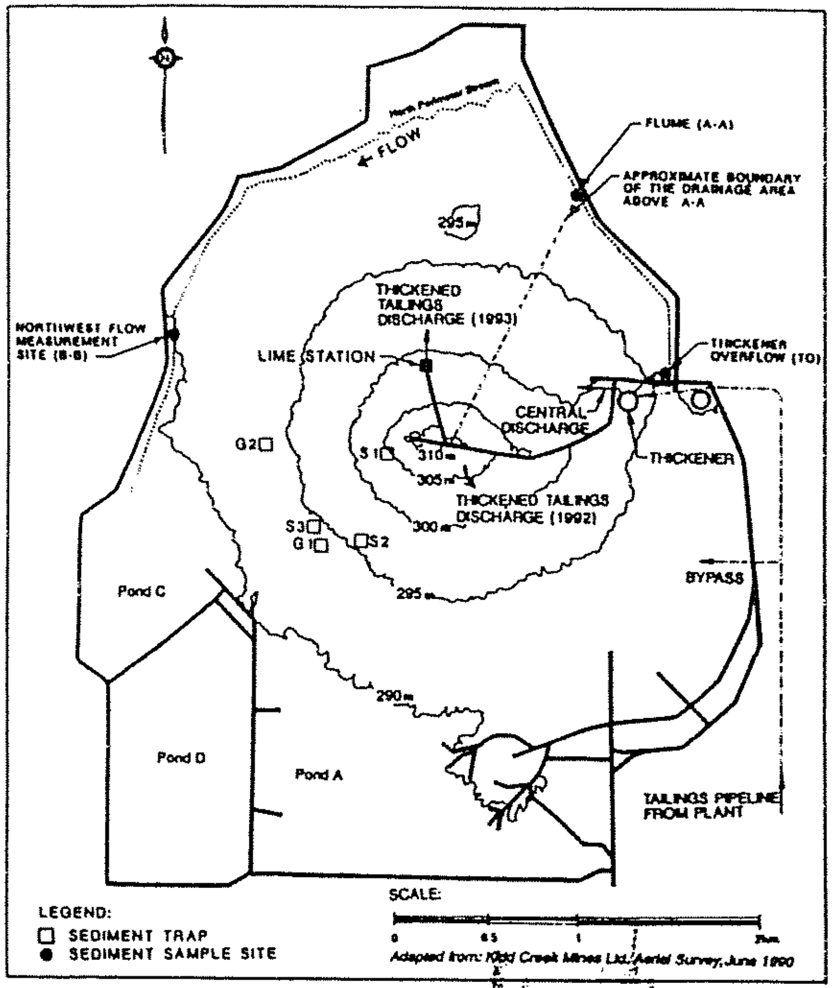


Figure 1. Kidd Creek tailings cone

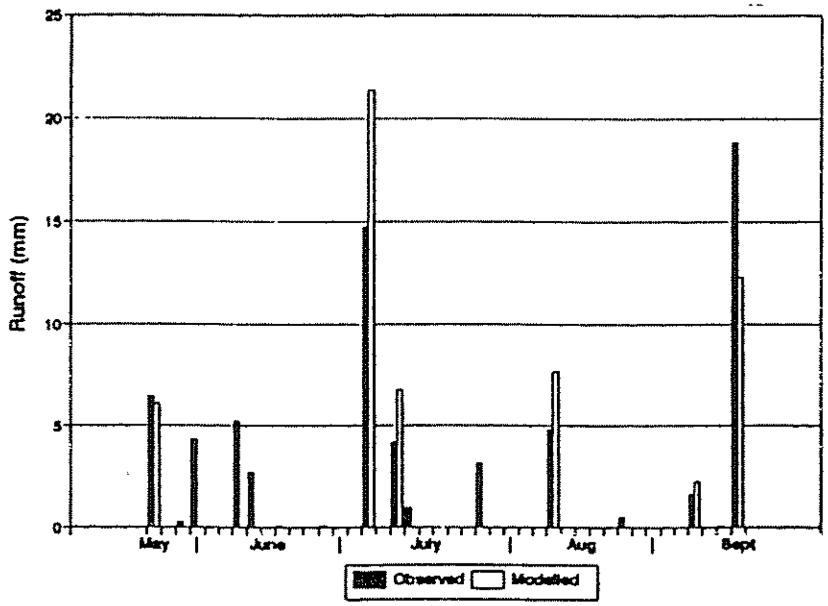
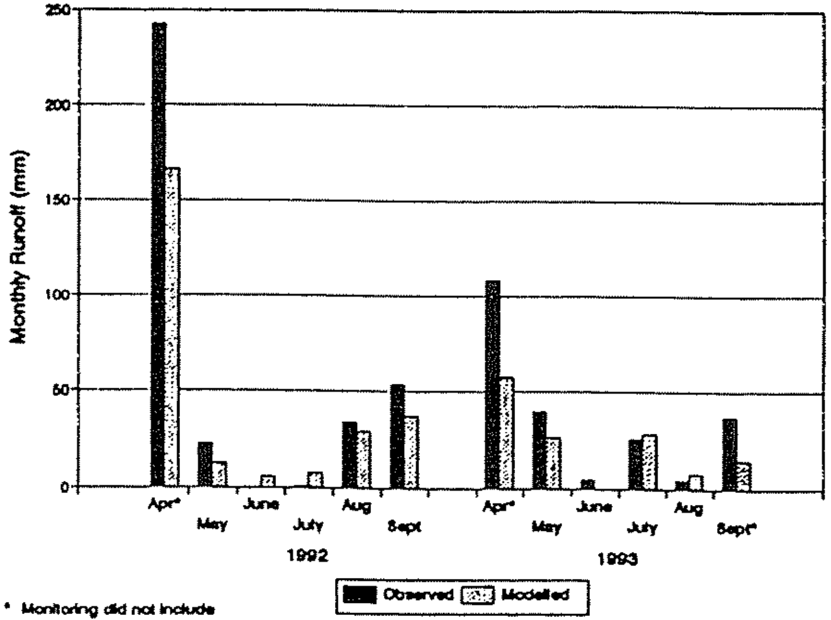


Figure 2. Hydrologic calibration - daily runoff at box G1



* Monitoring did not include the entire month.

Figure 3. Hydrologic calibration - monthly runoff at A-A

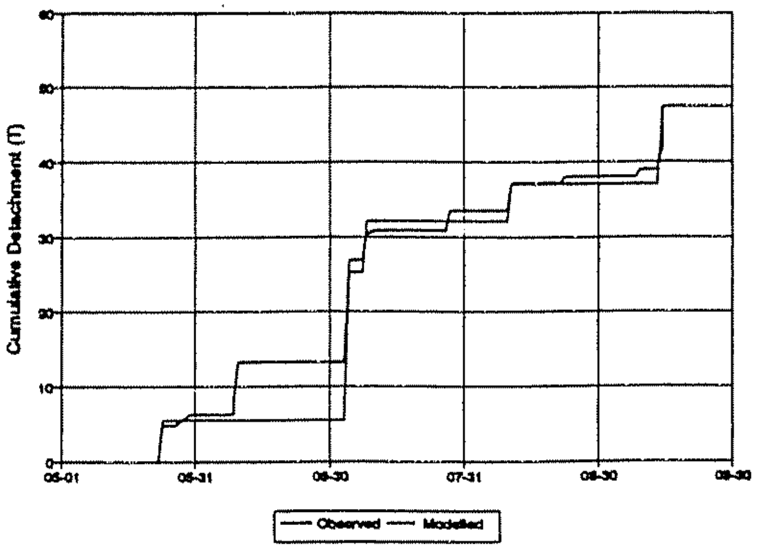


Figure 4. Erosion calibration:
sediment yield at G1 during the intensive monitoring period

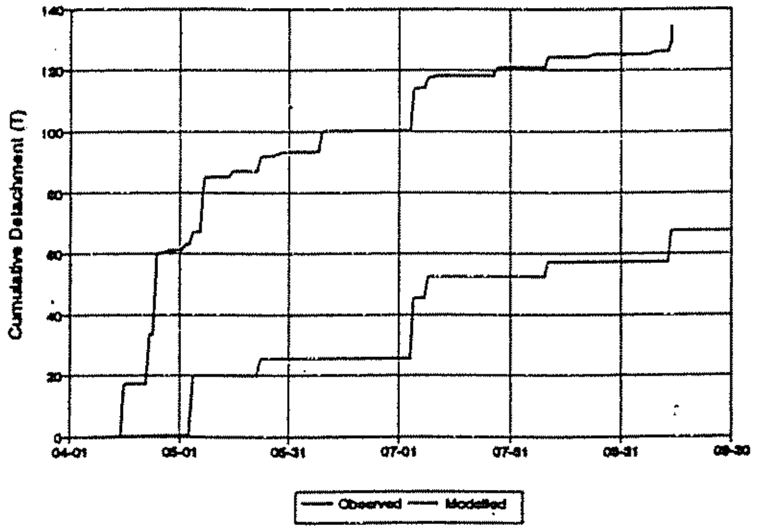


Figure 5. Erosion calibration:
sediment yield at G1 for the complete 1993 season

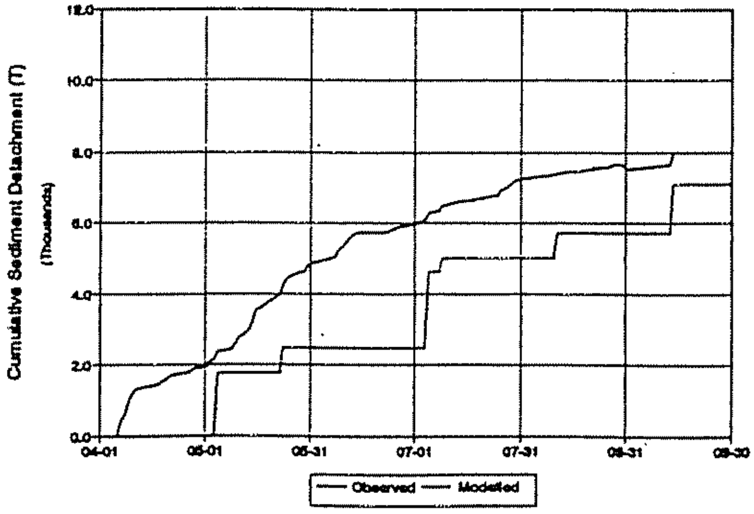


Figure 6. Erosion calibration:
sediment yield at A-A, 1993

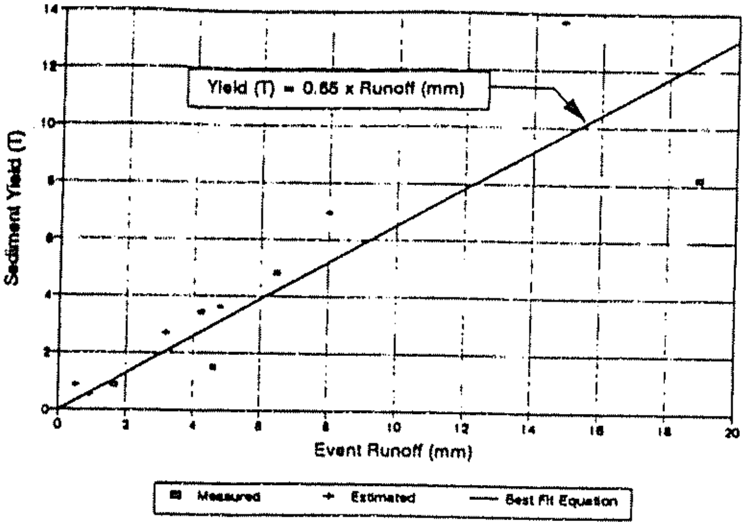


Figure 7. Simplified model: Correlation of daily sediment yield with daily runoff

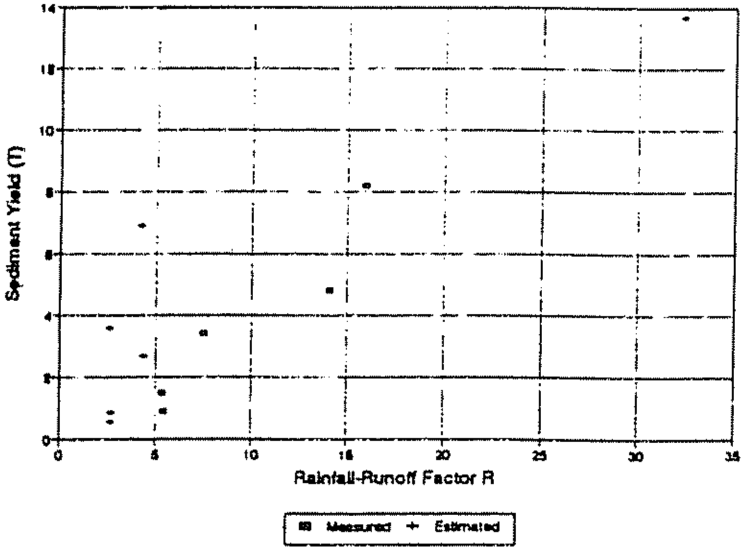


Figure 8. Correlation of the sediment yield at G1 with the USLE rainfall-runoff factor.

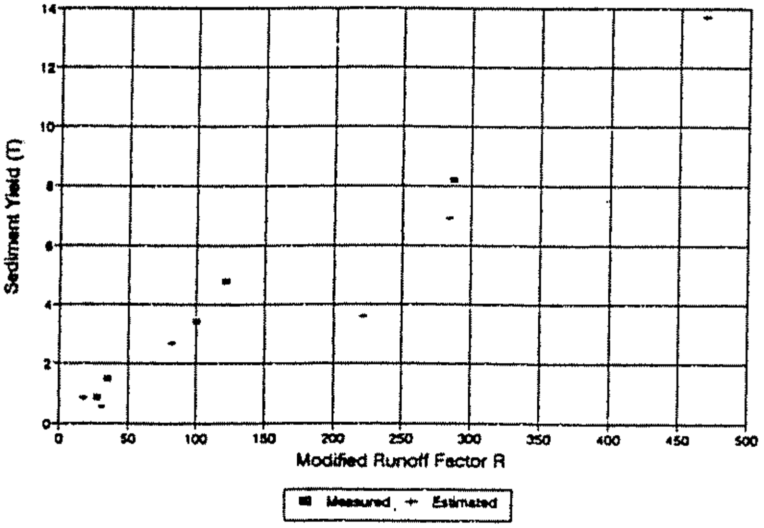


Figure 9. Correlation of the sediment yield at G1 with the MUSLE modified runoff factor.