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COMPARISON OF LOCAL INFILTRATION EXCESS, OVERLAND FLOW AND ASSOCIATED EROSION BEHAVIOR WITH RIVER BEHAVIOR AT THE CATCHMENT SCALE

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Modeling overland flow and erosion behavior is a very important scientific task today to prevent environmental impacts from human activities, as well as physical disasters such as floods and desertification. This project has identified the impacts from selective logging in Malaysia by comparing hydrological parameters, both at a local and a catchment scale. Measurements of rainfall, overland flow, and suspended sediment flux were recorded for a year with a resolution of five minutes. A Data Based Mechanistic (DBM) modeling approach was applied to facilitate physical interpretation of the results, which provided credible conclusions. The significant alteration of the area's hydrologic regime, due to human interventions, is apparent. The extreme nonlinearity of the rainfall-suspended sediment flux relationship reduced the efficiency of the models, and did not allow reliable forecasting. Nevertheless, useful conclusions have been drawn from the comparison of hydrologic parameters at different scales. The DBM models described the physical processes well and provided satisfactory results.

INTRODUCTION

In the last three decades there has been a proliferation of research on rainfall-runoff modeling, and there is an abundance of literature in this area. The new possibilities and challenges arising today address the most outstanding problems on a priority basis, making for a rapid progress of the science (Singh, 1982).

In 1961, Sugawara proposed a “tank-type” model to describe the flow of Japanese streams, and in 1971 the Storm Water Management Model (SWMM) was produced on behalf of the United States Environmental Protection Agency. Many significant models were also produced during the 1970s, such as the Constrained Linear System (CLS) by Natale and Todini (1974), the U.S. Agriculture Research Service Model in 1975, and the STORM model in 1976. Over the last two decades, many hydrological models of overland flow and associated erosion have been developed. Significant efforts have been made by Singh (1978), Chorley (1978), Akan and Yen (1981), Lima (1988), Young and Beven (1994), and many others who have extensively studied the hydrological behavior of different environments, and provided valuable information to better understand complex hydrologic processes. In particular, Moore and Clarke (1981) presented a new approach to rainfall-runoff modeling by replacing the single storage element, which was used to represent interception and soil moisture storage, with an infinite population of stores. The models were very efficient initially , but during the evaluation process some deficiencies became apparent. Lima (1988) produced a soil water transport model by combining the kinematic wave equations with the matrix flux potential. The advantage of this model was that it required a limited amount of input data and provided credible predictions of the soil moisture content.

Another significant piece of research came from Guy et al. (1987), who studied the interrelationships between rainfall, overland flow and erosion. They found that there is a strong connection between rainfall and sediment-transport capacity, which is a notion that has been widely adopted by many scientists during the last decade. Finally, Young and Beven (1994) have examined a data based mechanistic (DBM) modeling approach to rainfall-runoff systems and have shown its benefits.

This project constitutes a part of a NERC funded hydrology project which took place in a tropical forest in Malaysia in 1995. Selective logging was conducted in Borneo’s tropical forest between 1988 and 1990, and this research was undertaken to identify the environmental impacts of the activity.

The study uses a Transfer Function (TF) model with a Data Based Mechanistic (DBM) approach to compare the overland flow and erosion behavior at a local and catchment scale,and quantify potential changes in the environmental processes of the area due to selective logging.

The Project Site

The research area is the Batu Catchment, which lies in the northeast part of the Danum Valley Field Centre (DVFC) in Sabah, Borneo (Figure 1). It has an area of 0.441 km^2. The geological characteristics of the area comprise a melange formation that mainly includes mudstones and sandstones. The upper soil is classified as a FAO Harpic Alisol (Alh) which is a relatively unstable soil (Chappell et al., 1999). The climate in this region is equatorial with modest annual seasonality, and the mean rainfall for a 11 year period is 2,778 mm. Additionally, the intensity of the rainfalls is relatively high since events greater than 50 mm/hr have a return period of 23.3 days and events greater than 100 mm/hr have a return period of 139.6 days (Chappell et al., 1999).

Data from three sites were used this project. Site 1 on the main river drains the entire Baru catchment. It receives significant contributions of overland flow and suspended sediment from the

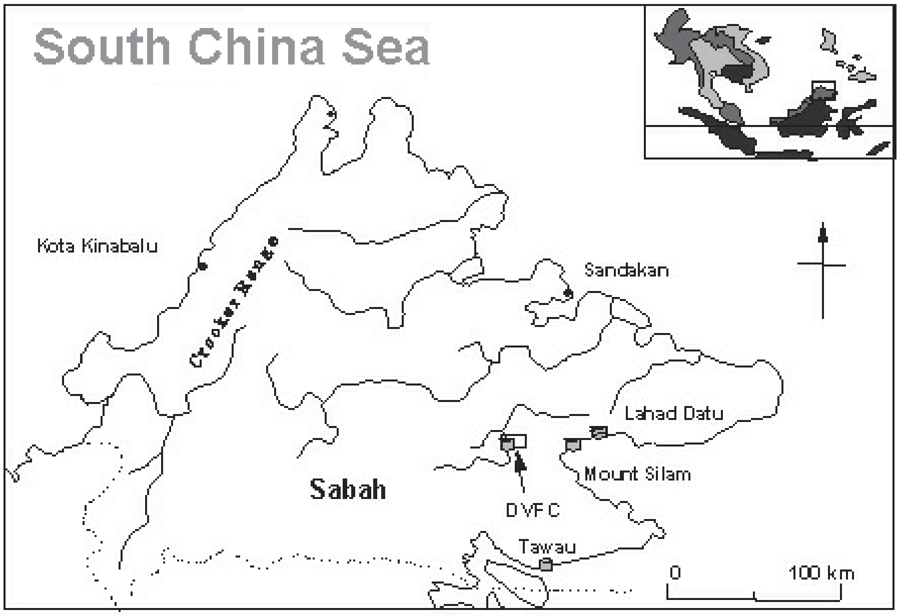

Figure 1. Map of Sabah. The Baru experimental catchment is based at the DVFC area.

other two study sites . Site 6a (0.0003 km^2) is a small site, which has been significantly influenced by a haulage road that was constructed during the logging period. Site 3b (0.0006 km^2) is a small-scale undisturbed slope. The incorporation of Site 6a in this project offers the opportunity to show the environmental impacts from human activities in the area. The sites are shown in Figure 2.

METHODS

A gauging network has been constructed in the Baru catchment and measurements of rainfall (mm), instantaneous discharge ($m^3s^{-1}km^{-2}$) and instantaneous suspended sediment concentration ($kgs^{-1}km^{-2}$) were taken using equipment comprised of 120° V-notch weirs, tipping-bucket systems and turbidity probes. The measurement period is from 1 July 1995 to 30 June 1996, and the data were taken every 5 minutes, which provides a good resolution for a reliable analysis.

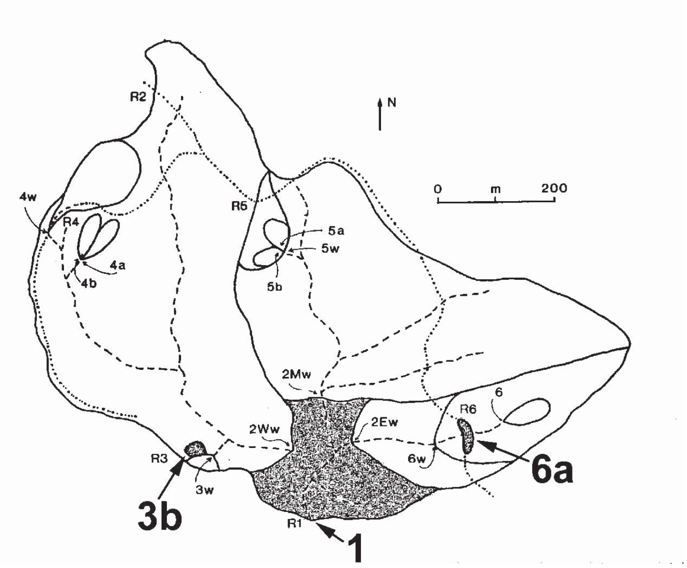

Figure 2. Map of Baru catchment and the project sites.

In this project a single-input single-output (SISO) Transfer Function model (TF) was applied to the data (Figure 3). This is a simple model that provides the output by multiplying the input with a transfer function which is a function of the backward shift operator ($z^{-i}y(k)=y(k-i)$) and the model parameters (Young, 1993).

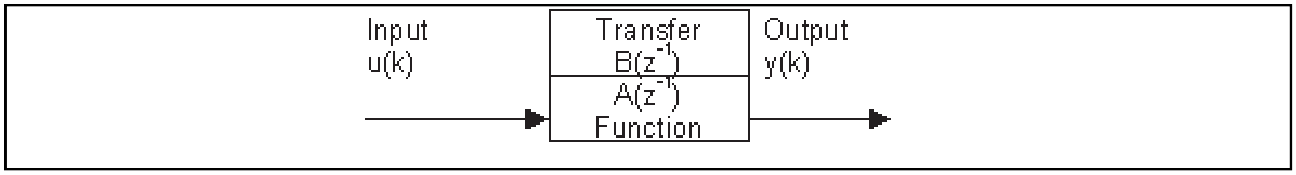

Figure 3. Single-input, single-output Transfer Function (TF) model.

The general equation that describes the model is:

$$y(k)=\frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)}u(k-d) \tag{1}$$

where y is the output, u is the input, and d is the pure time delay. The denominator and the numerator polynomials are given by the equations:

$$\begin{aligned} A\left(z^{-1}\right) &= 1+a_1z^{-1}+a_2z^{-2}+\cdots+a_nz^{-n} \\ B\left(z^{-1}\right) &= b_o+b_1z^{-1}+b_2z^{-2}+\cdots+b_mz^{-m} \end{aligned} \tag{2}$$

There are only two parameters in this model, A and B, which facilitates the physical interpretation of the modeling results and eliminates the risk of over parameterization. TF models have been widely and successfully used, and there is significant literature on their characteristics, which further increases the credibility of these models.

The simplified-refined-instrument-variable (SRIV) algorithm (Young, 1985) has been utilized to identify the models and to estimate their parameters. The SRIV algorithm uses a recursive technique to analyze the data and to derive the best applicable model. The choice is based on the coefficient of determination (R_T^2) and on the Young Information Criterion (YIC). Particularly, the coefficient of determination (R_T^2) is a statistical index that expresses the model's fit and physical explanation in the given data. The equation that describes this index is:

$$R_T^2=1-\left(\sigma^2/\sigma_y^2\right) \tag{3}$$

where σ^2 is the variance of the model residuals and σ_y^2 is the variance of the data. The best fit occurs when R_T^2 approaches 1.

The Young Information Criterion (YIC) is a more complex index since it attempts to estimate the model fit and the parameters efficiency by focusing on over-parameterization avoidance. The function used to calculate the YIC is:

$$\mathrm{YIC}=\log_e\left(\sigma^2/\sigma_v^2\right)+\log_e\{\mathrm{NEVN}\} \tag{4}$$

where NEVN is the normalized error variance form (Young and Beven, 1994).

A first-order, linear modeling approach was first attempted to explain the hydrological system of the area with the simplest available model, but the results indicated a more sophisticated solution was required. The need to incorporate nonlinearity in the models was apparent, and nonlinear filters were applied to the model inputs.

First, soil moisture nonlinearity has been introduced to the system by applying the effective rainfall model (Jakeman et al., 1990):

$$u(k) - S(k)r(k)$$

$$S(k) = S(k-1) + \frac{r(k) - S(k-1)}{tc} \tag{5}$$

where $u(k)$ is the transformed input of the model, $S(k)$ is the effective rainfall, $r(k)$ is the rainfall and tc is a time constant describing the wetting-drying period in hours. This approach takes into account the water storage effects in the model. This is a realistic approach since soil moisture comprises a crucial factor for the hydrological regime of the area, as illustrated in the qualitative observation stage of the project. This improves the modeling procedure since the efficiency of the models increases significantly with the incorporation of effective rainfall.

Another nonlinear filter has been used for input to overcome the prevailing nonlinearity of the system and compare its results with the effective rainfall results. Young and Beven (1991) proposed a bilinear filter where overland flow is low-pass filtered rainfall itself. They used the output of the model to transform the input:

$$u(k) = u(k)y(k)^{p} \tag{6}$$

where $u(k)$ is the input of the model, $y(k)$ is the output and p is a constant number that can be derived by examining the power relationship between the input and the output.

The main feature of the bilinear model is that it adjusts the rainfall data to better approximate overland flow at each moment. Rainfall peaks are amplified where overland flow is high, while they are reduced where the flow is low. This filter also provides very efficient models, as will be apparent later in this study. Careful interpretation of the results is required since this approach may introduce a deterministic aspect to the modeling procedure.

A proportion of 27% of the data series was used to identify the models. The remainder of the data series was used to evaluate the model at a later stage. During the modeling procedure, the model parameters, (*a*) and (*b*), have been estimated, as well as the time constant (TC), and the steady state gain (ssG). Parameter (*a*) provides a picture of the response of the output to the input, while parameter (*b*) provides a measure of the productivity of the system in terms of its output. The time constant (TC) describes the lag-time between the input and the output peaks, and the steady state gain (ssG) is a normalized index for the system's productivity since parameter (*b*) is often relatively constrained.

After having completed an identification of the models, a careful interpretation of the results will be attempted and a description of the hydrological characteristics of the area will be presented.

RESULTS

The average annual rainfall for the study period is 2,897 mm (Table 1). Figure 4 shows a great variation in the data, with frequent storms and sudden changes from light to heavy rain, which is to be expected due to the tropical climatic type of this region. The most significant extreme events

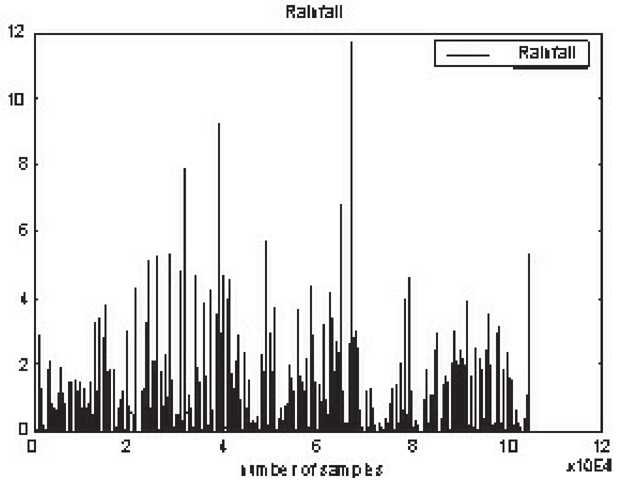

Figure 4. Rainfall data series (5 minutes data, in mm).

include the 74 mm rainfall of 21 October 1995 and the 37 mm rainfall of 16 February 1996, which have the highest intensity (11.64 mm/5min) for the entire recording period (Table 2).

Discharge determines suspended solids flux and affects many significant environmental processes. The discharge at Site 1 is expected to be much higher than the other sites, for both instantaneous measurements and annual flow, since Site 1 represents the catchment scale site and the main river, while Sites 3b and 6a are small scale subcatchments. The average instantaneous discharge at Site 1 is 0.059 $m^3s^{-1}km^{-2}$, at Site 3b it is 0.0013$m^3s^{-1}km^2$, and at Site 6a it is 0.0047 $m^3s^{-1}km^{-2}$ (Table 1).

Table 1. Annual and Average Values of Discharge and SS-Flux for Each Site

	Average annual rainfall	Annual discharge	Annual SS-Flux	Average inst. disch.	Average inst. SS-flux
site	mm	mm	t/km^2	m^3s^{-1}/km^2	$kg/s/km^2$
1	2,896.70	1867	592	0.059	0.0187
3TB	-	31.87	24.83	0.0013	0.0011
6TB/A	-	77.79	98.75	0.0047	0.006

Table 2. Discharge and SS-Flux During the Extreme Events

					21 Oct '95	19 Jan '96
	Area	An. Discharge	An. SS-Flux	An. SS-Flux	SS-Flux	SS-Flux
		mm	t/km^2	t	t	t
Site 1	0.441	1867	592	261.07	44.26	105.19
Site 3b	0.0006	31.87	24.83	0.0149	0.0019	0.0005
Site 6a	0.0003	77.79	98.75	0.0296	0.0059	0.0101

The higher value at Site 6, in relation to Site 3b, is possibly due to the haulage road at this site, resulting in a decrease in infiltration capacity. The annual discharge at Site 1 was 1.87x10^6 m^3km^{-2} (1867 mm), while it was 3.19x10^4 m^3km^{-2} (31.87 mm) at Site 3b, and 7.78x10^4 m^3km^{-2} (77.79 mm) at Site 6a (Table 1).

The most significant extreme event occurred on 19 January 1996. It produced a large amount of surface runoff at Site 1, accounting for 11% of the annual discharge [2.0872x10^5 m^3km^{-2} (208.72 mm)]. At Site 3b the runoff was 9.812x10^3 m^3km^{-2} (9.812 mm), which is 31% of the annual value (Table 2).

The annual suspended sediment flux (SS-flux) for Site 1 is 261 tonnes (592 t/km^2), while for Site 3b the value is 0.015 tonnes (24.83 t/km^2), and for Site 6a it is 0.030 tonnes (98.75 t/km^2, Table 1). At Site 1 measurements showed 0.0187 kg/s/km^2 of SS-flux, while at Site 3b the value was 0.0011 kg/s/km^2 and at Site 6a it was 0.0060 kg/s/km^2 (Table 1). The relatively high SS-flux at Site 1 (Figure 5) is expected since there is perennial flow in this catchment. The ss-flux extreme event was also recorded in 19 January 1996 with a measurement of 238.52 t/km^2 (105.19 tones), which constitutes 40% of the annual SS-flux. At Site 3b the most extreme event occurred in 9 November 1995 when 17.40 t/km^2 of sediment flux was measured (71% of the annual value), while at Site 6a the 19 January 1996 event was the most extreme with 33.74 t/km^2 (0.01 tonnes) of sediment flux, which comprises 34% of the annual value (Table 2).

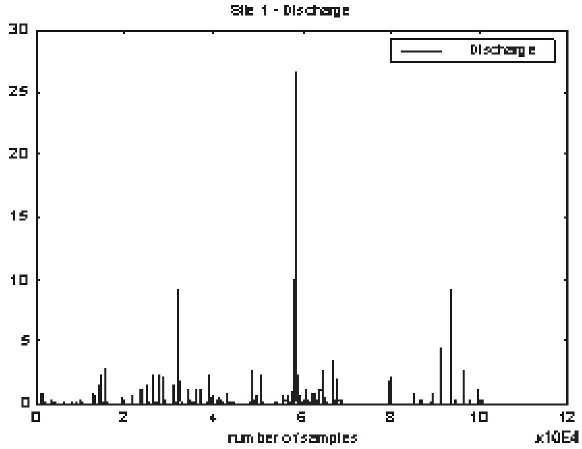

Figure 5. Instantaneous discharge (m^{3}s^{-1}km^{-2}) at Site 1.

DYNAMIC MODELING

Rainfall – Overland Flow Modeling

Linear Models

Although there is nonlinearity in the system rainfall-discharge relationship, as has been mentioned before in this study, the results of the linear models are satisfactory. In particular, the Site 1 model has a coefficient of determination (R_T^2) of 0.68, while Site 3b has a R_T^2 of 0.61, and Site 6a is a less efficient model withR_T^2 of 0.58 (Table 3). The fact that the Site 1 model (Figure 6) is more efficient than the other sites is due to the significant amount of overland flow missing values that Site 3b (23,370 missing measurements) and Site 6a (50,273 missing values) have due to technical problems with the equipment. This problem affected the model abilities to correlate the undisturbed input with the disturbed output, and therefore the efficiency of the models for these two sites is reduced.

Parameter (a) indicates a very flashy response of the overland flow at Site 6a and a slower response for Sites 1 and 3b (Table 3). A reason that can partially explain this result is that the extent of the area plays a significant role in the response of a hydrological element (overland flow) to a specific input such as the rainfall. In large-scale sites the response will be slower than in small-scale sites where the hydrological conditions can change very quickly. Nevertheless, in this case it is not only a matter of extent since the differences in the parameter (a) are significant even for sites of similar size, such as Site 3b and 6a. After examining the characteristics of each site, another explanation can be found for the increased value of parameter (a) at Site 6a: the haulage road influences the hydrological behavior of the area to a great degree. This artificial construction decreases the permeability of the soil and overland flow occurs soon after rainfall begins. This is one impact of man's interference with the local environment due to selective logging.

By considering the steady state gain (ssG), Site 1 has a high productivity (ssG=1.84, Table 3), which is expected since it is the main river of the Baru catchment and receives water from many other surrounding sites. The significant difference in this site gain in relation to productivity at Sites 3b and 6a implies that the overland flow contribution from these sites may not be adequate to explain the large ssG of Site 1. There may also be a contribution from subsurface water to Site 1 overland flow. The high productivity of Site 6a (ssG=0.25) in relation to Site 3b (ssG=0.1, Table 3), even though Site 6a has half of the area of Site 3b, shows again that the haulage road has significantly altered the hydrological regime of the area.

Table 3. Rainfall-Discharge Models (Linear Approach)

Input	Output						
Rainfall	Discharge						
Sites	Model	Rt2	YIC	a	b	TC (min)	ssG
1	113	0.6855	-11.4452	-0.9609	0.072	125.3277	1.8399
3b	111	0.6095	-9.3525	-0.5331	0.049	7.9489	0.1049
6a	112	0.5825	-6.6973	-0.2237	0.1952	3.3387	0.2514

The large time constant (TC=125 min) calculated for the Site 1 is another indicator of the relatively slow processes that take place at catchment scale sites such as Site 1, while at smaller scale sites the time constants are much lower (8 min for Site 3b and 3.3 min for Site 6a) since the response to rainfall is relatively immediate. Again, the extremely low time constant for Site 6a illustrates the environmental impact of the existing road.

Effective Rainfall Models

The effective rainfall filter introduces the important concept of soil water storage and takes into account the nonlinearity of the system. Improved models with higher efficiencies are expected to be produced by using this filter for model input. This is the case as shown by the model coefficient of

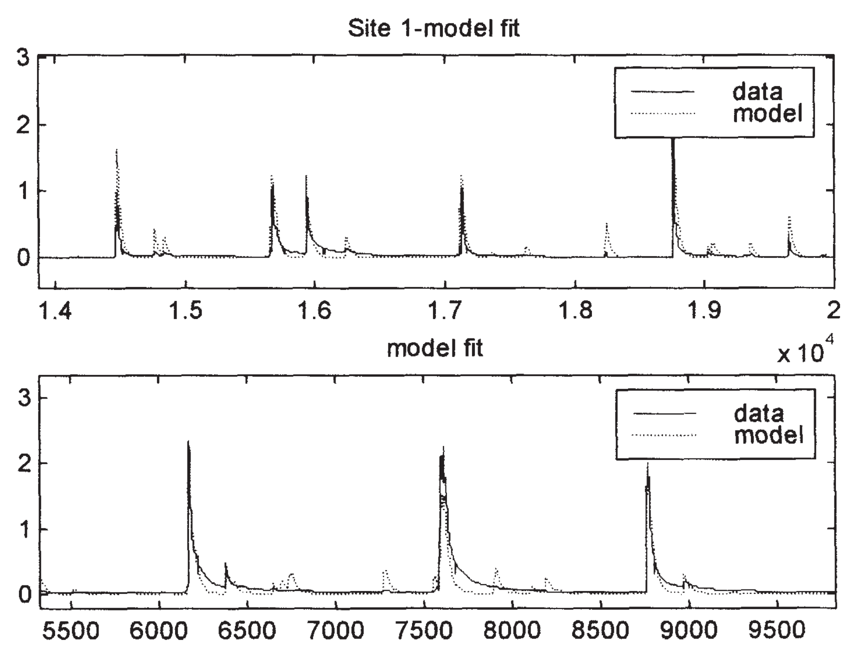

Figure 6. Rainfall-Discharge model fit for site 1.

determination (R_T^2) which is 0.8 for Site 1 (linear model: 0.68, Figure 7), 0.82 for Site 3b (linear model: 0.61) and 0.69 for Site 6a (linear model: 0.58). A significant improvement in the models for Sites 1 and 3b was seen, while the efficiency of the Site 6a model remained relatively low. This is due to the large number of missing data at this site (47% of the overland flow data series). There is a significant disturbance to the model identification procedure because the existing data are not able to adequately describe some events, and as a result a model with relatively low efficiency is produced.

The interpretation of the results should be different with these models, since the input is no longer rainfall but effective rainfall, which incorporates the soil moisture aspect. Parameter (a), which continues to be low for Site 1 (-0.96), higher for Site 6a (-0.54) and even higher for Site 3b (-0.27, Table 4), describes the response of overland flow in relation to the effective rainfall in this case. When the soil moisture is high, Site 1 has a relatively slow response to overland flow while Site 6a has a much faster response and Site 3b has a flash flood response.

Several implications arise from this result. The recorded response times illustrate the natural evolution of overland flow after soil moisture is maximized, which excludes the impact of artificial constructions, such as the haulage road at Site 6a.

The steady state gain (ssG) at Site 1 is 0.98, which is almost half of the respective value of the linear model (1.84). This indicates that there is a significant contribution of soil water storage in the overland flow of Site 1 since the effective rainfall seems to play the most crucial role in the discharge of this site (ssG=0.98, Table 4). The rainfall component alone cannot cause the increased productivity recorded in this site (ssG=1.84 for the linear model). Similar conclusions can be drawn for the other sites since their steady state gains (ssG) are also reduced significantly in relation to the linear model (Tables 3 and 4). This also implies that the soil moisture is high, especially at Site 3b where the discharge is only 5.8% of the effective rainfall, and the response of the discharge is very flashy.

The time constant (TC) is reduced, which is also expected since the effective rainfall is the dominating factor for discharge development, as can be seen in the relevant figures where overland

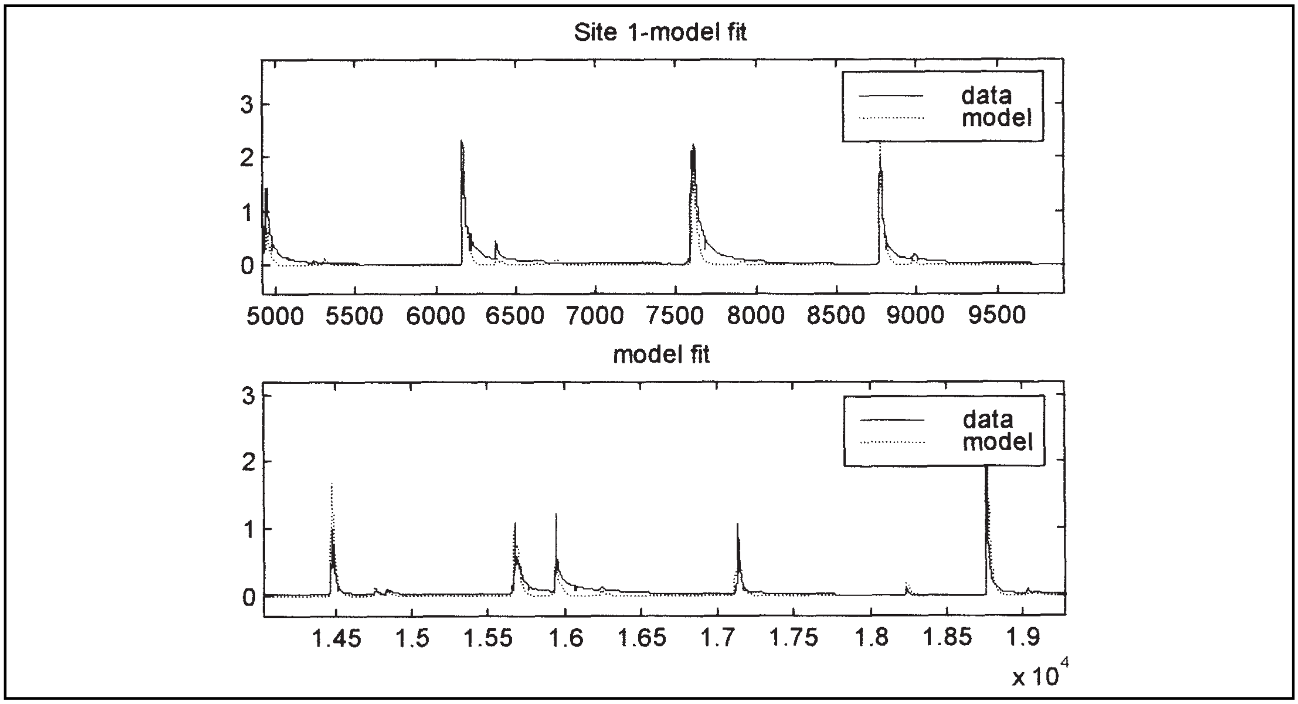

Figure 7. Rainfall-discharge model for site 1 (Effective rainfall filter).

Table 4. Rainfall-Discharge Models (Effective Rainfall filter)

Input	**Output**						
Effective rainfall	**Discharge**						
Sites	**Model**	**Rt2**	**YIC**	**a**	**b**	**TC (min)**	**ssG**
1 (tc=60)	112	0.8006	-12.2907	-0.9428	0.0562	84.9016	0.9825
3b (tc=10)	111	0.8234	-9.5828	-0.2674	0.0421	3.7907	0.0575
6a (tc=10)	110	0.6925	-9.1572	-0.5365	0.0733	8.0296	0.1581

flow peaks follow effective rainfall peaks with a short time delay. However, the time constant remains much higher at Site 1 (85 min) than at the other sites (3.7 min at Site 3b and 8 min at Site 6a, Table 4) due to the large scale of this site in relation to the small scale Sites 3b and 6a.

At Site 6a the changes in the model properties (the parameters, and TC and ssG) from the linear to the nonlinear approach do not follow the pattern of the respective changes in the other sites. While at Sites 1 and 3b there is a reduction in the values of parameter (*a*) and TC, at Site 6a there is an increase of the respective values in relation to the linear model. Site 6a is not affected by the water storage regime as much as the other sites because the haulage road is the most important aspect determining its hydrological behavior.

Bilinear Model

The best power values for the bilinear models have been estimated by using a similar technique to Monte Carlo simulation. The SRIV algorithm has been used to identify the model parameters.

The results of this modeling approach are very satisfactory (Figure 8) since the efficiency for Site 1 (0.81) has almost the same value as in the effective rainfall model (0.80), while the coefficient of determination is significantly increased for the Site 3b (0.90) as well as for Site 6a (0.82, Table 5). These results are expected since the bilinear model strongly correlates input with output, and this may sometimes produce a constrained outcome. The results of this model should be carefully interpreted to avoid drawing erroneous conclusions.

The response of the discharge in the transformed input is about the same at Site 1 (-0.95) as in the previous models, which illustrates again a relatively slow response, probably due to the large areal extent of Site 1. Site 3b presents a substantially faster response (-0.54), similar to the one that was calculated in the linear model (-0.53), and Site 6a has the flashiest response (-0.48), which is significantly lower than the linear model (-0.22, Table 5). The effects of the artificial construction in the area can still be inferred from parameter (a), as well as from the other properties of this model (TC, ssG).

The steady state gain (ssG) is higher in the bilinear model than in the linear model for all three sites, and since the output of the model is always the same (discharge), the transformed rainfall must determine this difference in the model productivity. The gain for Site 1 is large (2.45), which implies that the specific input cannot lead to the site's increased productivity. It can be concluded that other hydrological factors contribute to the gain of the system (possibly groundwater). At Sites 3b and 6a even a small proportion of the input is enough to produce the recorded discharge which comprised 24% of the total input for Site 3b and 36% for Site 6a. The significant productivity of Site 6a is probably due to the anomaly of the haulage.

The time constant (TC) for the bilinear models has remained high for Site 1 (99 min), while it has almost maintained the same value as in the linear model for Site 3b (8.1 min), and has increased

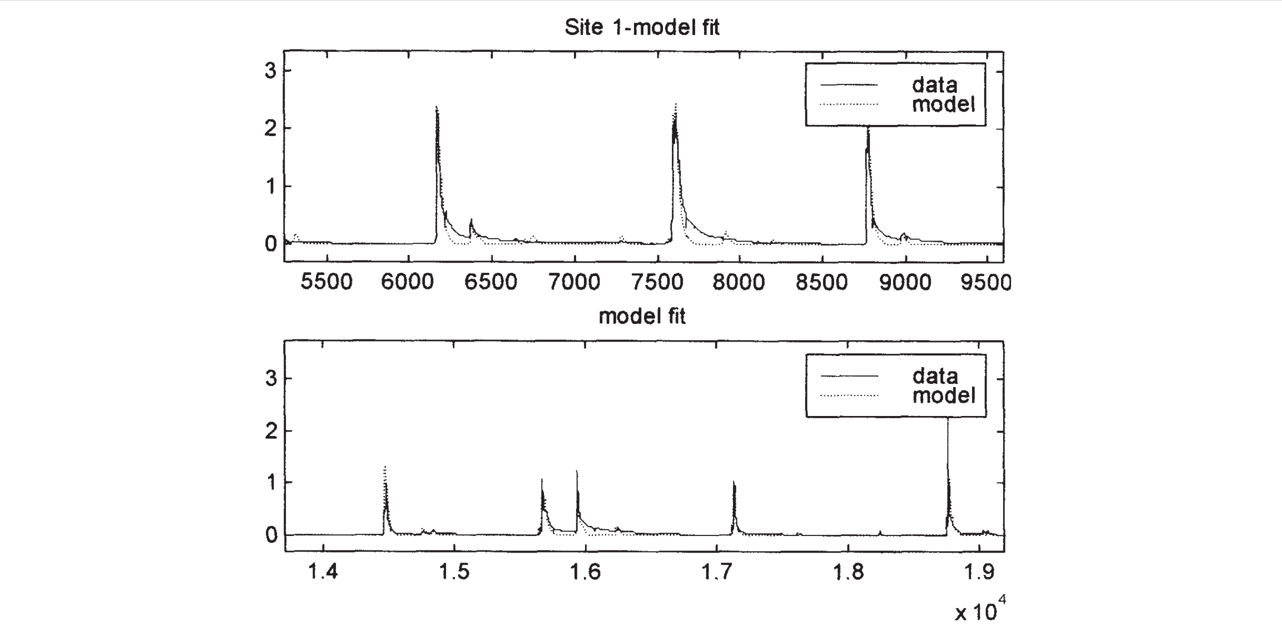

Figure 8. Rainfall-discharge model for site 1 (bilinear filter).

significantly at Site 6a (6.7 min, Table 5). Again, the extent of the sites and their particular characteristics have determined these values as seen before in this study.

Rainfall-SSflux Modeling Subsystem

The rainfall-SSflux subsystem is a much more nonlinear system than rainfall-discharge and this was illustrated extensively in previous parts of this project. Consequently, the rainfall-SSflux models are not expected to be as efficient as the rainfall-discharge models since the suspended sediment flux is influenced by many other factors besides rainfall, such as regional geological properties, extreme events and soil moisture conditions. By considering only rainfall as the model input, not very efficient results are obtained. Nevertheless, it is useful to attempt this modeling approach since significant conclusions about the erosional behavior of the area can be drawn.

Linear Model

The efficiency of the linear models is very low. Site 1 presents a R_T^2 of 0.17, while for Site 3b the respective value is 0.20 and for Site 6a is 0.14 (Table 6). These models cannot describe the system and subsequently are not appropriate either for forecasting or for credible conclusions. In order to increase the model efficiency, second order models have been adopted, but the coefficients of determination remained at the same low levels, indicating once again the high nonlinearity of the system (Figure 9, Table 6).

Table 5. Rainfall-Discharge Models (Bilinear Filter)

Input	Output						
Bilinear filter	Discharge						
Sites	Model	Rt2	YIC	a	b	TC (min)	ssG
1 (p=0.4)	111	0.8091	-12.3909	-0.9509	0.1203	99.2815	2.45
3b (p=0.5)	110	0.9045	-12.8202	-0.541	0.1088	8.14	0.237
6a (p=0.5)	110	0.8165	-10.6301	-0.4767	0.1894	6.7479	0.3618

However, it can be said that this model follows similar patterns that have been observed in the linear rainfall- overland flow discharge model. Particularly, the response of the SS-flux to the rainfall

Table 6. Rainfall-SSflux Models (Linear Approach)

Input	Output							
Rainfall	SS-flux							
Sites	**Model**	**Rt2**	**YIC**	**a**	**b**		**TC(min)**	**SsG**
1	114	0.1745	-7.1828	-0.774	0.3209		19.5143	1.4197
3b	111	0.2015	-5.6614	-0.1783	0.0978		2.8994	0.119
6a	112	0.1354	-1.2013	-0.0624	0.5837		1.802	0.6225
Second order models								
1	124	0.1797	-3.4184	-0.7327	0.1169	0.2545	16.0738	1.3893
3b	122	0.2463	-2.2473	-0.0938	0.1686	-0.0729	2.1132	0.1056
6a	121	0.1413	0.3717	-0.0214	-0.2551	0.8273	1.3006	0.5847

is relatively slow for Site 1 (*a*=-0.77) while it is faster at Site 3b (*a*=-0.18) and it is extremely flashy at Site 6a (*a*=-0.06). This behavior of Site 6a is probably because there is abundant sediment available from the haulage road and, as soon as rainfall begins, overland flow quickly forms and sediment is mobilized.

As for the steady state gain (ssG), Site 1 has a great productivity since the amount of SS-flux is 1.42 times higher than the rainfall. This can be explained by the large amount of discharge that is recorded at this site as well as by the contribution of remote sources and events that have been observed (landslides, soil mass movements). The gain at Site 3b is significantly lower (0.12) which is expected due to its small extent and limited amount of overland flow. Even though Site 6a is also a small site with no perennial overland flow, its gain regarding the SS-flux is about 5 times higher than the gain at Site 3b (ssG=0.62, Table 6). This is another piece of evidence for the substantial disturbance that the haulage road has caused in the environment of this area.

By observing the time constants (TC) for these models, it can be stated that they maintain the patterns they had in the linear discharge models but the differences between the sites have now become smaller. The SS-flux peak is observed only 19.5 min after the rainfall peak at Site 1, while the respective time for Site 3b is 2.8 min, and for Site 6a 1.8 min (Table 6). These time constants illustrate a flashier response of the SS-flux to the rainfall than discharge to the rainfall. This may be

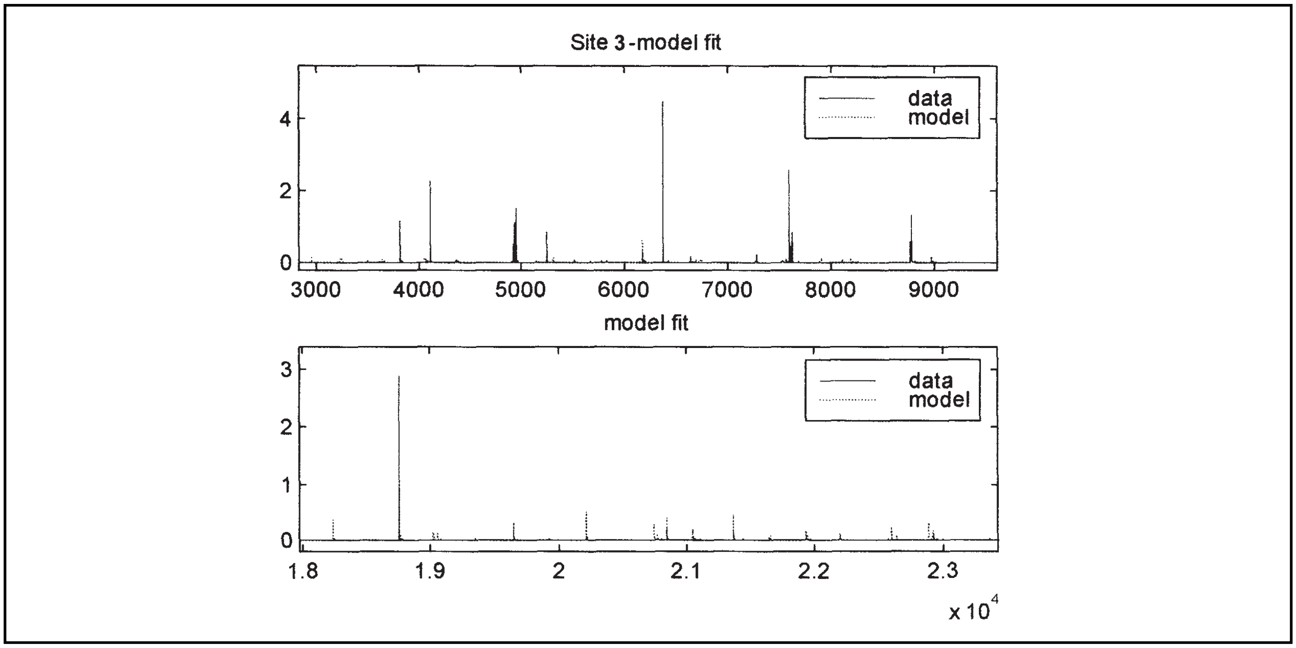

Figure 9. Rainfall-SSflux model for site 3b (linear approach).

explained by the fact that sediment particles begin to move in the infiltration stage, possibly due to the subsurface flow, while the overland flow is formed later on.

Effective Rainfall Model

The incorporation of nonlinearity in this system by using the effective rainfall filter provided measurable improvement in the results of the models. In particular, the coefficient of determination (R_T^2) for Site 1 is 0.498, while in the linear model it was 0.175, and at Site 6a it is 0.31, while in the linear model it was 0.135 (Table 7). However, at Site 3b there is no significant improvement in the efficiency of the model, which is probably due to the high number of SS-flux missing values. The gauging station had been damaged by an electrical storm during the measurement period and there is substantial bias in this model. It can be seen in Figure 10 that the model underestimates almost all the events in the data series, which is expected since the missing values include the most important extreme events, and consequently the model cannot realistically correlate the effective rainfall to the SS-flux.

Useful information can be obtained by interpreting the results of these models. The pattern of the different site responses in the SS-flux remains about the same as in the linear model. Site 1 presents a relatively slow response (-0.60), while Site 3b has a quicker response (-0.39), and Site 6a has an extremely flashy response (-0.06, Table 7). Even though a very detailed analysis of these model results cannot be done due to their low efficiencies, it is important to illustrate changes of the parameters between the linear and the nonlinear models, and compare them for the different sites.

The steady state gain (ssG) is significant for Site 1 (1.06), while it is significantly lower for Site 3b (0.06), and is relatively high for Site 6a (0.45, Table 7). These values probably indicate again that there is a great amount of sediment available at Site 1 and that the contribution of sediment from remote sources is also substantial to this site. The productivity of Site 3b is not large, which is expected. The great SS-flux produced at Site 6a comes possibly from the haulage road.

The time constants (TC) maintain the pattern observed in the linear model but they have very different values in some sites. At Site 1, TC is significantly lower than in the linear model (9.89/19.5min), and at Site 3b the nonlinear time constant is much higher than in the linear model (5.35/

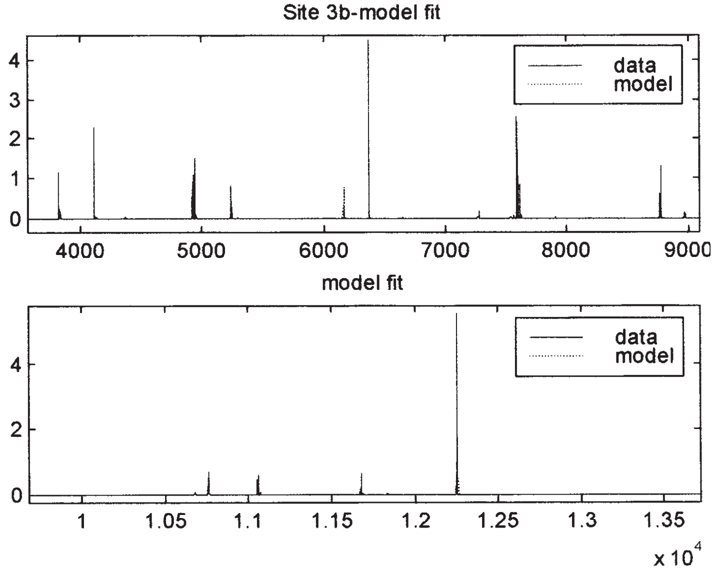

Figure 10. Rainfall-SSflux model fit for Site 3b (Effective rainfall filter).

Table 7. Rainfall-SSflux Models (Effective Rainfall Filter)

Input	**Output**						
Effective rainfall filter	**SS-flux**						
Sites	**Model**	**Rt2**	**YIC**	**a**	**b**	**TC (min)**	**ssG**
1 (tc=10)	114	0.4979	-8.7934	-0.6033	0.4215	9.8934	1.0625
3b (tc=3)	110	0.1751	-9.1402	-0.3931	0.0366	5.3548	0.0603
6a (tc=1)	112	0.3107	-1.1993	-0.027	0.4379	1.3843	0.4501

2.89min). This is probably due to the different roles that soil water storage plays in these sites. At Site 1 the soil moisture facilitates the SS-flux and therefore movement of sediment occurs soon after the water storage begins to increase, while at Site 3b it seems that the soil moisture does not influence the SS-flux significantly. Again, further investigation and incorporation of other factors that influence the erosional behavior of the catchment should be conducted to produce more efficient models, and to be able to draw more credible conclusions.

Bilinear Model

The bilinear model provides a great improvement of the efficiencies of the models, which is expected since this filter defines the input by using the output component, increasing their correlation significantly. A very careful interpretation of the results is required since the input does not describe clearly any physical process in these models, and ‘‘secure” inferences about the hydrological regime of the area cannot be made.

The parameters in these models tend to validate the previous model results since they present the same patterns as the linear and effective rainfall models (Table 8). Site 1 has the slowest response in relation to the other sites while Site 6a has the fastest. Site 1 has the greater ssG while Site 6a has the lowest (Table 8). This is probably due to a deficiency of the model since Site 6a has a significant SS-flux production as has been illustrated in the previous models. Finally, Site 1 has the largest time constant (TC) and Site 6a has the smallest one, which is also in accordance with the respective observations of the previous modeling approaches.

Another significant feature that should be mentioned at this point is that although the model coefficients of determination are very high (Table 8), the model fit appears to have substantial inadequacies (Figure 11). Apparently the bilinear filter forces the model to fit the big events well while, it underestimates many of the smaller events. Thus, the model achieves a great efficiency by describing the extreme and the very small events, but it does not apply well to the rest of the events that comprise the minority in the specific data series.

After the identification of all of the aforementioned models, a calibration and evaluation process was conducted by applying the identified models to different parts of the data series. The results were similar to the original models and the parameters presented about the same patterns as in the initially identified models. Thus, it can be said that the credibility of the aforementioned models is relatively

Table 8. Rainfall-SSflux models (Bilinear Filter)

Input	**Output**						
Bilinear filter	**SS-flux**						
Sites	**Model**	**Rt2**	**YIC**	**a**	**b**	**TC (min)**	**ssG**
1 (p=1)	110	0.9545	-13.2628	-0.371	0.4121	5.0425	0.6552
3b (p=0.8)	110	0.6999	-6.1198	-0.0494	0.3001	1.6624	0.3157
6a (p=1)	110	0.9658	-7.5382	-0.0117	0.199	1.1235	0.2013

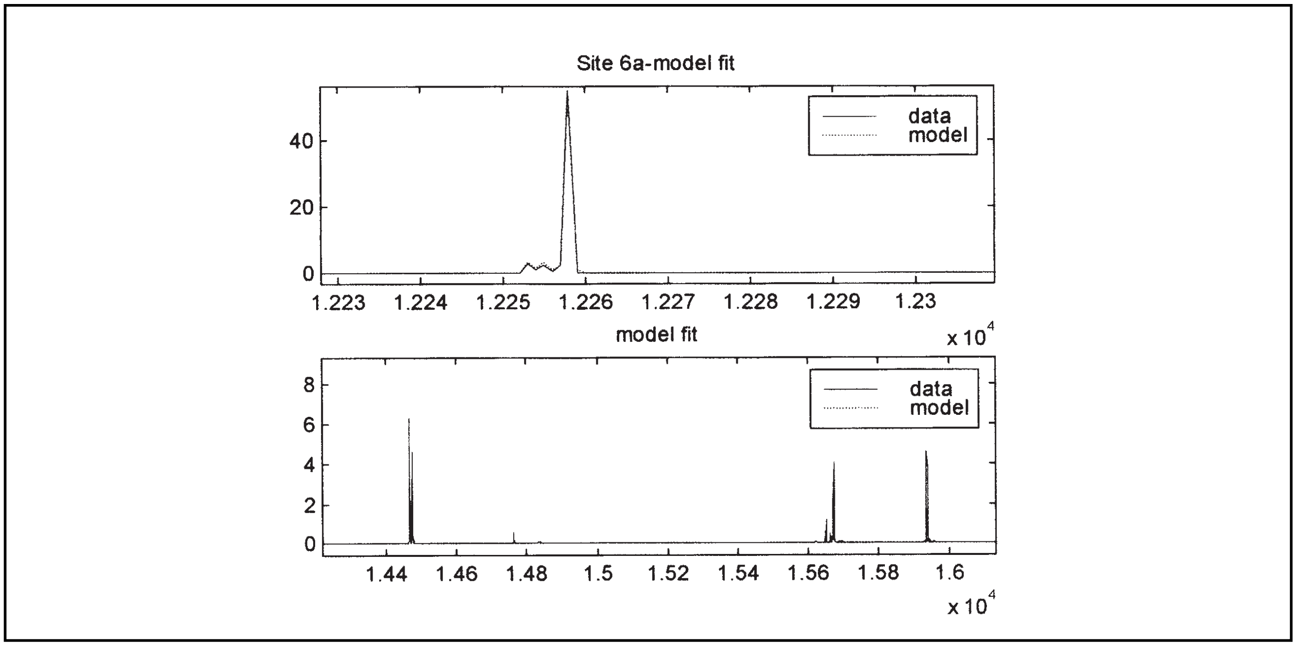

Figure 11. Rainfall-SSflux model fit for site 6a.

high, and considering the available data, their results were satisfactory. Nevertheless, further efforts to acquire a more complete data series and better statistical elaboration of the data should be conducted to further improve these models, and to validate them as appropriate for reliable forecasting.

DISCUSSION

Nonlinearity

During the modeling process as well as through the observational stage of the project an important aspect was the nonlinearity of the system. Several researchers (Tong, 1990; Jakeman et al., 1990, Astakie et al., 1996) have shown the substantial nonlinearity that dominates hydrological processes such as overland flow and suspended sediment flux in relation to rainfall. In the qualitative observations of these parameters in this study at different scale sites, this nonlinearity has been seen for overland flow and SS-flux events. Several other factors (such as soil/geological characteristics, groundwater flow and storage, soil moisture,etc.) influence these processes and make the relationships between rainfall-overland flow and rainfall-SSflux nonlinear. Even though the regional rainfall-discharge subsystem showed nonlinearity, the linear models used in this study presented high efficiency and described this process relatively well.

To test various modeling approaches and achieve a solution to overcome the nonlinearity problem, nonlinear filters to the inputs were used, as well as a higher order models wherever necessary. Careful interpretation of the model results avoided erroneous conclusions, and a qualitative study of the data was combined with the modeling procedure to validate the inferences.

Model validity was tested by applying different parts of the data series to the models and by comparing their parameters and efficiencies.

In the rainfall-SSflux subsystem the nonlinearity was significantly higher than in the rainfall-discharge subsystem, which is expected. The dynamics of the SS-flux phenomenon are influenced by a variety of factors, while the interrelationship between rainfall and discharge is very strong. In the effective rainfall-SSflux models, the efficiency was not high enough to provide credible results and a careful physical interpretation of the models' parameters was required. Finally, the bilinear model showed high efficiency, which is expected since the input is redefined with the use of output, but this approach places constraints on the model.

Site specific characteristics

The responses of the discharge and SS-flux are generally slower at the catchment scale site than at the smaller scale sites. Large rainfall events can easily affect local scale areas while they need significant time to initiate hydrological processes at the catchment scale. The most important feature of the discharge and SS-flux is the anomaly that Site 6a presents. Site 6a has relatively fast responses, probably due to the haulage road that was constructed in the area during the selective logging period. The model parameters indicate that responses at Site 6a are almost twice as fast for discharge and SS-flux, than at Site 3b even though Site 6a covers only half the areal extent of Site 3b. This enhances the haulage road impact concept since such construction significantly affects the infiltration capacity of the area and provides a great source of sediment. The model results, specifically the large differences between the parameters of the undisturbed Site 3b and the parameters of Site 6a, illustrated some of the environmental impacts from selective logging in the area.

The results also showed significant variations in the sediment availability from site to site. At Site 1 relatively high amounts of sediment are produced soon after the initiation of rainfall events, which indicates the high availability of sediment within or near the existing river channel. Large SS-fluxes that have been observed during some extreme events imply a significant contribution of remote sediment sources such as landslides and mass movements during these events. Site 3b shows a relatively low productivity of the suspended sediment, mainly due to its small extent and to its topography, geology and vegetation. In contrast, Site 6a has high sediment productivity mainly caused by the haulage road, which alters the hydrological behavior of the area.

Similar observations can be made on discharge. At Site 1 the measured discharge is very high since this site comprises the main river of the catchment and a large amount of its flow is be supplied by the other subcatchments of the area. This is shown by the large steady state gain (ssG) of this site model, which is almost double the total rainfall, and implies that the other sites contribute significantly to increased discharge. The measured discharge at Site 3b is relatively low because of increased infiltration capacity, which only large rainfall events exceed and cause overland flow (Horton, 1933).

Although Site 6a is also a small-scale site, the observed discharge is relatively high due to the haulage road. The road significantly decreases infiltration and overland flow appears more often and in larger amounts than at Site 3b, which implies potential danger for flooding and detrimental effects on the fauna and flora of the area (Price et al., 1996). Once again the important environmental impacts from man's intrusion in the area become apparent from this site's modeling results.

An attempt to depict the amount of nonlinearity due to infiltration at Site 1 was made by considering infiltration as the input of a model and discharge as the output. The proportion of the water that had infiltrated during the project period was calculated by subtracting the discharge from the rainfall measurements at Sites 3b and 6a, because the discharge measurements in these sites do not include subsurface flow, which is included at Site 1 measurements.

The results of the infiltration models were similar to the results of the linear rainfall-discharge model of Site 1. This illustrates that infiltration is not the crucial factor for nonlinearity in the system. The soil moisture is probably the element responsible for causing the high nonlinearity that has been observed in the rainfall-discharge subsystem of this area, and this notion is enhanced by the significant improvement of the model efficiency when the effective rainfall filter was incorporated into their input (Merz et al., 1997). If a more efficient model is essential for a forecasting perspective, then the nonlinearity of the system should be taken into account, and measuring the soil moisture conditions would be an appropriate step.

The impacts from the haulage road that has been constructed at Site 6a for the purposes of selective logging were significant since the hydrologic regime of this site has been altered to a great degree. This has been illustrated by comparison with undisturbed Site 3b. The sediment availability at Site 6a has significantly increased, the amount of discharge recorded in this site is also large, and the time response of the system to rainfall is reduced in relation to Site 3b.

Also, emphasis should be given to the fact that the model efficiency increased with the incorporation of the nonlinear filters, particularly the effective rainfall filter (Jakeman et al., 1990). This was most evident in the discharge models. This filter did not operate well with the SS-flux models, due to increased nonlinearity. The bilinear filter (Young and Beven, 1991) gave very good results for all the hydrological systems, but its ability to produce unconstrained models is poor.

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