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Comparisons of local infiltration-excess, overland flow and associated erosion behaviour with river behaviour at the catchment scale

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Abstract

Modeling overland flow and erosional behaviour is a very important scientific task today to prevent environmental impacts from human activities as well as physical disasters such as floods and desertification. In the particular project the impacts from selective logging that occurred in Malaysia has been attempted to identify and quantify by comparing hydrological parameters both in local and catchment scale. Measurements of rainfall, overland flow and suspended sediment flux have been recorded for a year with a resolution of five minutes. A Databased Mechanistic (DBM) modeling approach has been applied to the data to facilitate physical interpretation of the results, which provided credible conclusions. The significant alteration of the area's hydrologic regime, due to human interventions, has become apparent. The great non-linearity of the rainfall-suspended sediment flux system reduced the efficiency of the models and did not allow reliable forecasting to be made. Nevertheless, useful conclusions has been drawn from the comparison of hydrologic parameters in different scales and should be emphasized that DBM models described very well the physical processes and provided satisfactory results.

Keywords

Hydrologic modeling, overland flow, erosion, catchment scale

INTRODUCTION

In the last three decades there has been a proliferation of research on rainfall-runoff modeling, which leads to an abundance of literature in this area. The new possibilities and challenges arising nowadays will allow addressing the most outstanding problems on a priority basis for rapid progress of hydrology (Singh, 1982).

In 1961 Sugawara described a "tank-type" model concerning the flow status of Japanese streams and in 1971 the Storm Water Management Model (SWMM) was produced on behalf of the Environmental Protection Agency. Many significant models were also produced during the 1970's, 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. Moreover, as we come to the last two decades thousands of hydrological models, concerning overland flow and associated erosion have also been produced. It should be stated that significant efforts have been made by Singh (1978), Chorley (1978), Akan and Yen (1981), Lima (1988), Young and Beven (1994) and many other researchers who have extensively studied the hydrological behaviour of different environments and provided us with valuable information in order to understand these complex hydrologic processes. Particularly, Moore and Clarke (1981) presented a new approach to rainfall-runoff modeling by replacing the single store element that was used to represent the interception and the soil moisture storage, with an infinite population of stores. The models produced initially were very efficient but during the evaluation process some deficiencies became apparent. Furthermore, 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, Rudra and Dickinson (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 from many scientists during the last decade. Finally, Young and Beven (1994) have examined the databased mechanistic (DBM) modeling approach to rainfall-runoff systems and have depicted its benefits.

This project constitutes a part of a NERC funded Hydrology project which took place in a tropical forest in Malaysia in 1995. Particularly, selective logging has occurred in Borneo's tropical forest between 1988 and 1990 and a research is undertaken to identify the environmental impacts of this activity.

This will occur by using a Transfer Function (TF) model with Data-Based Mechanistic (DBM) approach to compare the overland flow and erosional behaviour at a local and at a catchment scale and quantify potential changes in the environmental processes of the area, due to selective logging.

The site of the project

The extent of the research area is 0.441 km^2 and lies to the north-east of the Danum Valley Field Centre (DVFC) in Sabah, Borneo (figure 1). The geological status of the area comprises a melange formation that includes, mainly, mudstones and sandstones whereas the upper soil is classified as a FAO Harpic Alisol (Alh) which is a relatively unstable soil (Chappell et all., 1999). The climate in this region is characterised as equatorial with modest annual seasonality and the mean rainfall for a 11 year period is 2,778 mm. Additionally, the intensity of the rainfalls are relatively high since events with >50 mm/hr have a return period of 23.3 days and events with >100 mm/hr have a return period of 139.6 days (Chappell et al., 1999).

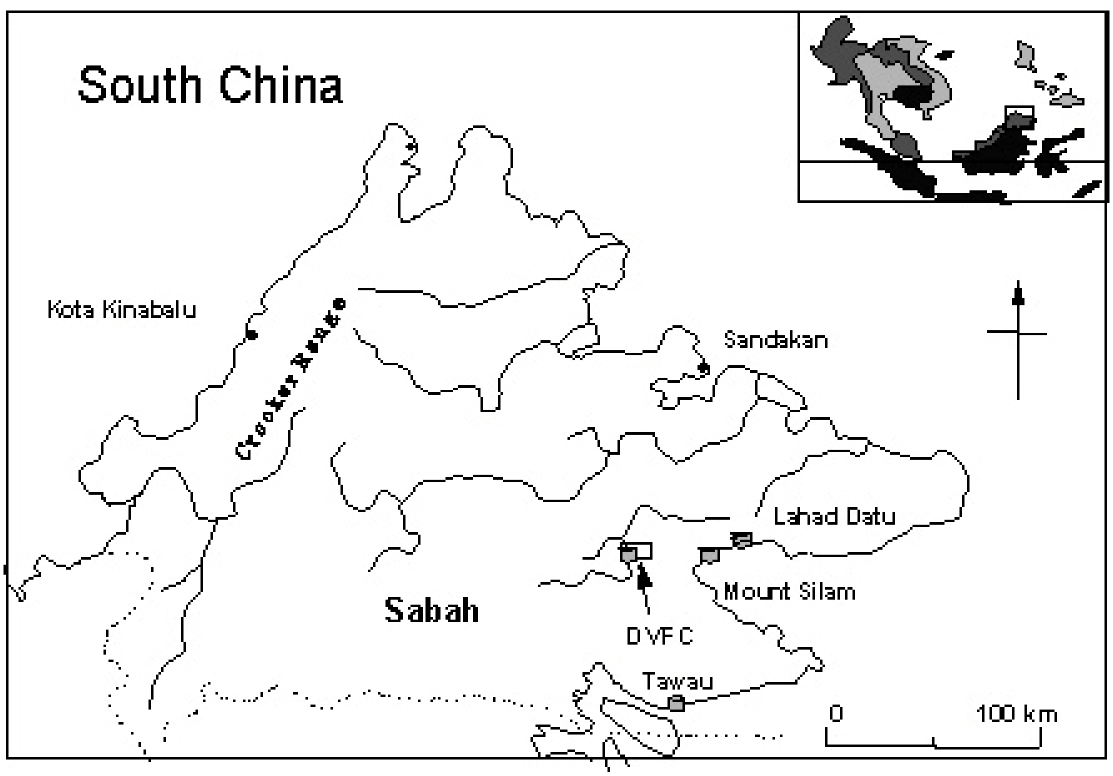

Figure 1. Map of Sabah. The Baru experimental catchment is based at the DVFC area.

For the purposes of this project the data from three sites were utilized. Particularly, site 1 represents the whole Baru catchment (0.441 km^2, main river) and therefore significant contribution from the other sites regarding the overland flow and the suspended sediment concentration is expected. Site 6a (0.0003 km^2) is a small site which has been significantly influenced by the haulage road that had been constructed there during the logging period (figure 2). Particularly, the incorporation of site 6a in this project offers the opportunity to illustrate the environmental impacts from the human activities in the area and this can be well achieved if a comparison with the behaviour of site 3b (0.0006 km^2) which is a small-scale undisturbed slope will be attempted (figure 2).

METHODS

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

In this project a single-input single-output (SISO) Transfer Function model (TF) has applied on the data. This concerns 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).

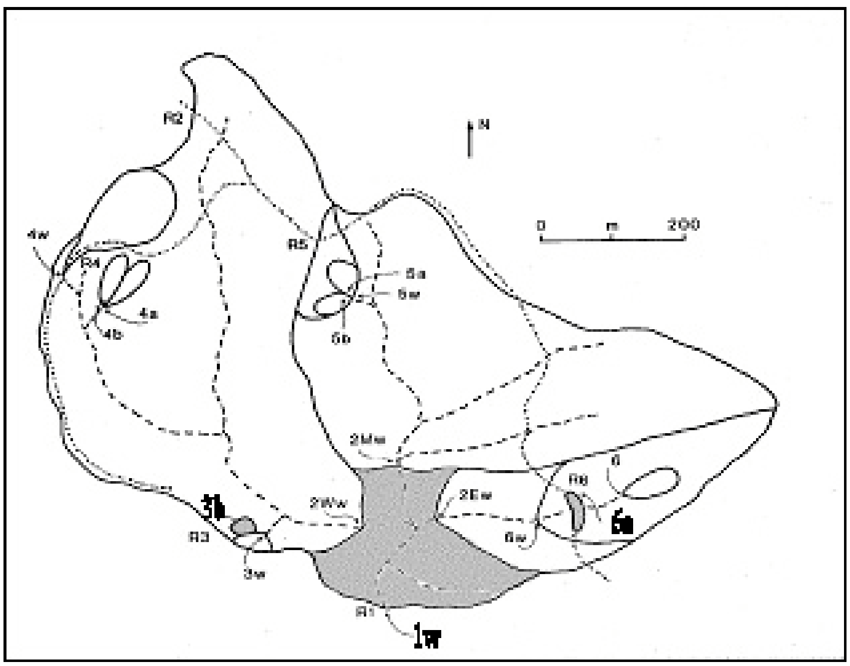

Figure 2. Map of Baru catchment and the sites of the project

The general equation that describes the model is:

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

Equation (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:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + ... + a_n z^{-n}$$
$$B(z^{-1}) = b_o + b_1 z^{-1} + b_2 z^{-2} + ... + b_m z^{-m}$$

Equation (2)

Consequently, it can be seen that there are only two parameters incorporated in this model (A and B) and this will facilitate the physical interpretation of the modelling results and will eliminate the danger of over-parameterization. Additionally, the Transfer Functions (TF) models have been widespread, successfully used and thus there is significant literature on their characteristics, which further increases the credibility of these models.

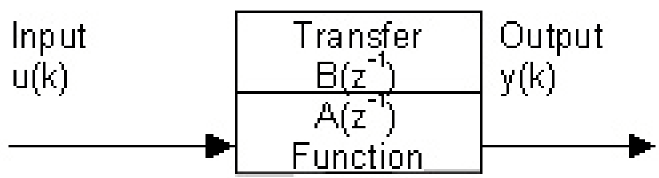

Figure 3. Single-input, single-output Transfer Function (TF) model.

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:

$$R_T^2 = 1 - (\sigma^2/\sigma_y^2)$$

Equation (3)

Where σ^2 is the variance of the model residuals and $\sigma_y{}^2$ 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:

$$YIC = \log_e(\sigma^2/\sigma_y^2) + \log_e\{NEVN\}$$

Equation (4)

Where NEVN is the normalised error variance form (Young and Beven 1994).

Furthermore, a first-order, linear modelling approach has been attempted in the first place to illustrate the possibility of explaining the hydrological system of the area with the simplest available model but the results indicated the demand for more sophisticated solutions. Consequently, the need for incorporation of the non-linearity in the models has been apparent and thus non-linear filters have been applied to the inputs of the models.

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

$$u(k) = S(k)r(k)$$

Equation (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 contributes in taking into account the water storage effects in the produced model which is a pragmatic thing to do since soil moisture comprises a crucial factor for the hydrological regime of the area as it has been illustrated in the qualitative observational stage of the project. This is reassured during the modelling procedure since the efficiency of the models increase significantly with the incorporation of the ‘effective rainfall’ approach.

Furthermore, another non-linear filter has been used in the input of the model under study in order to overcome the prevailing non-linearity of the system and compare its results with the ‘effective rainfall’ ones. Particularly, Young and Beven (1991) proposed a ‘bilinear’ model by taking under consideration that the overland flow is a low-pass filtered rainfall itself. Thus, they used the output of the model to transform the input:

$$S(k) = S(k-1) + \frac{r(k) - S(k-1)}{tc}$$ **Equation (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.

It can be stated that the main feature of the ‘bilinear model’ is that attempts to adjust the rainfall data to approach better the overland flow data at each moment. Therefore, the 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 further down in this study but careful interpretation of their results should take place since it probably introduces a deterministic aspect in the modelling procedure.

At this point it should be stated that a proportion of 26.9% of the data series had been used to identify the models, in order to maintain the possibility to evaluate them by applying them to the rest of the data series in a latter stage. Additionally, during the modelling procedure, the parameters of the model, (a) and (b) have been estimated, as well as the time constant (TC) and the steady state gain (ssG). Particularly, parameter (a) provides a picture for the response of the output to the input while parameter (b) offers a measurement of the productivity of the system as concerns the output. Furthermore, the time constant (TC) describes the lag-time between the input’s and the output’s peaks and finally the steady state gain (ssG) is a normalized index for the system’s productivity since parameter (b) is often relatively constrained. After having completed the identification of the models, a careful interpretation of the produced results will be attempted and a description of the hydrological characteristics of the area will be presented.

RESULTS

The average rainfall for the examined period is 2,896.7 mm annually (table 1) and it can be seen from figure 4 that there is a great variation in the data, with lots of storms and sudden changes from light rains to heavy ones. This is expected due to the tropical climatic type of this region which presents significant fluctuations in the weather conditions. The most significant extreme events in the examined time period include the 74 mm rainfall of the 21st October 1995 and the 37 mm rainfall of the 16th February 1996 which illustrated the highest intensity (11.64 mm/5min) for the entire recording period (table 2).

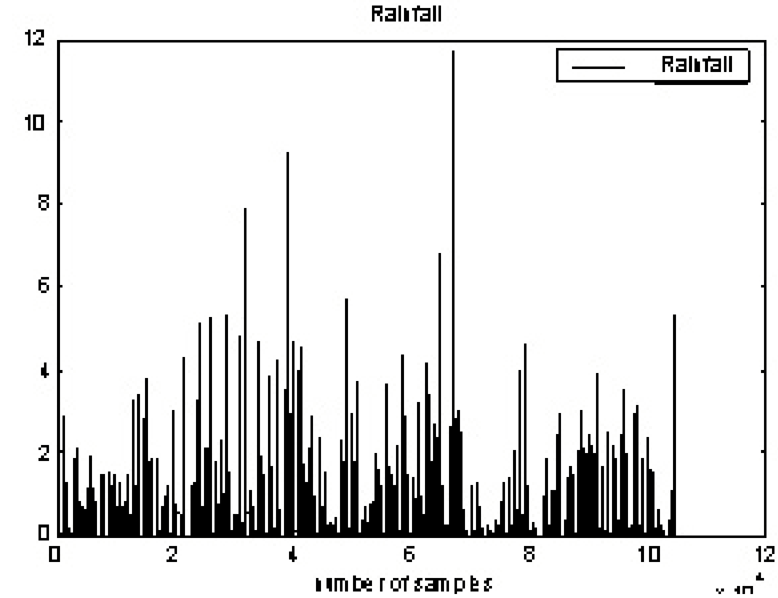

Figure 4. Rainfall data series (5 minutes data, in mm)

Discharge is an important factor in this area since it mostly determines suspended solids flux and affects many significant environmental processes. Specifically, the discharge in site 1 is expected to be much higher than in the other sites, for both instantaneous measurements and annual water flow, since site 1 represents the catchment scale site with the main river of the area while sites 3b and 6a are low scale subcatchments. Indeed, the average instantaneous discharge in site 1 is 0.059 $m^3s^{-1}km^{-2}$ while in site 3b it is 0.0013$m^3s^{-1}km^2$ and in site 6a it is 0.0047 $m^3s^{-1}km^{-2}$ (table 1). The higher value of site 6, in relation to site 3b, is observed possibly due to the haulage road that exists in this site directing to the decrease of the area's infiltration capacity. Furthermore, the annual discharge in site 1 has been recorded to be $1.87*10^6$ m^3km^{-2} (1867 mm) while has been $3.19*10^4$ m^3km^{-2} (31.87 mm) in site 3b and $7.78*10^4$ m^3km^{-2} (77.79 mm) in site 6a (table 1).

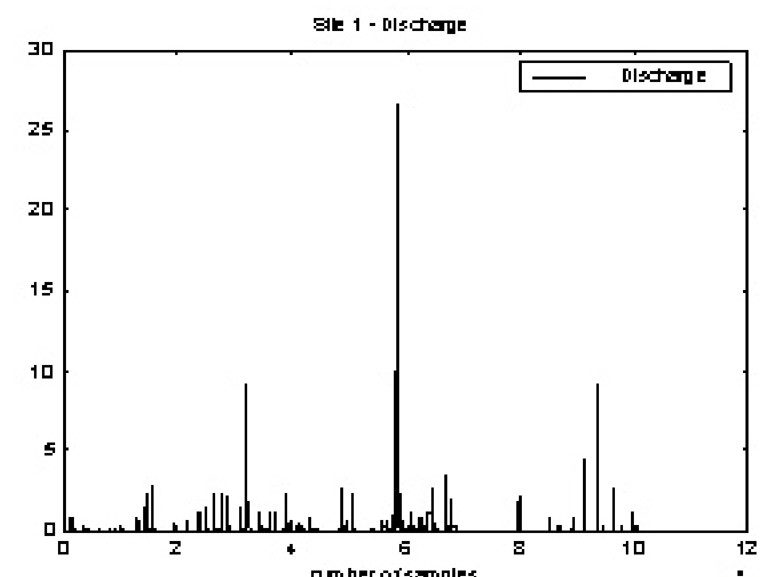

Figure 5. Instantaneous discharge ($m^3s^{-1}km^{-2}$) at site 1

As far as the extreme events are concerned, the most significant is the 19th January 1996 event that produced a vast amount of surface runoff in site 1 accounting for 11.18% of the annual discharge of this site [$2.0872*10^5$ m^3km^{-2} (208.72 mm)] and $9.812*10^3$ m^3km^{-2} (9.812 mm) of water for site 3b which is 30.78% of the annual value (table 2).

The annual SS-flux for site 1 is 261 tonnes (592 t/km^2) while for site 3b the respective value is 0.015 tonnes (24.83 t/km^2) and for site 6a is 0.030 tonnes (98.75 t/km^2, table 1). Furthermore, regarding the average suspended sediment flux values, in site 1 the measurements indicated 0.0187 kg/s/km^2 of SS-flux, while in site 3b the respective value was 0.0011 kg/s/km^2 and in site 6a it was 0.0060 kg/s/km^2 (table 1). The relatively high SS-flux values in site 1 (figure 5) are expected since there is perennial flow in this catchment scale site. The most extreme event of this parameter has also been recorded in 19th January 1996 when 238.52 t/km^2 (105.19 tones) of SS-flux were measured which constitutes 40.29% of the annual SS-flux. In site 3b the most extreme event occurred in 9th November 1995 since 17.40 t/km^2 of SS-flux have been measured (70.7% of the annual value) while in site 6a the 19th January 1996 event was the most extreme with 33.74 t/km^2 (0.01 tonnes) of sediment flux which comprises 34.17% of the annual value (table 2).

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^{3}s^{-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

DYNAMIC MODELING

Rainfall – overland flow modeling

Linear models.

Although there is non-linearity in the system rainfall-discharge as it has been mentioned before in this study, the results of the linear models are satisfactory. Particularly, site 1 model indicates a coefficient of determination (R_T^2) of 0.68 while site 3b provides a R_T^2 of 0.61 and site 6a offers a less efficient model with R_T^2 0.58 (table 3). The fact that site 1 model (figure 6) is more efficient than of 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 of the equipment. This put barriers in the models' efforts to correlate the undisturbed input with the disturbed output and therefore the efficiency of the produced models for these two sites is reduced.

Furthermore, parameter (a) indicates a very flashy response of the overland flow in site 6a and a less fast response for sites 1 and 3b (table 3). A reason that can partially explain this result is that the extent of the area plays significant role in the response of a hydrological element (overland flow) in a specific input such as the rainfall. Particularly, it is expected that in large-scale sites the response will be slower than in low-scale sites where the hydrological conditions can change very quickly. Nevertheless, in this case is not only a matter of extent since the differences in the parameter (a) are significant even for sites with similar size such as site 3b and 6a. Indeed, after examining the characteristics of each site another explanation can be produced for the increased value of parameter (a) in site 6a. Particularly, the haulage road that exists in the area influences in a great degree the hydrological behaviour of the area. This artificial construction increases the impermeability of the soil and therefore overland flow occurs soon after rainfall begins. This is a potential impact of human's interference to the local environment due to selective logging.

Moreover, by taking into consideration the steady state gain (ssG) it can be stated that site 1 has a great productivity (ssG=1.84, table 3) which is expected since it comprises the main river of the Baru catchment and acquires water supply from many other surrounding sites. The significant difference in this site's gain in relation to sites' 3b and 6a productivity possibly implies that the overland flow contribution from these sites is not adequate to explain the great ssG of the site 1 and thus there is also contribution of underground water in site's 1 overland flow. Furthermore, 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 extent of site 3b, indicates again that the haulage road has altered the hydrological regime of the area significantly.

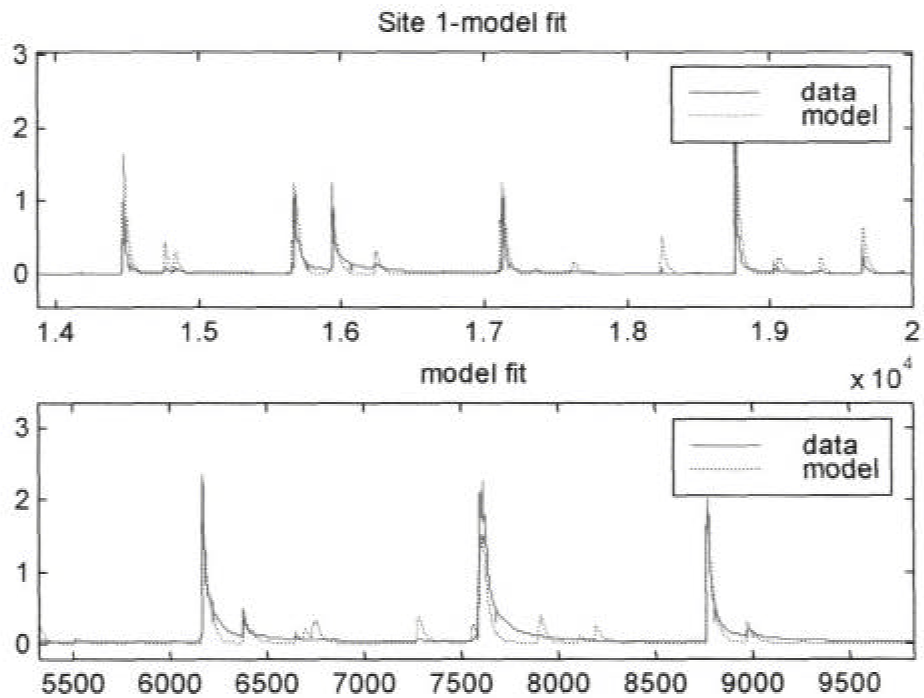

Figure 6. Rainfall-Discharge model fit for site 1.

Finally, the great time constant (TC=125 min) calculated for the site 1 is another indicator for the relatively slow processes that take place in the catchment scale sites such as site 1 while in the low scale sites the time constants are much lower (8min for site 3b and 3.3 min for site 6a) since the response in the rainfall is relatively immediate. Again, the extremely low time constant for site 6a illustrates the environmental impacts that the existing road causes in this site.

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

Effective rainfall models.

The 'effective rainfall' filter introduces the important concept of the soil water storage and therefore contributes in taking into account the non-linearity of the system. Thus, improved models with higher efficiencies are expected to be produced by using this filter in the input of the models. Indeed, this is the case since the coefficient of determination (R_T^2) 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). Consequently, it can be stated that a significant improvement in the models for the sites 1 and 3b took place while the efficiency of site's 6a model remained relatively low. Probably, this is due to the great number of missing data of this site, since 47.69% of the complete overland flow data series is missing. Thus, there is a significant disturbance in the model's identification procedure because the existing data are not able to describe adequately some events and as a result a model with relatively low efficiency is produced.

The interpretation of the results should have a different basis with these models, since the input is not the rainfall any more but the effective rainfall which incorporates the soil moisture aspect. Therefore, 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 type of respond of overland flow in relation to the effective rainfall in this case. Particularly, when the soil moisture is high, site 1 has a relatively slow response as concerns the overland flow while site 6a has a much more fast response and site 3b has a really flashy response. Several implications arise from this result since the recorded response times illustrate the natural evolution of overland flow appearance after maximization of soil moisture, which excludes the artificial constructions impact on the phenomenon.

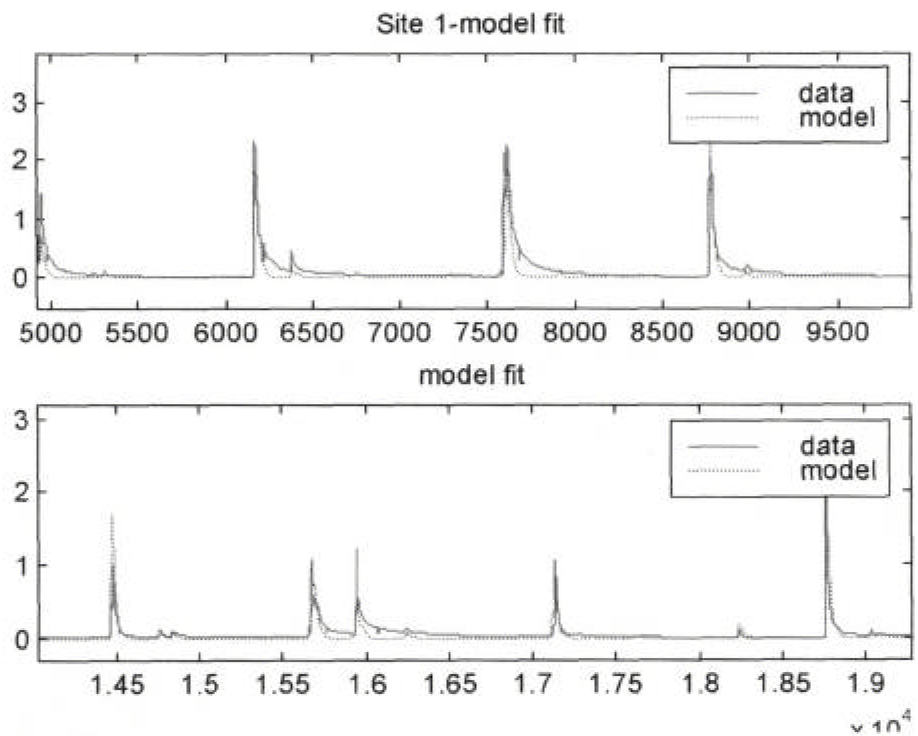

Figure 7. Rainfall-discharge model for site 1 (Effective rainfall filter).

Further, the steady state gain (ssG) in site 1 is 0.98 which comprise almost half of the respective value of the linear model (1.84). This indicates that there is significant contribution of the 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 site 1 (ssG=0.98, table 4) while only the rainfall component can not cause such an increased productivity recorded in this site (ssG=1.84 in 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). Additionally, this also implies that the soil moisture is probably high, especially in site 3b where the discharge comprises only the 5.8% of the effective rainfall and the response of the discharge is very flashy.

As far as the time constant (TC) is concerned, it can be stated that this is also reduced, something that is also expected since the effective rainfall is the dominating factor for the discharge development as it can be observed in relevant figures where overland flow peaks follow effective rainfall peaks within a short time delay. However, time constant remains much higher in site 1 (85 min) than in the other sites (3.7 min in site 3b and 8 min in site 6a, table 4) which is due to the large scale of this site in relation to the small scale sites 3b and 6a.

Furthermore, it can be argued that in site 6a the changes in the model properties (parameters, TC, ssG) from the linear to the non-linear approach do not follow the pattern of the respective changes in the other sites. Particularly, while in sites 1 and 3b there is a reduction in the values of parameter (a) and TC, in site 6a there is an increase of the respective values in relation to the linear model. This, probably illustrates that site 6a is not affected by the water storage regime as much as the other sites and that is because the haulage road is the most important aspect that determines the hydrological behaviour of this site.

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

Bilinear model.

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

The results of this modeling approach is 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 the site 6a (0.82, table 5). Nevertheless, it has to be stated that these results are expected since the bilinear model correlates strongly the input with the output and this may sometimes produce constrained outcome. Thus, careful interpretation of the results of this model should be also done to avoid drawing erroneous conclusions.

As far as the response of the discharge in the transformed input is concerned, it is about the same in site 1 (-0.95) as in the previous models which illustrates again a relatively slow response, probably due to the great extent of the site 1. Further, site 3b presents a substantially faster response (-0.54) which is similar to the one that has been calculated in the linear model (-0.53) and site 6a has the most flashy response (-0.48) which is significantly lower than of the linear model (-0.22, table 5). Nevertheless, 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) .

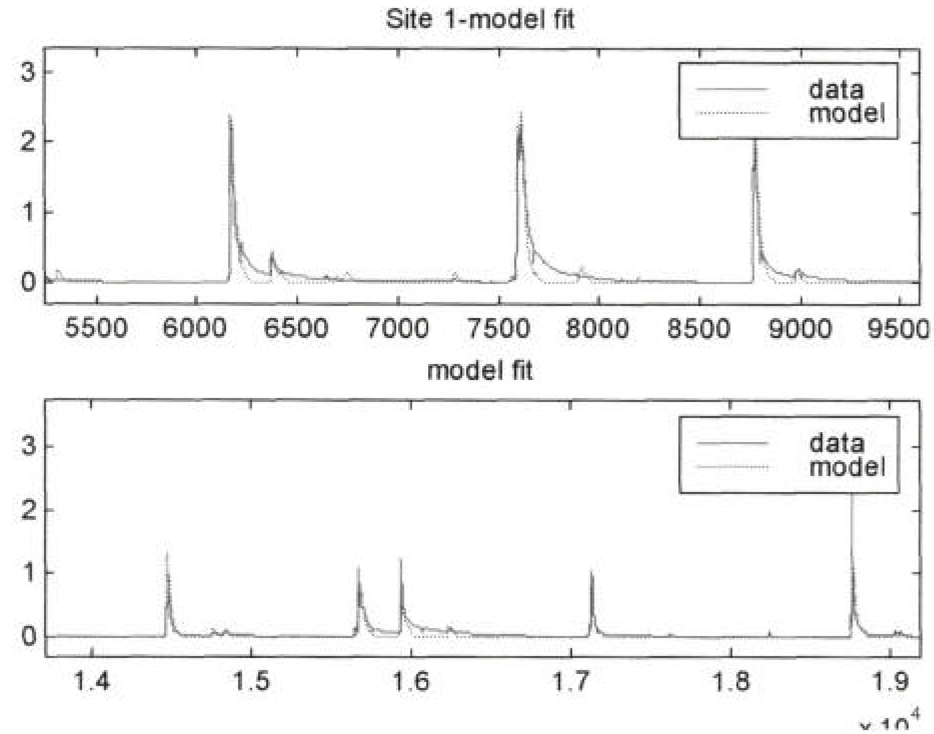

Figure 8. Rainfall-discharge model for site 1 (bilinear filter).

Particularly, 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 models' productivity. Moreover, the gain for site 1 is great (2.45) which implies that the specific input can not lead to the sites' increased productivity and therefore it can be concluded that some other hydrological factors contribute to the gain of the system (underground water possibly). On the other hand, in 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 that the haulage road causes in the area.

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 significantly in 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.

Table 5. Rainfall-discharge models (Bilinear approach).

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

Modelling rainfall-SSflux subsystem.

The rainfall-SSflux subsystem is a much more non-linear system than rainfall-discharge and this has been illustrated extensively in previous parts of this project. Consequently, the rainfall-SSflux models are not expected to be as efficient as the rainfall-discharge ones since the suspended sediment flux is influenced by many other factors except for rainfall, such as the regional geological properties, the extreme events and the soil moisture conditions. Thus by considering only rainfall as the model's input not very efficient results can be acquired. Nevertheless, this modelling approach is useful to be attempted since significant conclusions about the erosional behaviour of the area can be drawn.

Linear model.

As it is expected the efficiency of the linear models is very low and particularly 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). Therefore, these models cannot describe the system very well and subsequently are not appropriate neither for forecasting nor for credible conclusions. In order to increase the models' efficiency, second order models have been adopted but the coefficients of determination remained to the same low levels indicating once again the high non-linearity of the system (figure 9, table 6).

However, it can be said that the similar patterns that have been observed in the linear discharge model are followed in this model, too. Particularly, the response of the SS-flux to the rainfall is relatively slow for site 1 (a=-0.77) while it is faster in site 3b (a=-0.18) and it is extremely flashy in site 6a (a=-0.06). This behaviour of site 6a is probably because there is a lot of sediment available from the road that exists there and thus as soon as the rainfall begins, overland flow is formed quickly and motivation of sediment occurs soon after.

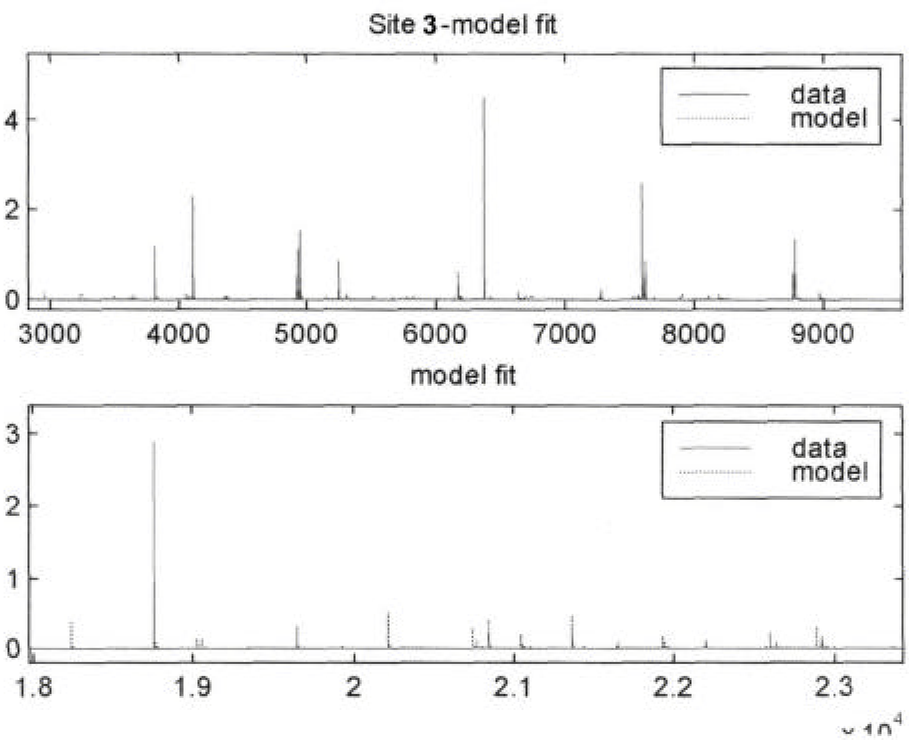

Figure 9. Rainfall-SSflux model for site 3b (linear approach).

Furthermore, as concerns 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 and this can be explained by the large amount of discharge that is recorded in this site as well as by the contribution of remote sources and events that have been observed (landslides, soil mass movements). The gain in site 3b is significantly lower (0.12) which is expected due to its low extent and limited amount of overland flow. Moreover, 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 site's 3b gain (ssG=0.62, table 6). This constitutes another piece of evidence for the substantial disturbance that the haulage road has caused in the environment of this area.

Finally, 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 lower. Particularly, the SS-flux peak is observed only

19.5 min after the rainfall's peak in site 1 while the respective time for site 3b is 2.8 min and for site 6a 1.8 mins (table 6). These time constants illustrate a flashier response of the SS-flux to the rainfall than of the discharge to the rainfall and this may be explained by the fact that sediment particles begin to move in the stage of infiltration and due to the subsurface flow while the overland flow is formed later on.

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

Effective rainfall model.

The incorporation of non-linearity in this system by using the 'effective rainfall' filter provided measurable improvement in the results of the models. Particularly, the coefficient of determination (R_T^2) for the site 1 is 0.498 while in the linear model was 0.175, and in site 6a is 0.31 while in the linear model was 0.135 (table 7). However, in site 3b there is not any significant improvement in the efficiency of the model which is probably due to the high number of SS-flux missing values since the gauging station had been damaged by an electrical storm during the measurement period in this site and therefore there is substantial bias in this model. Further, 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 can not correlate realistically the effective rainfall to the SS-flux.

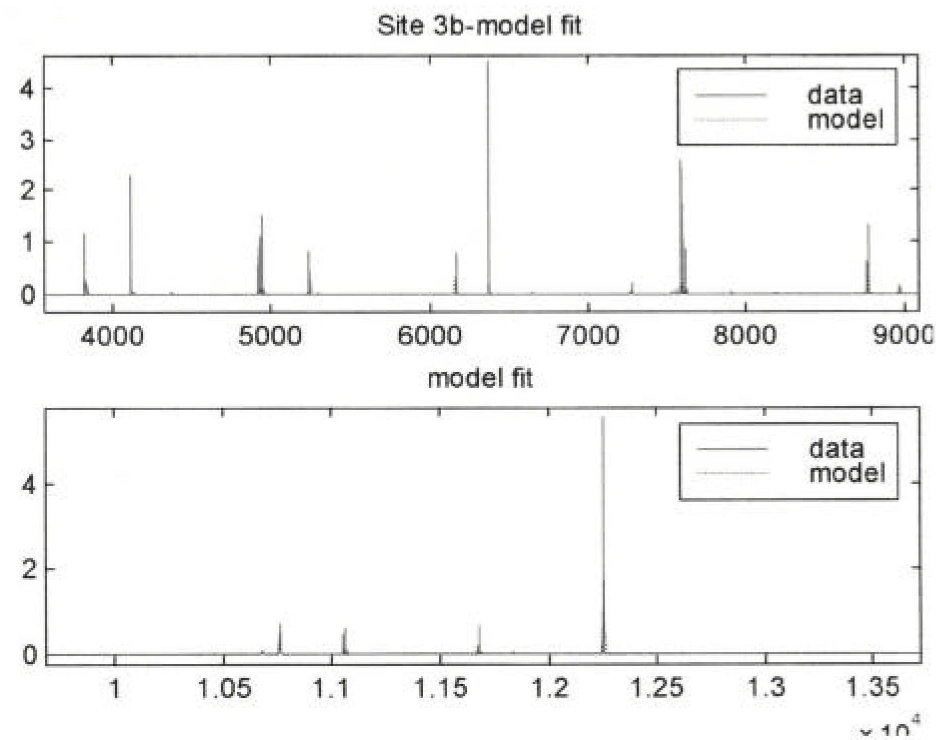

Figure 10. Rainfall-SSflux model fit for site 3b (Effective rainfall filter).

Nevertheless, useful information can be acquired by interpreting the results of these models. First of all, the pattern of the different sites' responses in the SS-flux remains about the same as in the linear model. Thus, site 1 presents a relatively slow response (-0.60) while site 3b has a more fast response (-0.39) and site 6a has an extremely flashy response (-0.06, table 7). At this point should be stated that even though a very detailed analysis of these models results cannot be done due to their low efficiencies, it is important to illustrate the changes of the parameters between the linear and the non-linear models and to compare them for the different sites.

Thus, it can be said that the steady state gain (ssG) is significant for site 1 (1.06), while 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 great amount of sediment available in site 1 and that the contribution of sediment from remote sources is also substantial to this site. Further, the productivity of site 3b is not large which is expected and finally the great SS-flux produced in site 6a comes possibly from the artificial construction of the area as mentioned before.

As concerns the time constants (TC), it can be argued that they maintain the pattern observed in the linear model but they have very different values in some sites. Particularly, in site 1 TC is significantly lower than in the linear model (9.89/19.5min) and in site 3b the non-linear time constant is a lot higher than in the linear model (5.35/2.89min). Probably, this is due to the different roles that soil water storage plays in these sites. In site 1 the soil moisture facilitates the SS-flux and therefore movement of sediment occurs soon after the water storage begin to increase while in site 3b seems that the soil moisture do not influence the SS-flux significantly. Again it has to be stated that further investigation and incorporation of other factors that influence the erosional behaviour of the catchment should be done in order to produce more efficient models and to be able to draw more credible conclusions.

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

Bilinear model.

The bilinear model provides a great improvement as concerns the efficiencies of the models which is expected since this filter defines the input by using the output component which increases their correlation significantly. Consequently, very careful interpretation of the results should take place since the input does not describe clearly any physical process in these models and therefore 'secure' inferences about the hydrological regime of the area cannot be made.

Nevertheless, it can be stated that the parameters in these models accredit the previous models results since they present the same patterns with the linear and 'effective rainfall' models (table 8). Further, site 1 has the slower response in relation to the other sites while site 6a has the fastest one. As far as the steady state gain (ssG) is concerned, it can be argued that again site 1 has the greater ssG while site 6a has the lowest one (table 8). The latter fact probably occurs due to a deficiency of the model since site 6a has a significant SS-flux production as it 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 modelling approaches.

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

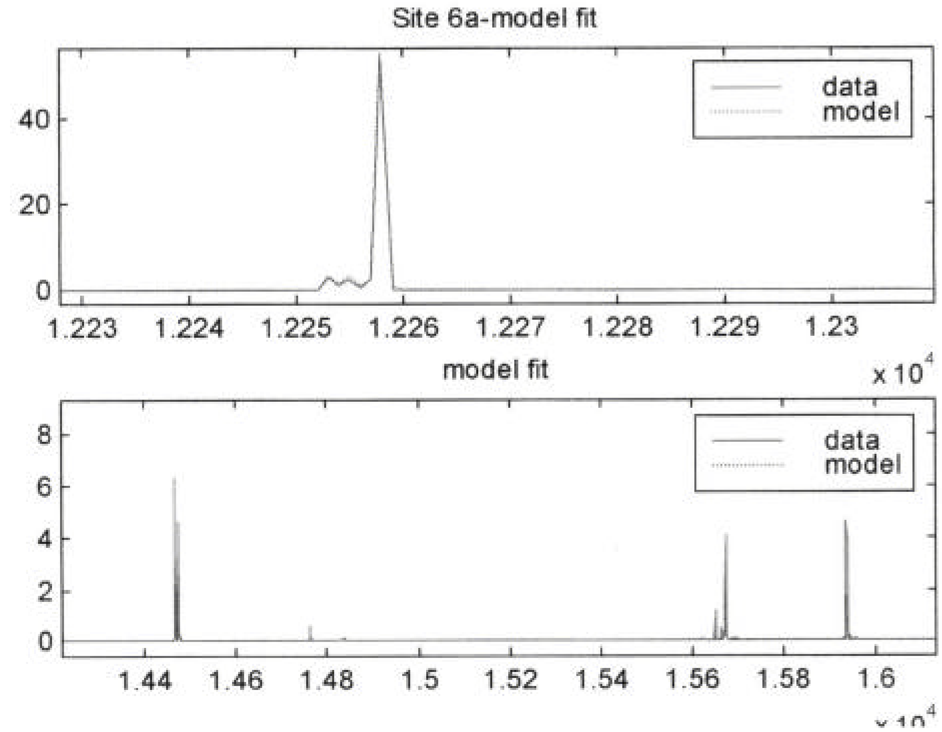

Figure 11. Rainfall-SSflux model fit for site 6a

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

At this point it should be stated that after the identification of all of the aforementioned models a calibration and evaluation process had taken place by applying the identified models to different parts of the data series. The produced results were similar to the original models' ones 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 high and that considering the available data, their results were satisfactory. Nevertheless, further efforts concerning acquiring more complete data series and better statistical elaboration of the data should be made in order to further improve these models and constitute them appropriate for reliable forecasting.

DISCUSSION

Non-linearity

During the modelling procedure as well as through the observational stage of the project an important aspect that became apparent concerned the non-linearity of the system. Particularly, several researches [Tong, 1990; Jakeman et al., 1990, Astakie et al., 1996] have pictured the substantial non-linearity that dominates hydrological processes such as overland flow and suspended sediment flux in relation to the rainfall. Moreover, in the qualitative observations of these parameters in various-scaling sites which have been analysed in this study, this non-linearity has been depicted by observing overland flow and SS-flux events without any respective rainfall to exist. This indicates that several other factors (such as soil/geological characteristics, underground flow and storage, soil moisture, etc.) influence these processes and make the relationships between rainfall-overland flow and rainfall-SSflux non-linear. Particularly, even though the regional rainfall-discharge subsystem presented non-linearity, mainly caused by the soil moisture conditions, the linear models used in this study presented high efficiency and described this process relatively well.

Nevertheless, in order to test various modelling approaches and achieve a solution to overcome the non-linearity problem non-linear filters to the inputs have been used as well as a higher order modelling effort wherever necessary. In addition, a careful interpretation of the models' results took place in order to avoid drawing erroneous conclusions and a qualitative study of the data was combined with the modelling procedure to accredit the inferences that have been made.

At this point, it should be stated that models' validity has been tested by applying different parts of the data series to the models and by comparing their parameters and efficiencies.

It should be mentioned that in the rainfall-SSflux subsystem the non-linearity has been recorded to be significantly higher than in the rainfall-discharge subsystem, an expected result, since the dynamics of the SS-flux phenomenon are influenced by a variety of factors while the interrelationship between rainfall and discharge is very strong. Furthermore, in the effective rainfall-SSflux models the efficiency was not high enough to provide credible results and therefore a careful physical interpretation of the models' parameters occurred. Finally, the bilinear model illustrated high efficiency, which is expected since the input is redefined with the use of output raising in that way constraints on the modelling procedure.

Discussion about the site specific characteristics.

By observing the models' parameters, it can be argued that the responses of the discharge and SS-flux are generally slower in the catchment scale site than in the smaller scale sites. This is expected, since the great rainfall events can easily affect local scale areas while they need significant time to initiate hydrological processes in the catchment scale site. However, the most important feature concerning the responses of the discharge and SS-flux in the examined sites is the 'anomaly' that site 6a presents. Particularly, site 6a has relatively fast responses to the aforementioned hydrological elements and this probably occurs due to the haulage road that has been constructed in the area during the selective logging period. Furthermore, the models' parameters indicate that responses in site 6a are almost twice as fast, concerning the discharge and SS-flux, than at site 3b even though site 6a covers only half the extent of site 3b. This enhances the haulage road impact concept since such constructions significantly affect the infiltration capacity of the area and provide a great source of sediment. Thus, it can be stated that the models' results and specifically the great differences between the parameters of the undisturbed site 3b and the parameters of site 6a illustrated some of the environmental impacts from the selective logging in the area.

The models' results also indicated significant variations in the sediment availability from site to site. Particularly, in 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. Additionally, the great SS-fluxes that have been observed during some extreme events imply the significant contribution of remote sediment sources such as landslides and mass movements during these events. Moreover, site 3b presents relatively a low productivity regarding the suspended sediment and this is mainly due to its small extent and to its characteristics including topography, geology and vegetation of the area. In contrast, site 6a illustrates high sediment productivity and this is mainly caused by the haulage road which alters the hydrological behaviour of the area significantly.

Respective observations, based on the models' results can also be made on discharge. In site 1 the measured discharge is very high since this site comprises of the main river of the catchment and a notable amount of its flow seems to be supplied by the other subcatchments of the area. Additionally, this is further accredited by the great steady state gain (ssG) that this site's model illustrates which is almost double the total rainfall and implies that the other sites contribute significantly to this site's increased discharge. Moreover, the measured discharge at site 3b is relatively low, probably because of an increased infiltration capacity which allow only great rainfall events to exceed it, and according to Horton (1933), to cause the overland flow. On the other hand, although site 6a is also a small scale site, the observed discharge is relatively high which is due to the disturbance that the haulage road causes. The road significantly decreases the infiltration capacity and thus overland flow appears more often and in larger amounts than in site 3b which implies potential danger for flooding and detrimental effects on the fauna and flora of the area (Price et al, 1996). Conclusively, it can be stated that once again the important environmental impacts from the man's intrusion in the area become apparent from this site's modelling results.

Additionally, it should be argued that an attempt to depict the amount of non-linearity that comes from infiltration in site 1 took place by considering the infiltration as the input of a model and the discharge of this site as the output. Particularly, the proportion of the water that had been infiltrated during the projects' period has been calculated by subtracting the discharge from the rainfall measurements in sites 3b and 6a. This is because the discharge measurements in these sites do not include the subsurface flow which is included in site's 1 measurements. The results of the infiltration models' were similar to the results of the linear rainfall-discharge model of site 1 and this illustrates that infiltration is not the crucial factor for the non-linearity in the system. Thus, the soil moisture is probably the element responsible for causing the high non-linearity that has been observed in the rainfall-discharge subsystem of this area and this notion is enhanced by the significant improvement of the models efficiency when the 'effective rainfall' filter was incorporated into their input (Merz et al, 1997). Consequently, if a more efficient model is essential for a forecasting perspective then the non-linearity of the system should be taken into account and measuring the soil moisture conditions would be an appropriate step.

Conclusively, it can be argued that the impacts from the haulage road that has been constructed in site 6a for the purposes of selective logging were significant since the hydrologic regime of this site has been altered in a great degree, which has been illustrated through the comparison with the parameters of the undisturbed site 3b. The sediment availability in site 6a has significantly increased, the amount of discharge recorded in this site is also great and the time response of the system to the rainfall is reduced in relation to site 3b. Also emphasis should be given at the fact that the models efficiency increased when the incorporation of the non-linear filters and particularly the 'effective rainfall' filter (Jakeman et. al.,1990) occurred, particularly in the discharge models while this filter did not cooperate well with the SS-flux models, probably due to their increased non-linearity. Moreover, the bilinear filter (Young and Beven, 1991) gave very good results for all the hydrological systems but its ability to produce unconstrained models is relatively low.

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