Hydrology and Earth System Sciences, 3(2), *285–294* (1999) © EGS

Hydrology & Earth System Sciences

A new approach for estimating suspended sediment yield

Rikard Lidén

Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden
e-mail for corresponding author: smhi@harare.iafrica.com

Abstract

A semi-distributed conceptual model, HBV-SED, for estimation of total suspended sediment concentration and yield at the outlet of a catchment was developed and tested through a case study. The base of the suspended sediment model is a dynamic hydrological model, which produces daily series of areal runoff and rainfall for each sub-basin as input to the sediment routine. A lumped measure of available sediment is accumulated continuously based on a linear relationship between log-transformed values of rainfall and erosion, while discharge of suspended sediment at the sub-basin outlet is dependent on runoff and amount of stored available sediment. Four model parameters are empirically determined through calibration against observed records of suspended sediment concentration.

The model was applied to a 200 km^2 catchment with high altitude differences in the tropical parts of Bolivia, where recorded suspended sediment concentrations were available during a two-year period. 10,000 parameter sets were generated through a Monte Carlo procedure to evaluate the parameter sensitivity and interdependence. The predictability of the model was assessed through dividing the data record into a calibration and an independent period for which the model was validated and compared to the sediment rating curve technique.

The results showed that the slope coefficients of the log-transformed model equations for accumulation and release were much stronger than the intercept coefficients. Despite an existing interdependence between the model parameters, the HBV-SED model gave clearly better results than the sediment rating curve technique for the validation period, indicating that the supply-based approach has a promising future as a tool for basic engineering applications.

Introduction

Research on soil erosion and sediment transport modelling is today focused mainly on the development of distributed models where the transport processes are described by physical or conceptual equations (Lørup and Styzcen, 1996; O'Connell and Todini, 1996; Summer *et al.*, 1998). Distributed models are needed to gain a better understanding of the processes causing soil erosion and sediment transport and, furthermore, they are requisites for assessing the effects of changes in land use or erosion control practices.

However, in most engineering applications the problem of soil erosion and sediment transport is restricted to estimating long-term average values for design and management purposes, e.g. addressing future siltation of reservoirs or total amount of material transport to river mouths for pollution control. The long-term average values are most often needed for an arbitrary point in a river system with a catchment area of the order of hundreds or thousands of square kilometres. On this scale, detailed data on hydrology, meteorology, geology and land use are generally scarce, especially in developing countries where sediment yield estimates are frequently needed because of the large and rapid expansion of the infrastructure.

The use of distributed models under these conditions is extremely difficult since the limited available data do not allow the model to be distributed to a level where enough homogeneity is obtained in each cell. To solve the problem, the models must be adapted to available data coverage (Fleming and Al Kadhimi, 1982) and to the spatio-temporal scale of investigation (Caussade and Prat, 1996). In most applied cases, this means the use of lumped empirical models as for example the Universal Soil Loss Equation (e.g. Wischmeier and Smith, 1978) or the sediment rating curve (e.g. Gregory and Walling, 1973). The shortcomings and uncertainty of these model approaches have, however, been pointed out in many studies (e.g. Wischmeier, 1976; Walling, 1977; McBean and Al-Nassri, 1988) and much research has been directed to improve the USLE and sediment rating curve techniques and applicability (e.g. Williams, 1975; Mizumura, 1989; Renard *et al.* 1991; Jansson, 1996).

This paper describes an approach to estimate total suspended sediment (SS) yield based on a combination of simple hydrological modelling and the concepts behind both the USLE and rating curve techniques. The key idea is to simulate soil erosion with the aim of estimating the amount of mobilised sediment within a catchment, which is available to be flushed out at the outlet through a rating curve equation. The importance of the temporal variations in sediment availability has been shown in several studies (e.g. Walling and Webb, 1982; Bathurst *et al.*, 1986) and the supply-based approach proposed in this paper is similar to the one proposed by VanSickle and Beschta (1983), who described the sediment concentration, $C(t)$, during a single storm event as

$$C(t) = \alpha Q(t)^{\beta} \cdot g[S(t)] \qquad (1)$$

where $Q(t)$ is discharge, S is a storage variable, $g[S(t)]$ is the washout function, t is time and α, β are empirical coefficients. The use of a positive valued function $g(S)$, i.e. decreasing concentration as S decreases, gives possibilities to describe the hysteris effect most often found for SS concentration and runoff (e.g. Walling, 1977; Williams, 1989). Previous researchers have used the supply-based concept to model SS transport in small catchments (e.g. Moore, 1984; Kelly, 1992) and VanSickle and Beschta (1983) obtained very good results when applying Eqn. (1) to simulate SS concentration for single storm events in a small catchment in Oregon.

To estimate the sediment supply to the system between storm events, VanSickle and Beschta (1983) used a lumped input to reset the storage variable prior to each storm. The suggested alternative solution is to introduce continuous modelling of mobilised sediment accumulation and SS discharge based on daily rainfall and runoff simulated by a semi-distributed hydrological model with moderate input data demands. The objectives of the present paper are therefore to describe the HBV-SED model, which has been developed to simulate daily SS concentration and yield based on the above suggested ideas, and to assess the model structure and model performance through a case study in the tropical parts of Bolivia.

The HBV-SED model

The HBV-SED model is based on the hydrological model HBV-96 (Bergström, 1976, Lindström *et al.*, 1997), which produces continuous series of hydrological input data to the sediment yield routine. The HBV-96 hydrological model can be defined as a deterministic, conceptual and dynamic model. Model inputs are causally related to the outputs through simple equations that describe the major processes in water transport and free model parameters are empirically determined through calibration against observed river flow data. The model is run with a daily time step in a semi-distributed mode with sub-basins as the basic unit. Input data demands in a tropical climate are daily point rainfall, average monthly potential evaporation and daily runoff data for calibration purposes. Areal averages of the climatological data are computed separately for each sub-basin by a simple weighing procedure where the weights are determined by climatological and topographical considerations or by some geometric method like the Thiessen polygons.

Despite the model's rather crude distribution and conceptual equations, internal model variables such as soil moisture deficit and ground water fluctuation have been validated against observed data (Bergström and Sandberg, 1983; Andersson, 1988) and the model has proved to work well as a base for simulations of dissolved material transport (e.g. Arheimer and Brandt, 1998; Lidén *et al.*, 1999). A more detailed description of the HBV-96 model structure and applications is found in Lindström *et al.* (1997) and Singh (1995).

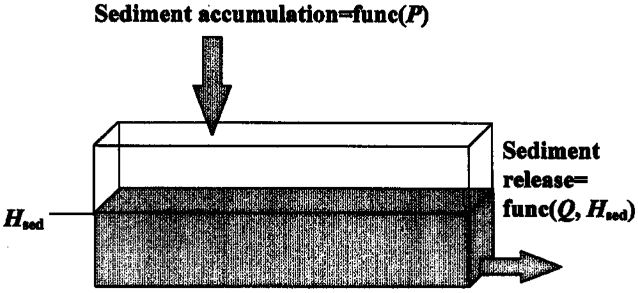


Fig. 1. *Basic structure of the suspended sediment yield routine in the proposed model approach. P denotes rainfall, Q denotes runoff and* H_{sed} *denotes catchment sediment storage.*

The HBV-SED sediment yield routine uses daily areal precipitation and river runoff for each sub-basin as input data from the hydrological model. It consists basically of two parts, an accumulation and a release routine (Fig. 1). The accumulation of available sediment in each sub-basin is a function of the areal precipitation in the sub-basin:

$$SS_{acc} = aP^{b} \qquad (2)$$

where SS_{acc} (tonnes day^{-1}) is accumulated mobilised sediment, P (mm day^{-1}) is areal rainfall and a (tonnes mm^{-b} day^{b-1}) and b (dim. less) are empirical model parameters. A linear relationship between the log values of sediment production and effective rainfall has been shown by e.g. Singh and Chen (1981) and Banasik and Walling (1996). Equation (2) also resembles the versions of USLE, where P^{b} represents a variant of the rainfall factor and a represents a lumped measure of the soil erodibility, slope length, slope steepness, land use and control practice factors.

The accumulation routine is run continuously adding mobilised sediment to the total sediment storage, H_{sed} (tonnes), that is available to be flushed out, while the release routine discharges suspended sediment yield, SS_{yield} (tonnes day^{-1}), at the outlet of each sub-basin according to:

$$SS_{yield} = H_{sed}\left(\frac{Q}{\mathrm{c}}\right)^{\mathrm{d}} \quad \text{if} \quad Q < \mathrm{c} \tag{3}$$

$$SS_{yield} = H_{sed} \quad \text{if} \quad Q \geq \mathrm{c} \tag{4}$$

where Q (mm day^{-1}) is runoff and c (mm day^{-1}) and d (dim. less) are empirical model parameters. Equations 3 and 4 can be described graphically (Fig. 2), where **c** is the upper limit when the whole sediment storage is discharged within one time step and **d** describes the shape of the curve when $Q \leq \mathrm{c}$. The same function is used in the HBV-96 model to describe the relationship between rainfall and recharge from the unsaturated soil zone and has proved to be very robust (Bergström and Graham, 1998). The function is also similar to Eqn. 1 (VanSickle and Beschta, 1983) with $\alpha = \mathrm{c}^{-\mathrm{d}}$, $\beta = \mathrm{d} - 1$ and $g(S)=H_{sed}$.

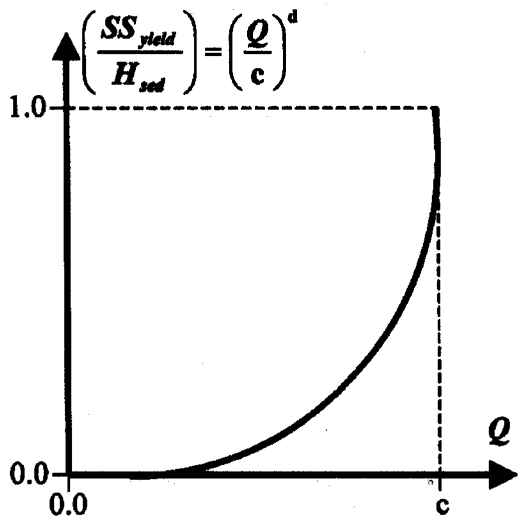


Fig. 2. *Graphical description of the release function for suspended sediment yield.*

Equations 2–4 can be linked together by introducing a time variable, t (days), which gives the differential equations:

$$\frac{dH_{sed}}{dt} = \mathrm{a}[P(t)]^{\mathrm{b}} - H_{sed}(t)\left(\frac{Q(t)}{\mathrm{c}}\right)^{\mathrm{d}} \quad \text{if} \quad Q < \mathrm{c} \tag{5}$$

$$\frac{dH_{sed}}{dt} = \mathrm{a}[P(t)]^{\mathrm{b}} - H_{sed}(t) \quad \text{if} \quad Q \geq \mathrm{c} \tag{6}$$

which can be solved numerically for each sub-basin in a catchment. In the present model version, the SS_{yield} for all sub-basins are summed each day to get the total yield for the whole catchment, thus assuming no further deposition in the main river channels.

Model application and evaluation

The HBV-SED model approach was tested using data from the Locotal river catchment located on the eastern slopes of the Bolivian Andes (Fig. 3). Total catchment area is 200 km^2 and the altitude ranges from 1700 to 4200 m a.s.l. The topographical features are dramatic with deep gorges, high ridges and steep slopes. Climatologically the area can be defined as tropical, with high temperatures and high amounts of precipitation. The precipitation is seasonal with a rainy season between October and April. The geology is characterised by four types of bed rock; quartzite, sandstone, mudstone and slates and the soil consists of thin moraine in the upper parts of the catchment where the quartzite dominates, while further down the soil becomes a mixture of glacial and fluvioglacial deposits. Human impact is very small in the catchment and the vegetation varies from very scarce in the upper parts to dense in the valleys.

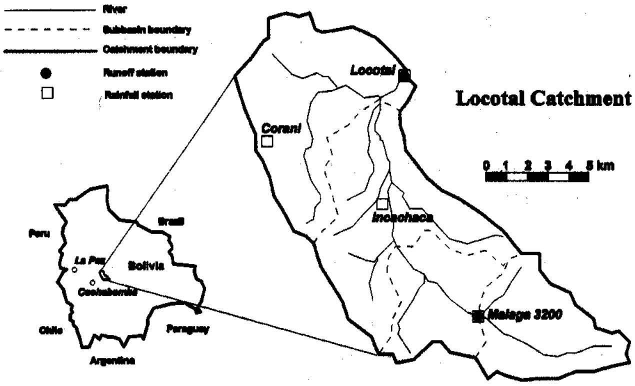


Fig. 3. *Map over the study area showing the location of hydrometeorological stations and the sub-basin division made for the HBV-SED model.*

Hydrological data from two runoff stations and daily rainfall data from four rain gauges were available (Fig. 3). The daily runoff values were based on continuous gauging of the water levels. Suspended sediment samples were taken with an US-D-49 depth-integrated sediment sampler at the Locotal runoff station during an intensive measurement campaign during the years 1972–74. During the high flow season, two samples a day were taken, while only one sample per day was taken during the low flow season. The mean concentration of the two samples taken during high flows was used as the observed daily values. Sediment samples were collected for 648 days during the period (Table 1).

The HBV-96 hydrological model was set up and calibrated for the two runoff stations, Malaga 3200 and Locotal, using the four rainfall stations as input data. The river catchment was divided into four sub-basins (Fig. 3) based on the location of the rainfall and runoff stations and

Table 1. Statistical description of the observed daily SS concentration data sampled during the period 1972–74 at the Locotal river flow station.

	SS concentration (g l^{-1})
No. of samples	648
Mean	0.537
Median	0.060
Std. Dev.	2.308
Min	0.000
Max	41.27
Skewness	10.98

the model parameters were determined through an automatic optimisation routine (Harlin, 1991), which was run for the period July 1967–June 1972.

To assess the HBV-SED parameter sensitivity and interdependence, 10,000 sets of model parameters were generated by a Monte Carlo procedure where the parameters were allowed vary in wide intervals ($0 < a < 4$, $0 < b < 3$, $20 < c < 60$, $1 < d < 7$). The parameter sets were used to perform 10,000 model runs for the period July 1972–June 1974, i.e. during the whole period with sediment sampling data. Model performance was determined through the explained variance, R^2, (Nash and Sutcliffe, 1970) for concentration:

$$R^2 = 1 - \frac{\Sigma(C_{\text{sim}} - C_{\text{obs}})^2}{\Sigma(C_{\text{obs}} - \bar{C}_{\text{obs}})^2} \tag{7}$$

and accumulated difference, *Acc. diff.*, between simulated and observed SS yield:

$$Acc.diff. = \frac{\Sigma(Q_{\text{sim}}C_{\text{sim}} - Q_{\text{obs}}C_{\text{obs}})}{\Sigma(Q_{\text{obs}}C_{\text{obs}})} \tag{8}$$

where C denotes SS concentrations, Q denotes runoff and the suffixes sim and obs denote simulated and observed respectively. To avoid effects from the choice of initial sediment storage, H_{sed}, the HBV-SED model was run from July 1967.

Model parameter sensitivity and interdependence were assessed in two ways: (i) through taking the best model performance and letting one parameter at a time vary, while the others were locked, and (ii) through computing a frequency diagram of parameter values, which give an 'acceptable' model performance when all the other parameters are allowed to vary freely. An 'acceptable' model performance was defined as $R^2 > 50\%$ and $Acc.diff. < \pm 20\%$.

The predictability of the HBV-SED model was evaluated through dividing the sediment data set into a calibration period, July 1972–June 1973, and a validation period, July 1973–June 1974, both covering one complete flow season. Like the parameter sensitivity analysis, the model was run from July 1967 to get a good initial state of H_{sed} and the best parameter set was then found by running 1,000 model runs for the calibration period where the model parameters again were generated through a Monte Carlo procedure. Best model performance was determined through a combination of R^2 and *Acc.diff*, similar to the suggestion of Lindström (1997):

$$R^2W = R^2 - ABS(Acc.diff.) \tag{9}$$

where R^2W denotes the volume-error-weighted explained variance and R^2 and *Acc.diff.* are defined in Eqns. (7) and (8) respectively. For comparison, the sediment rating curve for daily mean values was also optimised for the calibration period by the method of least squares for log-transformed SS concentration and total runoff. Because of transformation bias, which results in an underestimation of SS concentrations (Ferguson, 1986; Crawford, 1991), a non-parametric correction factor proposed by Duan (1983) was applied. The sediment rating curve was optimised both by using all data and by dividing the data into increasing and decreasing runoff. The relationships found between SS concentration and runoff were validated during the independent period.

Results and discussions

MODEL STRUCTURE AND PARAMETER VALUES

The HBV-96 hydrological model gave an explained variance of 0.88 and a volume error of –4% between simulated and observed total runoff for the two-year period with sampled SS data. Totally 3,413 HBV-SED parameter combinations (Fig. 4) of the 10,000 generated gave an explained variance for SS concentrations greater than zero, i.e. describing the variation better than the mean value (Nash and Sutcliffe, 1970). Figure 4 shows the importance of including the volume error in the optimisation process

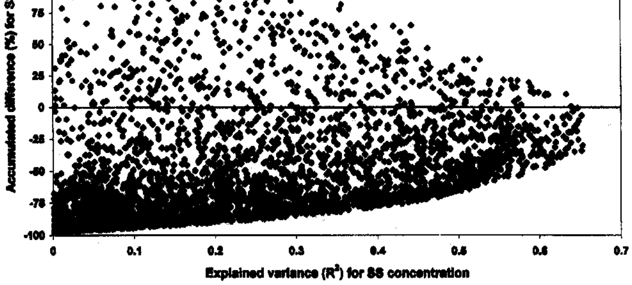


Fig. 4. *Scatter plot of the model result based on the 10,000 model runs with parameters generated through a Monte Carlo procedure. The graph shows all results where the explained variance (R^2) for SS concentration was greater than zero.*

since a R^2-value very close to the optimum value may give up to 50% error in the total simulated SS yield.

The best parameter combination obtained based on the whole SS data set was

$$SS_{acc} = 0.91P^{1.02} \tag{10}$$

$$SS_{yield} = H_{sed}\left(\frac{Q}{27.5}\right)^{5.29} \tag{11}$$

which explained 65 % of the variance in observed SS concentration and underestimated the SS yield by 7%. The direct sensitivity analysis where one parameter at a time was allowed to vary (Fig. 5) indicated that the **a** and **b** parameters were the most sensitive for estimating the SS yield. Assuming that sooner or later all eroded material, which has been mobilised, is flushed out at the outlet of a catchment, it is logical that the erosion parameters are the most important for long-term average SS yield. For the temporal variation, however, the discharge parameters should be more sensitive, which is also indicated in the upper graph in Fig. 5. On the other hand, the fact that a change in the erosion parameters, especially the **b** parameter, gave a large effect on the explained variance for SS concentrations indicates that the sediment availability is essential also for the temporal variation.

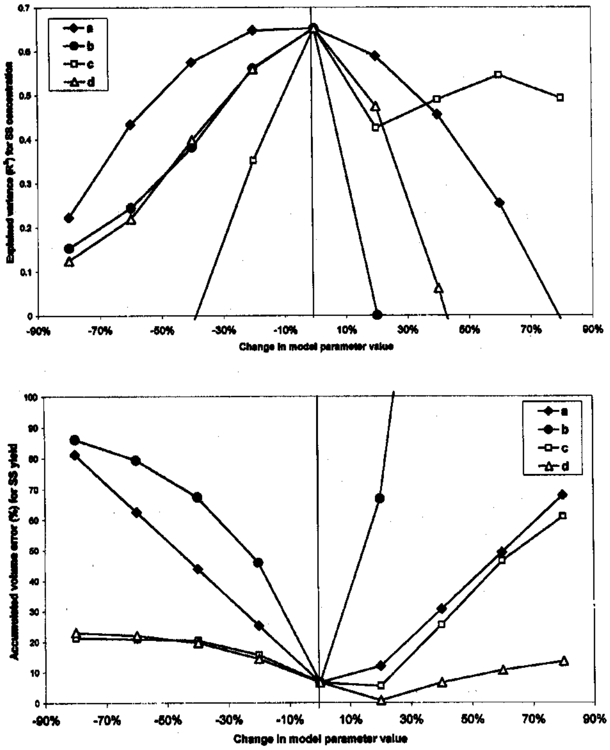


Fig. 5. *Sensitivity analysis of the four model parameters calculated through letting one variable vary while the others are locked on the maximum performance.*

Even if Fig. 5 implies that the optimum parameters found were fairly unambiguous, the very opposite is shown if the parameters are allowed to vary freely when the individual sensitivity of one parameter is assessed (Fig. 6). The existence of interdependence, as seen between the HBV-SED parameters, is inevitable to some degree in all empirical models, which emphasises the importance of using a correct optimisation procedure to find the 'best'parameter combination. From Fig. 6 it can be seen that:

- Parameter **a** is a superfluous parameter in the HBV-SED model since, in principle, any value of **a** may give an 'acceptable' model performance by tuning the other parameters.
- The optimum of parameter **c** is not well defined for values greater than 24 mm day^{-1} even if the highest frequencies are found around 30 mm day^{-1}.
- Parameters **b** and **d** each have a rather distinct optimum, indicating that the slope is superior in importance compared to the intercept value in the log-transformed functions of Eqns. 2 and 3.

Investigating the model parameters in more detail, by help of a global calibration procedure, revealed that **a** is superfluous because of a strong interdependence with parameter **b**. This indicates that the **a** parameter could be omitted from Eqn. 2.

The frequency distribution of parameter **b** contradicts the findings by Williams (1978), that source sediment production is proportional to the square of effective rainfall. Instead, sediment production in the Locotal catchment, according to Fig. 6, seems to be approximately linearly proportional to the effective rainfall assuming that total rainfall is almost linearly related to the effective rainfall, which is likely in a humid tropical climate. This result coincides well with the findings of Banasik and Walling (1996), who obtained a slope value close to one in the relationship between SS yield and effective rainfall for a 46 km^2 catchment in SW England.

The optimum values found for the slope parameter **d** (Fig. 6) fit well with the value of 4.75 (=3.75 in Eqn. 1) found by VanSickle and Beschta (1983) using a similar sediment discharge function. Comparing these values with the normal range (2.0 < **b** < 3.0) for the slope coefficient of the sediment rating curve (Morgan, 1986), indicates that the slope parameter becomes higher if the rating curve is combined with a sediment storage function. This was confirmed by the fact that the sediment rating curve relationship between the two-year SS yield and runoff data at Locotal had a slope value of 3.04. The reason for the higher slope coefficient is most probably that low SS concentration values during high runoff at the end of a storm event or at the end of the flow season can be explained by the sediment storage function instead of by the runoff alone.

Finally, the frequencies obtained for the parameter **c**, indicate that optimum values are found around 25–30 mm day^{-1}.

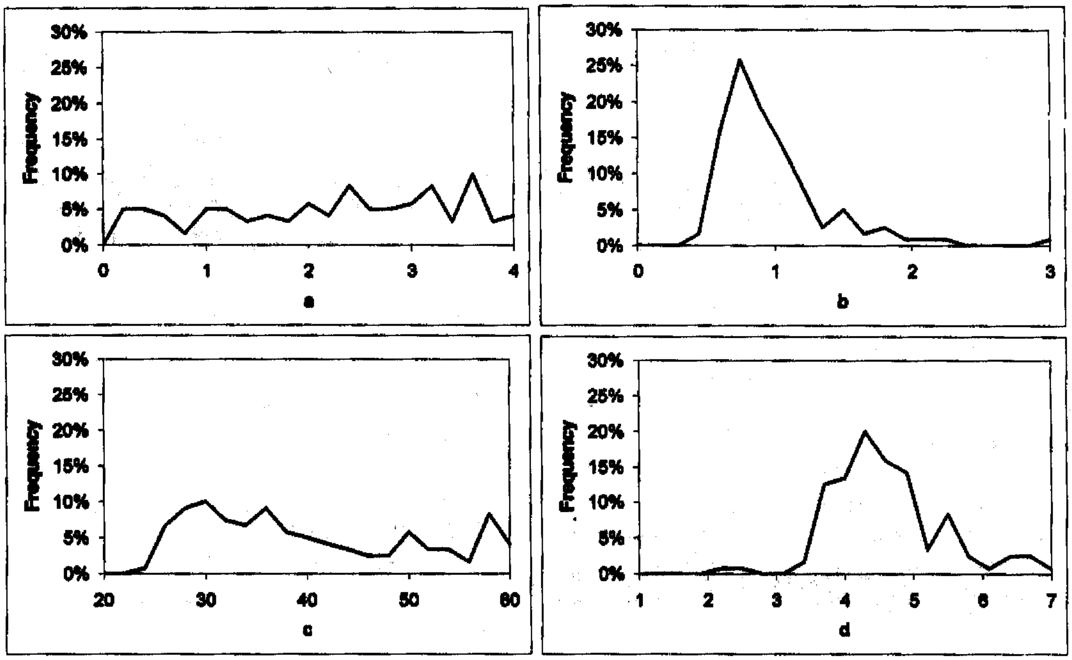


Fig. 6. *Frequency distribution of parameter values, which gives an 'acceptable' model performance if all other parameters are allowed to vary freely. The graphs are based on 10,000 model runs with parameters generated through a Monte Carlo procedure. An 'acceptable' model performance is defined as an explained variance (R^2) for SS concentrations greater than 0.50 and an accumulated difference between simulated and observed SS yield less than ±20%.*

This is even clearer if the 'acceptable' model performance is defined more closely, shown by the fact that the fifteen best model parameter combinations of the generated 10,000 all have $24 < c < 30$. This result is interesting because the Mean Annual Flood (MAF) for Locotal river is 27.8 mm day^{-1}, indicating that c is close to MAF. This means that the conceptually defined sediment storage, H_{sed}, is totally flushed out every second year on average, since MAF, by definition, has a return period of approximately two years. This is vital information since the ideal situation would be to cover at least two flush outs during the calibration period to estimate the HBV-SED erosion parameters accurately.

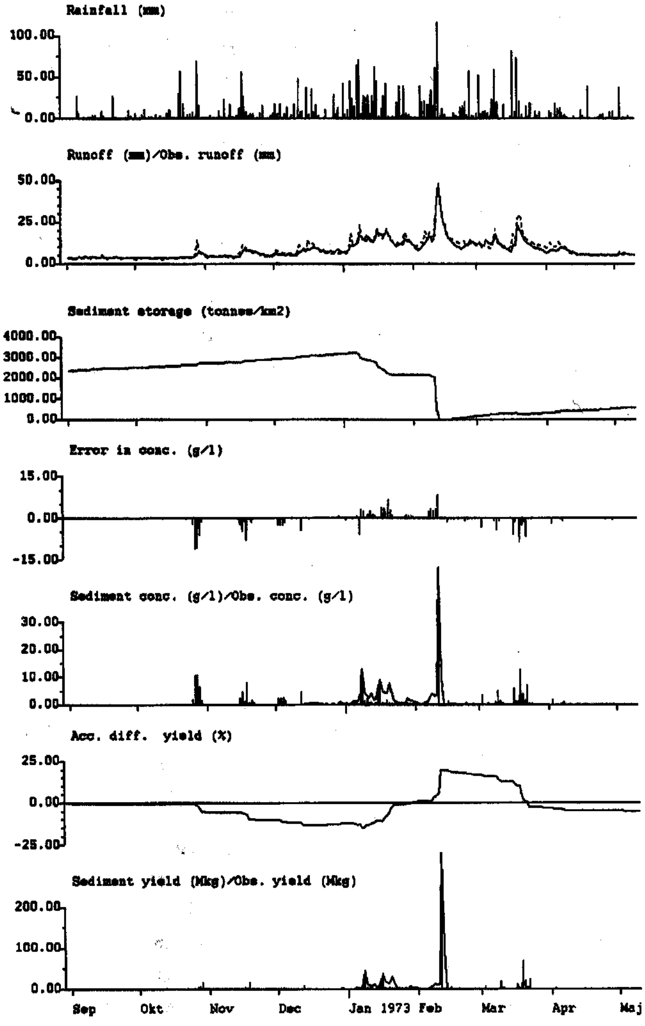
MODEL PREDICTABILITY

The comparison between the standard sediment rating curve technique and the HBV-SED approach (Table 2) shows clearly that the supply-based model approach gives better results both for the calibration and validation periods. The sediment rating curve technique performs especially poorly for estimating long-term SS yield; probably this can be traced to the problem of transformation bias correction, so that the results for *Acc. diff.* might have been improved by using other correction factors (Crawford, 1991).

Despite the better results for the HBV-SED model

Table 2. Coefficient of determination (r^2), explained variance (R^2) and volume error (*Acc.diff.*) for the calibration and independent validation periods using different methods to simulate sediment transport.

Model	Calibration 1972/73			Validation 1973/74		
	r^2_{conc}	R^2_{conc}	*Acc.diff.*	r^2_{conc}	R^2_{conc}	*Acc.diff.*
Sediment rating curve	0.27	0.26	+4%	0.19	0.09	+78%
Sediment rating curve (incr./decr. runoff)	0.33	0.21	+53%	0.14	−0.78	+133%
HBV-SED Model	0.70	0.64	−6%	0.45	0.39	+29%

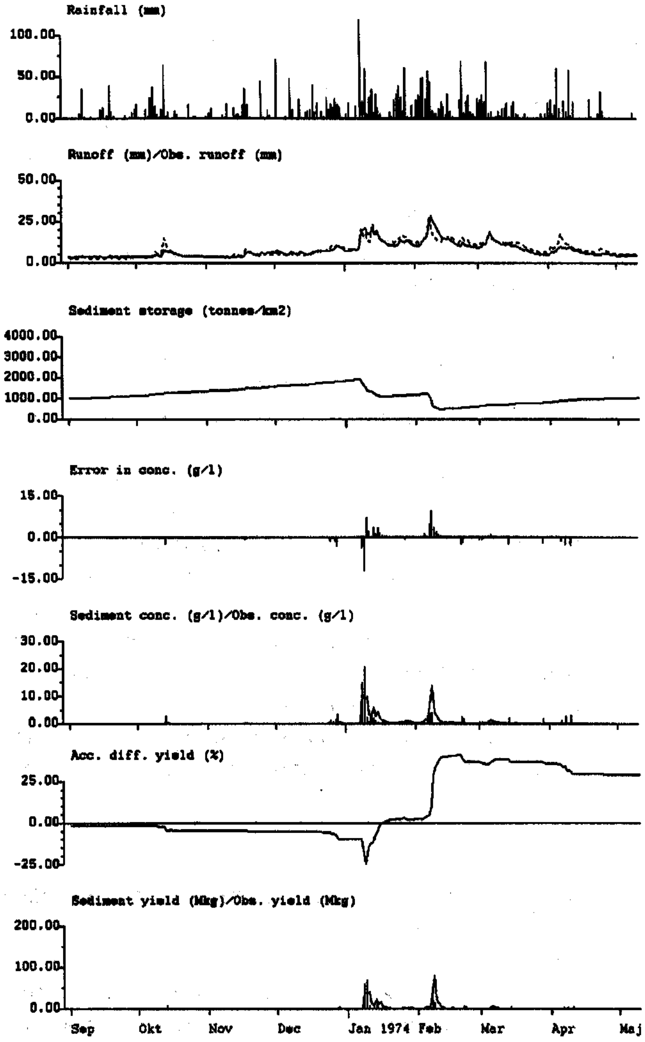


CALIBRATION PERIOD

Fig. 7. *Results of the HBV-SED model for the flow season during the calibration period. Observed SS concentration and yield are shown as bars while observed runoff is shown as a dashed line. Simulated SS yield is calculated from simulated runoff and simulated SS concentration, while observed yield is based on observed concentration and observed runoff.*

there is a significant decrease in model performance for the validation period compared to the calibration period, which also is seen when the model results are shown graphically (Figs. 7 and 8). This indicates that the one-year period for calibration was too short to obtain a generally good parameter combination, which is emphasised also by the fact that the model parameter set found (a = 3.31, b = 0.57, c = 32.2, d = 4.64) for the one-year calibration period differed from the one obtained if all SS data were used (Eqns. 10 and 11)

Furthermore, the accumulated difference between simulated and observed SS yield seen in Figs. 7 and 8 indicate a systematic error in the model performance, i.e. an underestimation during the start of the rainy season, followed by an overestimation during the high flows before the model again underestimates the yield towards the end. The main explanation of this systematic error is that the chosen model criterion used for the automatic calibration emphasises the peak in February 1973 at the expense of the low flow model performance. The problem of choosing a suitable criterion for calibration of conceptual hydrological models is well known (e.g. Bergström, 1991) and is relevant also for the proposed sediment model. In this case, the emphasis on peak performance is motivated by the fact that the flood peaks generate the bulk of the sediment transport in the studied catchment. Another explanation for the underestimation during the beginning of the wet season may also be that the sediment storage at this



VALIDATION PERIOD

Fig. 8. *Results of the HBV-SED model for the flow season during the validation period. Observed SS concentration and yield are shown as bars while observed runoff is shown as a dashed line. Simulated SS yield is calculated from simulated runoff and simulated SS concentration, while observed yield is based on observed concentration and observed runoff.*

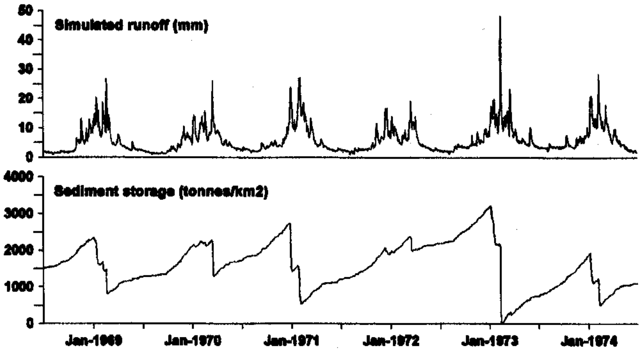


Fig. 9. *The simulated sediment storage for the period 1968 to 1974 based on the parameter set obtained by the automatic calibration using one year of sediment data.*

point is underestimated since no simulated accumulation occurs during the dry season.

In Fig. 9, the dynamics of the sediment storage can be seen for the whole simulated period, i.e. also for the period prior to 1972. In general, during the beginning of each wet season a net accumulation occurs, while the storage is depleted during the high peaks. The sediment storage is totally flushed out only once during the period and the amount of sediment stored prior to the large flood peak in February 1973 is a result of many years' accumulation. This fits well with the basic idea that sediment is mobilised during rainfall by splash erosion and/or surface runoff but is unable to reach the outlet of the catchment until a flow peak occurs and the sediment is therefore meanwhile deposited within or close to the river network system. However, since no data on riverine sediment transport were collected during the period prior to 1972, there is no possibility to confirm the accuracy in the simulated scenario.

On the other hand, the almost complete absence of sediment transport both in observed and simulated data after the high flow peak in February 1973 (Figs. 7 and 8) confirms the importance of sediment availability and that the proposed model approach manages to simulate this phenomena. Also during the validation period, the same phenomenon is indicated since the first flow peak causes higher sediment yield than the second although the second flow peak is higher. However, an increasing percentage of subsurface flow towards the end of the high flow season may also contribute to the pattern. Even if the HBV-SED model fails to describe fully the observed sediment graph, the simulated depletion of the sediment storage during the first peak reduces the error in simulated SS concentration and yield during the second flow peak.

Future perspectives and research

The above HBV-SED results indicate that the use of a hydrological model together with a supply-based approach to simulate SS transport has considerable advantages compared to direct simple empirical methods such as the sediment rating curve. Utilising a rather simple semi-distributed conceptual hydrological model as a basis for SS estimations meets the limited data coverage often encountered when assessing the sediment transport on a catchment scale and, furthermore, gives possibilities of simulating sediment yield based on both modelled runoff and SS concentrations. These advantages imply that the proposed model approach has a promising future as a tool for basic engineering applications. Future applications and research are, however, of importance to develop and validate the model continuously.

A major criticism of the proposed methodology may be the lack of connection between the model parameters and actual physical measures e.g. the specific location and accessibility of the sediment storage. It is, therefore, essential to note that the HBV-SED approach is not intended primarily to benefit research on deposition and remobilisation of sediment in river catchments, which is needed (Walling, 1988), but merely takes into account the importance of sediment storage within the sub-basin when simulating total SS transport at the outlet.

A framework for modelling erosion and sediment transport based on an upland catchment model, similar to this model, and an in-stream model for routing the Q and SS to downstream points have also been suggested by Green *et al.* (1998). The proposed HBV-SED model does not include any routing, i.e. deposition and resuspension, along the main river channels connecting different sub-basins, which probably must be taken into consideration when modelling transport in large river catchments. The relatively small catchment area for the catchment studied in Bolivia plus the large altitude differences within the catchment, most likely reduced the effects of main channel and overbank deposition. This is why the HBV-SED model gave good results despite the absence of model routines for this. A negligible sediment storage in the main channel of large river catchments was also found by Lambert and Walling (1986) and Atkinson (1995), indicating that river channel deposition has less importance than is generally believed. On the other hand, conveyance losses associated with overbank deposition probably can be very large, which is why the introduction and test of routines for sediment routing within the main river channels in the HBV-SED model is an obvious step in future development.

The evaluation of the HBV-SED model structure and parameters showed that the parameterisation of the model is not optimal. Ideally all model parameters should be independent of each other, which was not found for the proposed model structure. Future research on the parameterisation and alternative model equations is therefore important to identify the best model structure, which is essential in water quality modelling (Beck, 1983). Furthermore, the systematic underestimation of sediment yield at the beginning of the flow season implies that the processes during the dry season may also be important and that these need to be included in the model. The HBV-96 model used as the basis of the HBV-SED model gives an opportunity to include more hydrological variables e.g. effective precipitation, soil moisture deficit or groundwater fluctuations into the sediment routine.

A requisite for further research is, however, availability of long series of sediment data. Since the HBV-SED model, with its supply-based approach, simulates the memory in catchment sediment storage which stretches over several years, a correct evaluation of the model structure requires data records that cover a time period longer than the memory.

Acknowledgement

The Swedish Meteorological and Hydrological Institute (SMHI) funded the study and hydrometeorological data and sediment data were made available through Empresa Nacional de Electricidad (ENDE) in Bolivia. Thanks also to Prof. Sten Bergström for the initial ideas on the modelling approach and to Joakim Harlin for valuable comments on the manuscript.

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