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Dynamics of sediment discharge in relation to land-use and hydro-climatology in a humid tropical watershed in Costa Rica

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Abstract

Hydrology in humid tropical regions is often characterized by considerable natural variability and uncertainty. Hydrologic and land-use data from the Terraba basin in Costa Rica are used to analyze dynamics in sediment discharge processes during the period 1971–1993.

Time-series of log transformed sediment concentration and flow are analyzed with a Bayesian dynamic linear regression model (DLM) to detect changes in the sediment–flow relationship over time. Annual time-series of estimated sediment discharge based on the DLMs were regressed against various hydro-climatic variables based on the Southern Oscillation Index (SOI), rainfall, stream flow and rainfall erosivity. Hydro-climatic variables such as rainfall, stream flow and rainfall erosivity were also regressed against SOI. The results from the regression models, the presence of trends in the DLM slope and other hydro-climatic parameters for each sub-basin were used to compare the hydro-climatic and sediment response characteristics of the sub-basins.

Over 60% of the variability in hydro-climatic variables like rainfall, rainfall erosivity and stream flow is explained by SOI but less than 40% for sediment discharge measured at the basin mouth. The clustering of stations and sub-basins with respect to sediment discharge responses is different from that based on hydro-climatic characteristics. Stations or sub-basins corresponding to areas with large rates of deforestation and/or agricultural intensification and earthquake related soil disturbance tend to fall in one cluster. These sub-basins are characterized by an increase in the sediment–flow regression slope over time, and weaker relationship between sediment discharge and hydro-climatic variables such as SOI, rainfall and flow. In sub-basins undergoing rapid land-surface changes, variability in sediment supplies accounted for an estimated 50–90% of the variability in annual sediment discharge.

The methods described in this paper can be used to analyze many existing hydrologic time-series to detect land-use effects on watershed hydrology.

Keywords: Hydrology; Sediment discharge; Dynamic Linear model; ENSO; Land-use change; Costa Rica

1. Introduction

The sediment response of catchments is controlled by a complex function of ecological, climatic, and geomorphic processes. The fluvial regime of seasonally dry tropical basins is very dynamic due to intra-annual and inter-annual variability. The task of detecting and analyzing the impact of recent

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land-use and land-cover changes on the fluvial spatial and temporal dynamics is complicated by natural variability. The hydrology and sediment transport of tropical basins are usually more difficult to study than temperate basins because of insufficient data (Bruijnzeel, 1990), strong seasonality, and high intensity events. Quasi-periodic phenomena such as the El Nino–Southern Oscillation (ENSO) are some of the largest sources of inter-annual variability. In addition, extreme events can have lingering impacts, a good example being earthquake activity, which can influence sediment dynamics long after the direct seismic shock (Goswami, 1985). All these factors make it difficult to precisely estimate human disturbance impacts relative to those due to background natural processes.

Tropical forest conversion has been linked to several observed changes in fluvial regime. These impacts include increased surface runoff and increased sediment yield (Bruijnzeel, 1990, 1993). However, Bruijnzeel (1993) in a review of land-use effects on tropical humid basin hydrology and sediment yield noted the non-availability of adequately gauged catchments, the inability of most studies to account for large-scale weather patterns, and infrequent examples of rigorous statistical techniques.

Human impacts on larger basins (e.g. $>1000\ \text{km}^2$) with heterogeneous land-uses may be particularly difficult to detect. Strong spatial and temporal variation in tropical rainfall tends to mask effects of deforestation and land-use (Qian, 1983; Dyhr-Nielsen, 1986; Bruijnzeel, 1993). Sampling of high flows may be inadequate to detect effects of land-use on sediment yield, since large flushing events may mobilize massive amounts of sediment during unsampled periods. Moreover, as basin size increases, temporal lag between (on-site specific events and downstream effects) increases making linkages between land-surface processes and basin response difficult (Walling, 1983).

The Terraba River basin in Costa Rica offers a challenging opportunity to test our ability to detect and analyze changes in tropical hydrology and fluvial transport of sediment as a consequence of changing land uses that have occurred over a time-scale of several decades. Due to the occurrence of extreme rainfall events and areas of active seismic instability, natural erosive processes may mask the effects of human activities. However, the availability of several decades of hydrologic data including rainfall, flow and sediment concentration at multiple stations within one river basin is rare for the humid tropics (Bruijnzeel, 1988, 1990, 1993), and thus studies of the Terraba basin may make potentially important contributions to the science of tropical hydrology.

The use of dynamic linear model (DLM) methods in combination with other statistical and graphical methods in this study is motivated by its potential for capturing the complex hydrologic and fluvial dynamics of tropical humid basins.

2. Objectives

The objectives of this study were to:

1. Introduce DLM (Bayesian dynamic linear model) as a useful tool in studying dynamics of hydrology in general and tropical hydrologic systems subject to high natural variability and land-use change in particular. Analyze the temporal changes in sediment discharge in several catchments of the Terraba basin of Costa Rica over the period 1971–1993 using the DLM.
2. Demonstrate the estimation of a DLM based sediment discharge from sediment–flow time-series data that explicitly accounts for non-stationarity as an alternative to the use of static sediment-rating regressions applied to continuous flow data.
3. Relate these observed changes to land-cover/land-use change and inter-annual hydro-climatic fluctuations (ENSO) using the dynamic sediment discharge and other basin hydro-climatic variables.

3. Study area

The Terraba River basin (Fig. 1) drains an area of $4767\ \text{km}^2$ in the southern part of Costa Rica. Basin characteristics including land-forms, geology, soils, rainfall characteristics and land-use are described in greater detail elsewhere (Krishnaswamy et al., 2001; Krishnaswamy and Richter, 2001). A brief summary is presented here.

The Terraba basin is located in a structural depression

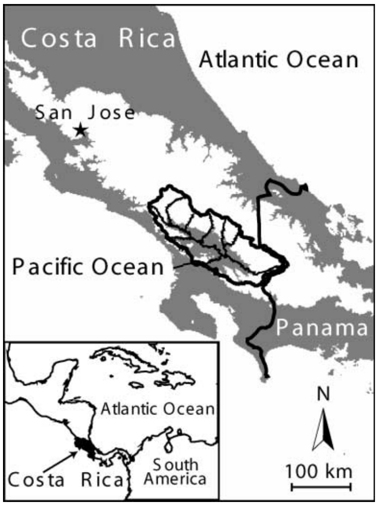


Fig. 1. Location of Terraba basin (thinner black line) within Costa Rica (thick black line) with major rivers in the basin marked. The Cordillera Talamanca and the Fila Costena (>300 m msl) are shown in white.

that continues into Panama and is bounded by the Fila Costena (Coast Range) on the south and the Cordillera de la Talamanca on the north. The maximum elevations of these two ranges are 1300 m (Cerro Canas Gordas) and 3819 m (Mt Chirripo), respectively. The Coast Range is composed of marine sedimentary rocks. The Cordillera de Talamanca are composed mainly of marine sediments and volcanic rocks. The highlands are characterized by steep slopes, and about 70% of the area above 300 m has >30% slope. The western and eastern portions of the valley are drained by the Rio General and Rio Coto Brus, respectively, which combine to form the Rio Terraba (Fig. 2).

Soil characteristics are correlated with landscape position and topography. In general, soils under protective vegetation are considered resistant to erosion and have rapid vertical drainage. However, the intense rainfall and forest conversion to cultivation and pastures makes them vulnerable to run-off and erosion.

Costa Rica is also seismically active and moderate and major earthquakes have caused extensive surface damage through liquefaction and landslide activity during intense rain events. This in combination with loss of forest cover and steep slopes has led to high rates of erosion and sediment discharge in parts of the Terraba basin (Mora, 1989).

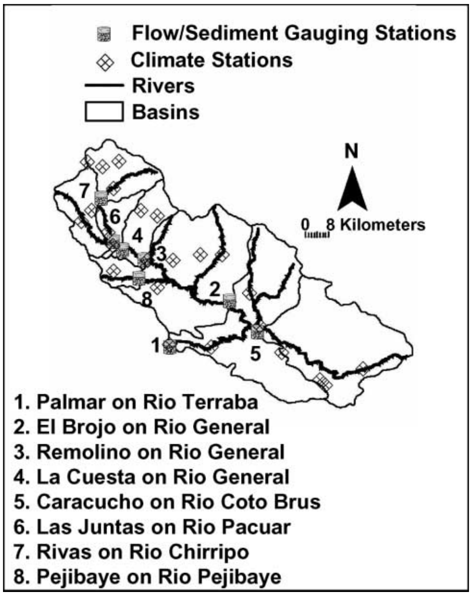


Fig. 2. Location of long-term smeteorological gauging and sediment sampling stations in the Terraba basin. There are eight stations for flow and sediment, 22 for rainfall and five for pan evaporation in all. Elevation is based on 1 km digital data.

3.1. Climate and hydrology

Climate in Costa Rica is described in detail elsewhere (Coen, 1983). The annual rainfall in the Terraba basin ranges from below 1500 to over 7000 mm and displays strong spatial, elevational and seasonal variations. The basin-wide rainfall averages $3139 \pm 418\ \mathrm{mm\ yr}^{-1}$ (mean ± standard deviation) based on 22 rain gauges operating between 1971 and 1988. The dry season (January–April) ranges spatially within the basin from one to five months, with 0–100 mm per month. In October, the wettest month, rainfall can exceed 1000 mm. The average pan evaporation is about $1233 \pm 71_{\mathrm{SD}}$ mm with a maximum of over 160 mm in March ($n = 5$, 1971–88 hydrologic years). The annual discharge of the Rio Grande de Terraba, Costa Rica's largest river, at the basin outlet (station at Palmar) for the period 1971–93 averages $2168 \pm 492_{\mathrm{SD}}$ mm. The runoff coefficient is therefore over 60% of annual rainfall.

The inter-annual precipitation pattern is influenced by the movement of the Inter Tropical Convergence Zone (ITCZ) (Portig, 1965). In addition, ENSO phenomena lead to considerable inter-annual variability. During years of high Southern Oscillation indices (La Nina), when the ITCZ is displaced northward, higher rainfall has been observed, with drier spells during El Nino years (Waylen et al., 1996). The Terraba basin's hydro-meterologic linkage to ENSO is one of the strongest in central America (George et al., 1998). Any particular hydrologic year can be categorized into one of three types: El Nino (drought), La Nina (wet) and normal, depending on the intensity of the ENSO forcing. Hurricanes are another serious perturbation that cause very heavy rainfall and massive flooding.

3.2. Vegetation

The Terraba basin has a wide range of natural ecosystems, a consequence of the diversity of geology, elevation, soil, landform and climate. Fire maintained Savannah-woodlands occur in the driest areas (Boucher et al., 1983; Kesel and Spicer, 1985). The less disturbed natural forests include 17 types (Soto and Gomez, 1993) ranging from lowland tropical humid forests to highland montane tropical forests and tropical boreal paramo with stunted shrub vegetation in the highest elevations (>3000 m).

3.3. Land use

Deforestation and human activities have substantially modified the vegetative cover of the basin. Except for protected areas such as the La Amistad Biosphere Reserve at high elevation, pastures have replaced the forest cover over about 80% of the basin area.

The Terraba basin experienced relatively rapid deforestation, expansion of cattle pastures and intensification of agriculture during the period 1960–1985. Dense forest areas (defined as >60% canopy cover) declined from about 75–80% of the basin area in 1961 to about 63% in 1972. By the early 1990s, only about 41% of the basin remained under dense forest cover, much of it restricted to high elevation areas falling in protected parks and indigenous reserves. Pasture expansion motivated by the export beef trade was the most widespread land-use change in the basin. While there was some secondary growth and recovery on cut-over lands, much of the clearing was of a permanent nature. Subsequently, some pasture areas were converted to row-crops. Sugarcane, coffee, corn, beans, and a variety of other crops and horticulture account for the cleared land. Intensive agriculture systems such as pineapple plantations were established and expanded in the 1980s often replacing former cut-over lands and pastures. This expansion was especially prominent on alluvial fans and river terraces at the foot of the Cordillera Talamanca.

Below La Amistad and other protected areas in the higher elevations, only small patches of forest remain intact. These serve as a reminder of the magnificent low-land forests that covered the basin barely half a century ago (Skutch, 1971).

4. Materials and methods

4.1. Rainfall and flow data

The quantity and quality of the data are primarily the result of a long pending hydro-electric dam first proposed by engineers in the early 1960s. All accessible monthly rainfall data (1971–1989) for 22 stations in the basin, collected by ICE, Costa Rica's national hydro-electric authority and IMN, the National Meteorological Institute of Costa Rica, were obtained from published bulletins (IMN, 1988; ICE, 1994a). Fluvial data were obtained from ICE, which runs the network of hydrologic monitoring stations in the Terraba basin (ICE, 1994b). These data included mean daily flow data in $m^3 s^{-1}$ for the eight nested gauging stations in the Terraba basin that spanned the period 1971–93 (Fig. 2 and Tables 1 and 2). These stations numbered 1–8 are identified in Fig. 2 and the independent sub-basins delineated from these stations (see Tables 1 and 2) are shown in the same figure. Monthly flow series were computed for independent sub-basins by mass-balance using the nested station data. Annual rainfall time-series for each of the stations was generated by averaging values for all stations upstream of a particular stream gauging station. Time-series of annual flow for each of the stations and sub-basins were obtained from the monthly values.

4.2. Peak flow data

The available records include maximum recorded instantaneous flow for each month as well, providing a useful time-series of peak flood flows across the

Table 1
Watershed characteristics and land-use change in sub-basins corresponding to gauging stations

Station	River	Elevation (station)	Area (km^2)	Rainfall (mm yr^{-1})	Flow (mm yr^{-1})	F/R	Forest cover (%)		Deforestation (% yr^{-1})	Agriculture (%) (in 1986–92)
							1972	1992		
Palmar	Terraba	13.06	4766.7	3043	2086	0.69	58.8	39.4	0.97	15.6
El Brujo	General	136.9	2401.2	2946	2199	0.75	44.8	30.2	0.73	16.5
Remolino	General	395	1075.5	3191	2347	0.74	36.5	30.8	0.29	7.3
La Cuesta	General	475	835.5	3301	2372	0.72	39.4	33.9	0.28	5.0
Caracucho	Coto Brus	98	1133.3	3346	1954	0.58	84.0	56.0	1.40	6.7
Las Juntas	Pacuar	490	322.7	2656	2086	0.79	18.5	15.0	0.18	0
Rivas	Chirripo	790	317.9	3719	2202	0.59	54.5	50.0	0.23	0
Pejibaye	Pejibaye	360	128	2096	1513	0.72	19.1	16.9	0.11	0

Terraba basin. The time-series of maximum monthly instantaneous flow recorded at each of the eight stations was used to examine trends in magnitude and frequency of peak flows. The 90 percentile for each station was computed, and all flows exceeding this value were plotted against time. The choice of the 90 percentile was based on experiences in previous studies in the humid tropics that indicate the following: land-use effects on peak discharges in tropical humid regions primarily affect the peak flows at the higher end of the distribution (Gilmour et al., 1982).

4.3. Rainfall energy data

Monthly rainfall energy was estimated as p_t^2/P, where p_t is the precipitation in month t and P is the average annual precipitation in the sub-basin over the entire period of record. The estimate used here is a modification of Fournier's erosivity index (Fournier, 1960). Annual rainfall erosivity was computed by the average of monthly values in a given year.

4.4. Sediment data

Monthly sediment concentration data, measured by depth integrated samples, were obtained for all stations, and these included some intensively sampled events. The sediment data set ranged between 242 and 299 samples per station for the period 1970–1993. Data collection at two of these stations (La Cuesta and Caracucho) was affected by flood and other events between February 1982–March 1984 and October 1988–April 1991, respectively.

The primary set of hydrologic stations included eight for stream flow and sediment, 22 for rainfall and five for evaporation. This hydrologic network (Fig. 2) is probably one of the best available hydro-climatic and fluvial sediment data sets for meso-scale basins in the humid tropics. This provides an important opportunity to examine hydrologic processes with

Table 2
Land-use change in Terraba Basin: Independent sub-basins located between nested gauging stations

Sub-basins	Station	River	Area (km^2)	Forest Cover (%)			Forest loss (% yr^{-1})	Agriculture (%) (in 1986–92)
				1972	1979	1992		
Changuena	Palmar	Terraba						
Cabagra, Limon			1233	63.0	60.0	42.0	1.05	22
Volcan, Ceibo	El Brujo	General						
Boruca			1198	55.0	32.0	31.0	1.2	26.5
Union	Remolino	General						
Pedro			240	26.5	NA	20.2	0.32	18.2
Penas	La Cuesta	General						
Blancas			195	49.3	NA	38.9	0.52	17.6

respect to their spatial patterns and temporal dynamics.

4.5. Southern Oscillation Index (SOI)

The time-series standardized values of the Southern Oscillation Index (SOI) were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2000). These were summed for each hydrologic year to obtain an annual SOI index.

4.6. Land-cover change

To estimate land-cover change through time, digital Landsat MSS data for 1979, 1986 and 1992 were processed and georeferenced to a common map projection. Supervised classification was used to identify forests, pastures and intensive agriculture. Details of the MSS land-cover data sets and classification are described elsewhere (Krishnaswamy, 1999a). Topographic maps of 1:200 000 and 1:50 000 as well as a published land-cover map (MIRENEM, 1988) covering the entire basin were used to obtain forest cover data. In addition, a published land cover (>80% canopy cover) map for the early 1970s (ICE, 1973) derived from aerial photographs was used as a baseline for the entire basin. Land-cover/land-use data from the mid 80s for three sub-basins, which were not adequately covered by the MSS images, were obtained from published sources (Calvo, 1998). The approximate land-cover/land-use change from the early 1970s to 1992 are shown in Tables 1 and 2.

4.7. Modeling basin sedimentation response

Land use and vegetation determine the land surface and soil conditions that control basin characteristics such as soil erodibility and susceptibility to run-off. Rainfall supplies the energy to dislodge available exposed soil. The transport capability as expressed in stream discharge controls the ultimate export of sediment from the basin. The dynamic sediment discharge from a basin can be modeled as a simple function of changing input hydrologic energy (rainfall erosivity), transportation capability (stream flow), and supply of erodible and transportable sediment. The change in supply can be associated with deforestation, subsequent land use, intensification of agriculture, as well as mass movement events such as earthquakes and land slides. All these contributing factors can vary in time leading to a non-stationary supply function for sediment.

Consider a data based regression between a measure of sedimentation (concentration or discharge) as a response variable and stream flow or some measure of rainfall erosivity as an independent variable. This typically could be based on log-transformed data. The regression coefficients (intercept and slope) can be considered as parameters unique to each sub-catchment expressing the sediment export characteristics of the basin. Consider the most common situation where log-transformed sediment concentration (C_t) is regressed against stream flow (Q_t) on some time-step:

$$\log_{10} C_t = A + B\log_{10}(Q_t) + \epsilon, \tag{1}$$

Let the intercept be called A and the slope, B. These parameters may reveal watershed and channel characteristics (Bogardi, 1961; Muller and Forstner, 1968; Piest and Miller, 1975; Arnett, 1979; Nolan and Janda, 1981; Mimikou, 1982; VanSickel and Beschta, 1983), including area, geomorphology, vegetation, and hydro-climatic factors.

B may be considered a measure of rate at which hydrologic energy is converted to geomorphic work (Rannie, 1978; Mimikou, 1982). Changes in B over time at a gauging station could be an indication of increasing sensitivity of the upstream watershed to hydrologic forcing. Many researchers (Arnett, 1979; Meade, 1982; Parker and Troutman, 1989; Lemke, 1991; Yu and Neil, 1994) have related parameter B to the availability of sediment in relation to available hydrologic energy. In a dynamic system, we can assume that changes in the watershed over time will tend to change estimates of parameter B over time.

In this paper, we fit a parsimonious regresssion model with parameters that are mechanistically realistic (Klemes, 1983; Troutman, 1985; Jakeman and Hornberger, 1993) and that evolve over time. This method uses the Kalman filtering equations and is known as a dynamic linear model (DLM). The method was introduced to hydrologic applications in both tropical and temperate systems (Krishnaswamy, 1999a,b; Krishnaswamy et al., 2000). Details of the DLM are available elsewhere (Pole et al., 1994; West and Harrison, 1997; Krishnaswamy, 1999b;

Krishnaswamy et al., 2000). Here a brief description is given.

We follow the basic procedure and consider dynamic linear models with observation equations using a monthly time-step:

$$\log_{10} C_t = A_t + B_t \log_{10} (\mathrm{FLOW}_t) + \epsilon_t \qquad (2)$$

In the DLM representation, consider the sediment system of Eq. (2):

$$Y_t = \log_{10} C_t = F_t' \boldsymbol{\theta}_t + v_t, \ \ v_t \sim N[0, V_t], \qquad (3)$$

where

$$F_t = (1, \log_{10} (\mathrm{FLOW_t}))$$

and

$$\boldsymbol{\theta}_t = (A_t, B_t).$$

In many applications, $V_t = V$, the observation variance is an unknown constant or changes very slowly with time, a situation often encountered in practice (Pole et al., 1994; West and Harrison, 1997).

The so-called dynamic aspect is modeled through the system equation.

$$\boldsymbol{\theta}_t = \boldsymbol{\theta}_{t-1} + \omega_t, \omega_t \sim T_{n(t-1)}[0, \mathbf{W}_t], \qquad (4)$$

where T is student t distributed random variable on appropriate degrees of freedom corresponding to progress in processing the time-series step by step and $\mathbf{W}_t$ is the dynamic covariance matrix. This equation is a deterministic relationship between parameter values at any time t to their values at time $t - 1$. The regression coefficient vector $\boldsymbol{\theta}_t = (A_t, B_t)$ performs a random walk about its previous level and its probability distribution is updated at each time-step using Bayes theorem:

$$p(\boldsymbol{\theta}_t | D_t) \propto p(Y_t | \boldsymbol{\theta}_t) p(\boldsymbol{\theta}_t | D_{t-1}), \qquad (5)$$

where D_t is the information available at time step t.

The observation and evolution equations together comprise the DLM. The covariance matrix $\mathbf{W}_t$ models the rate of change through time by the method of discount factor (West and Harrison, 1997). The discount factor δ is a number in [0,1]. Large values of δ model a process that changes slowly through time. In fact, $\delta = 1$ yields a process that is static through time and reduces to the usual linear regression model. Smaller values of δ lead to greater rates of decay of past information in relation to more recent data. Small values of δ model a process that changes rapidly. In the current study, the discount factors for the level A_t and the regression coefficient B_t were kept at 0.95 based on statistical correlation between similar variables in traditional rating curves and dynamic regression equivalents (Rannie, 1978; Krishnaswamy et al., 2000) as well on principles of conservative trend detection (Pole et al., 1994; Krishnaswamy, 1999a).

In this application A_t is interpreted as a dynamic regression intercept. In the current study, the regression slope B_t is however the parameter of interest. As discussed earlier, it is defined as the dynamic sediment coefficient, expressing the changing ability of a sub-basin upstream of a gauging station to convert available hydrologic energy into geomorphic work resulting in increasing sediment discharge.

In order to initiate the DLM, prior estimates of model parameters are required at time t_0. In the absence of informative priors from previous data, mechanistic intuition or expert opinion, two practical methods are available. One can fit a static model ($\delta = 1$), equivalent to ordinary regression that assumes no change in regression coefficients over time. The means and variances for regression parameters from this static model can be used to specify priors, along with a point estimate of the observation variance. The other alternative is to use reference analyses (Pole et al., 1994; West and Harrison, 1997). A small initial part of the time-series is used and the priors estimated. In this study, reference analyses were used to specify priors. To check sensitivity to priors we also used the static regression method and there was very little difference in the posteriors and especially the shape of the time-trend of the regression slope B_t, the main parameter of interest.

Once the one-step ahead estimates of the regression coefficients and their distributions, $p(\boldsymbol{\theta}_{t-k} | D_{t-k-1})$ are obtained, the retrospective probability distributions, conditional on all the data $p(\boldsymbol{\theta}_{t-k} | D_t)$ for all k, can be obtained through a backward recursive technique (Pole et al., 1994; West and Harrison, 1997). These estimates are particularly recommended when the objective is to assess historical changes in processes, rather than forecasting ability. In this study, only these 'smoothed' retrospective estimates of the regression coefficient and their 90% probability intervals (Fig. 3) are used. These Bayesian probability intervals give an unambiguous graphical and quantitative expression of uncertainty associated with the changes over time.

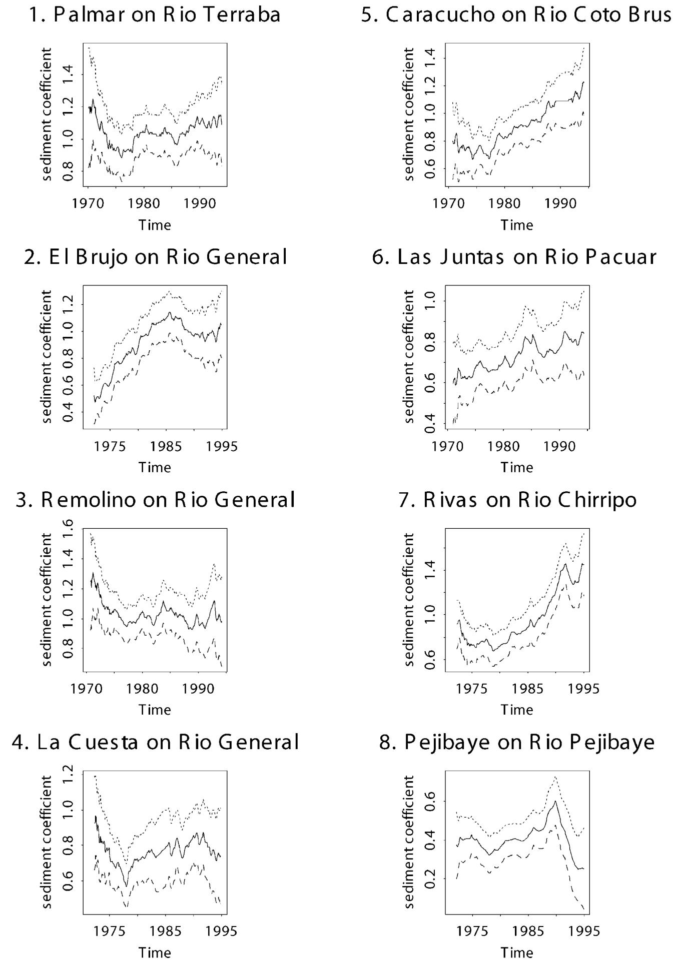


Fig. 3. Trends in dynamic sedimentation coefficients (B_t) with 90% probability intervals at gauging stations. These are the time-varying slopes in the DLM regressions: $\log_{10}$ (SEDC) $= A_t + B_t \log_{10}$ (FLOW$_t$) $+ \epsilon_t$ for the eight stations. The most significant change over time can be detected for station El Brujo, followed by Caracucho and Rivas.

Any significant structural changes or trends in the time-series of the posterior estimates of these parameters at each time-step could be indicative of change in the watershed or of hydro-climatic forcing. In addition, the impact of extreme events such as earthquakes or hurricanes on sediment–flow dynamics can be detected more easily compared to classical non-dynamic techniques. The changes in the parameters, whether abrupt or gradual can be interpreted mechanistically if the regression equation is a realistic, albeit simplified description of the hydrologic and sediment transport system.

Use of the DLM to detect environmental changes is an innovative application of the statistical method. Environmental related applications of DLM can be found in model structure identification and ecological modeling (Qian, 1997; Lamon et al., 2001). This paper emphasizes its utility as a useful tool in studying changes in complex tropical hydrologic systems.

4.8. Dynamic sediment discharge

The data situation most commonly encountered at gauging stations is the availability of continuous flow

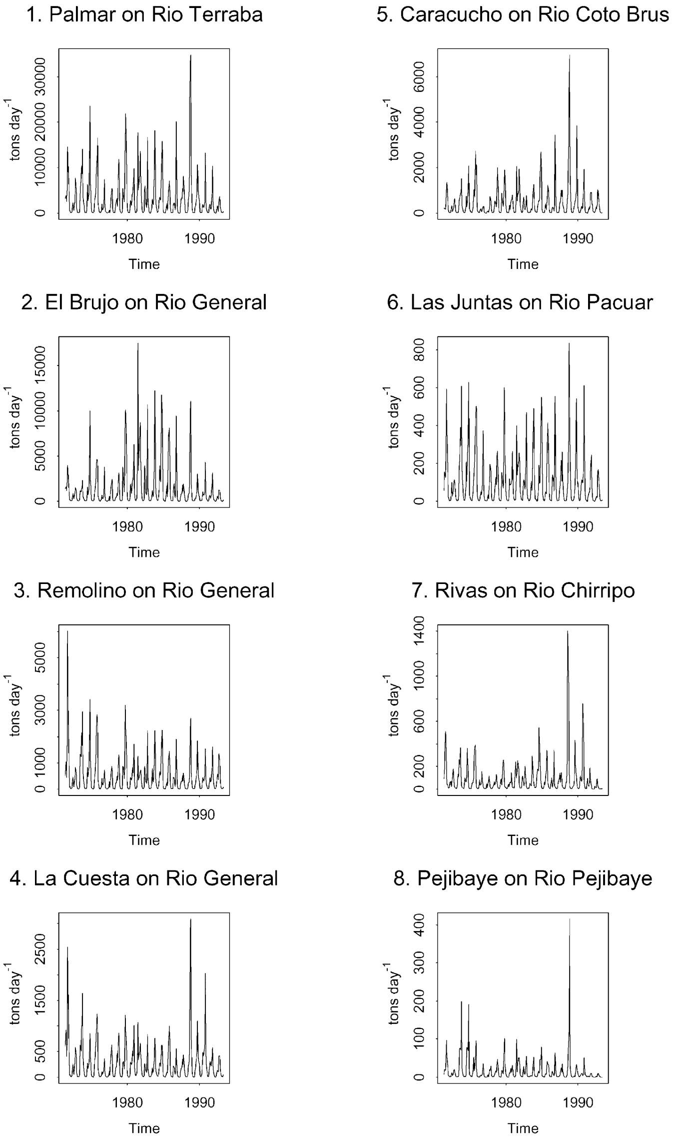


Fig. 4. Predicted monthly sediment discharge at gauging stations. These are estimated from predicted sediment concentrations from dynamic linear models and corresponding monthly averaged flow data. Monthly averages are expressed in tons day^{-1}.

data and a much smaller intermittent sub-set of days or events for which both sediment and flow were simultaneously measured. Empirical data based approaches are used to model some measure of sedimentation (i.e. sediment concentration or flux) as a non-linear power function of stream flow or discharge:

$$C_t = aQ_t^b \epsilon_1 \tag{6}$$

where C_t is usually flux averaged mean monthly suspended sediment concentration (mg l^{-1}) and Q_t is monthly average of corresponding stream flow (m^3 s^{-1}). In practice, log transformed sediment concentration and corresponding flow at a gauging station have been used to fit static linear regression models:

$$\log_{10} C_t = A + B\log_{10}(Q_t) + \epsilon_2, \tag{7}$$

Table 3
Hydro-climatic and sediment response factors, coefficients of determination (R^2) values of (1) basin hydro-climatologic variables with SOI as independent variable and (2) sediment discharge as response and hydro-climatologic variables as independent variables

No.	Station	River	Regression with SOI				Regression to Sediment discharge			
			Rainfall	Erosivity	Streamflow	Sediment	Rainfall	Flow (F)	Erosivity (E)	$E \times F$
1	Palmar	Terraba	0.73	0.62	0.57	0.38	0.59	0.79	0.75	0.85
2	El Brujo	General	0.68	0.58	0.6	0.06	0.07	0.37	0.12	0.16
3	Remolino	General	0.64	0.58	0.67	0.4	0.55	0.66	0.48	0.59
4	La Cuesta	General	0.63	0.57	0.62	0.44	0.7	0.81	0.69	0.79
5	Caracucho	Coto Brus	0.7	0.59	0.57	0.36	0.53	0.46	0.72	0.75
6	Las Juntas	Pacuar	0.5	0.54	0.62	0.57	0.61	0.81	0.65	0.7
7	Rivas	Chirripo	0.49	0.5	0.62	0.42	0.24	0.45	0.34	0.5
8	Pejibaye	Pejibaye	0.54	0.48	0.55	0.52	0.72	0.78	0.86	0.85

In this model, parameters A and B are invariant with time. The traditional approach to generating a time-series of estimated sediment discharge for a sub-basin is to fit a static regression model between sediment concentration and flow and apply this to the continuous daily flow data. These predicted sediment discharge time-series being based on a static unvarying relationship does not account for any non-stationarities in the sediment–flow relations of a basin.

The DLM approach described earlier offers an alternative to estimating sediment discharge time-series that are more realistic since it incorporates changes over time. The time-series of dynamic parameters (intercept and slope) of the log–log sediment–flow relationship were transformed to obtain a dynamic sediment rating equation. These were applied to the average monthly flow data in $\mathrm{m}^3\ \mathrm{s}^{-1}$ to obtain the time-series of predicted dynamic sediment discharge as a monthly averaged discharge per day for the eight stations:

$$Q_{\text{sediment}} \text{ in tons day}^{-1} = 0.0864(10^{[(A_t + B_t \log_{10}(\text{FLOW}_t))]})\text{FLOW}_t \quad (8)$$

These are shown in Fig. 4. The monthly sediment discharge estimated were aggregated in tons yr^{-1} on an annual basis. Estimates for independent sub-basins were computed using mass-balance using the nested stations.

The DLM approach not only provides estimates of the sediment coefficient $\mathrm{B_t}$ but also provides sediment discharge estimates that incorporate changes in the intercept and regression slope over time. This is in contrast to many sediment time-series estimates that apply a single 'rating' regression to the entire flow time-series and do not account for any changes in the sediment–flow relationship over the period of record.

4.9. Characterization of sub-basins: hydro-climatology, sediment supply, and ENSO

The annual sediment discharge (SEDANN) time-series for each station (obtained from the dynamic discharge method using DLM described earlier) was regressed against time-series of annually averaged hydro-climatic variables such as SOI, rainfall, rainfall erosivity, streamflow, and annual rainfall erosivity (RAINEROS) and transport capability (FLOW) combined in an interaction term. Two of these are shown as examples below for clarity:

$$\text{SEDANN} = A + B(\text{FLOW}) + \epsilon \quad (9)$$

$$\text{SEDANN} = A + B(\text{RAINEROS} \times \text{FLOW}) + \epsilon \quad (10)$$

In these models, the contribution of hydro-climatic factors to explaining the variability in sediment discharge can be assessed by the coefficient of determination, R^2. The variability in sediment discharge unexplained by the regression model $(1 - R^2)$ is assumed to be associated with other factors related to changes in sediment supply from the watershed as result of land-surface changes. These land-related processes include deforestation, regrowth, establishment of new land-uses, mass-wasting or landslides.

The sediment supply factors $(1 - R^2)$ as defined in this study are likely to be related to actual sediment supply variability, however it is to be treated as an exploratory and indicative tool. The supply factors from each of the regression models such as (9) and (10) (Table 3) in combination with trends in the sediment concentration coefficient (Fig. 3) can be analyzed to identify stations/sub-basins that have had changes in sediment response over time related to land-surface changes.

The methods described earlier were based on basins corresponding to the location of the eight gauging stations, four of which are nested with respect to the others, and four are independent (Fig. 2 and Tables 1 and 2). Cumulative statistical and spatial scale effects besides hydrologic dependence are likely to affect some of the results. Sediment discharge, rainfall erosivity and flow were calculated for sub-basins located between these nested stations and in combination with the original four independent stations/basins (no. 5–8 in Table 1) give a total of eight independent sub-basins (Tables 1 and 2). The sediment supply factor (as defined for the station data sets) was also estimated for the four additional delineated independent sub-basins.

In addition to these, the strength of extra-basin influence (SOI) on the hydro-climatology of a particular station/sub-basin was similarly assessed by fitting simple regression models to time-series of basin averaged annual rainfall, rainfall erosivity and stream flow as response variables and SOI as the independent variable. The measure of the strengths of these models (R^2) (Table 3) are all together considered as characterizing hydro-climatic response characteristics of the basins.

4.10. Cluster analyses

The stations and sub-basins correspond to differing hydro-climatic and sediment response characteristics. These have to be separated into groups using quantitative parameters. Cluster analysis is useful in analyzing multi-dimensional data sets. The quantitative sediment and hydro-climatic response characteristics of basins were assembled. These included the five R^2 values (e.g. Eqs. (9) and (10); Table 3) and the presence or absence of any significant trend in the sediment coefficient (Fig. 3) as well as the maximum yearly averaged sediment coefficient B_t for each basin yielding a total of seven sediment response parameters. Similarly, the hydro-climatic response parameters included R^2 values corresponding to the relationship between SOI as an independent variable and the following response variables: peak annual flows, rainfall and stream flow. In addition, the median and maximum annual rainfall erosivity and flow per unit area were included giving a total of six basin parameters.

Divisive, hierarchical cluster analyses (Kaufman and Rousseeuw, 1990) were done on the distance measures based on standardized variables separately for the hydro-climatic response and sediment response parameters. Comparisons with other cluster analyses methods were made to check the sensitivity to choice of method.

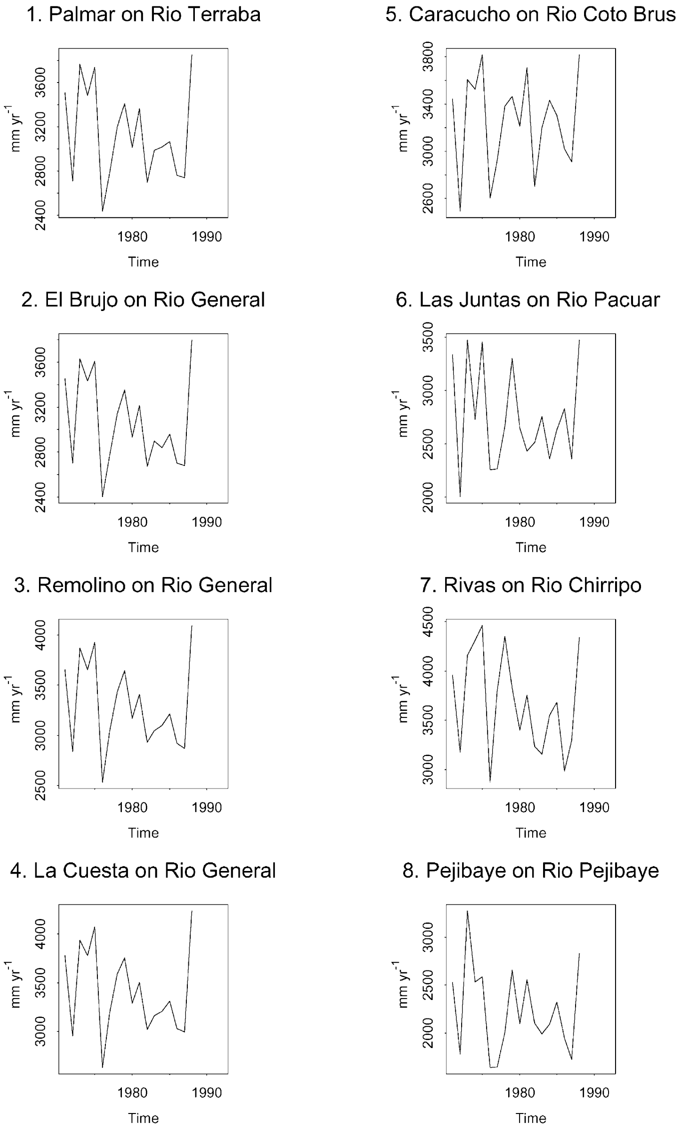
5. Results and discussion

5.1. Changes at the basin scale

As noted earlier, hydro-climatology in the Terraba basin is closely linked to the intensity of ENSO perturbations. Average annual rainfall upstream of each of the eight stream gauging stations from upstream sub-basins to the basin mouth, was strongly and positively linked to the SOI ($0.49 < R^2 < 0.73$, $n = 18$, $p < 0.0001$). A similar result was obtained for stream flow at each of these stations ($0.55 < R^2 < 0.67$, $n = 22$, $p < 0.0001$).

Annual rainfall was regressed against time to detect trends for all eight stations. Trends in basin-averaged rainfall are masked by one influential year, (1988 when hurricane Joan occurred in October), although negative slopes were obtained for seven of the eight stations. The regression performed after removing this one year yielded sufficient evidence for a decline in rainfall in most parts of the basin. Significant ($n = 17$, $0.01 < p < 0.1$) negative trends were obtained for five stations. The slopes ranged from -33.4 to -45.1 mm yr^{-1}. These trends are also seen in the graphical displays (Fig. 5).

The sediment coefficient B_t at the basin mouth at Palmar (Fig. 3) shows an initial short decline in the early 1970s (also noted at other stations on the Rio General) coinciding with the severe ENSO events of 1973 and 1976. Following this there is an increasing



1. Palmar on Rio Terraba

5. Caracucho on Rio Coto Brus

2. El Brujo on Rio General

6. Las Juntas on Rio Pacuar

3. Remolino on Rio General

7. Rivas on Rio Chirripo

4. La Cuesta on Rio General

8. Pejibaye on Rio Pejibaye

Fig. 5. Trends in annual rainfall upstream of gauging stations. Note the generally decreasing trend over time in many stations except for the hurricane year of 1988.

trend, although not significant. This is attributed to increased sediment supplies related to land-surface changes in various parts of the basin upstream.

The predicted sediment discharge from the dynamic linear models indicates a close coupling to the intensity of ENSO fluctuations. On an annual basis, sediment discharge was positively correlated to SOI for seven of the eight stream gauging stations ($n = 22$ years, $0.36 < R^2 < 0.52$, $p < 0.002$). The variability in annual sediment discharge from the entire basin during 1971–1992 hydrologic years was primarily controlled by hydro-climatologic variables to an extent of 59–85% (Table 3), and the remaining 15–41% can be attributed to changes in supply related to land-surface changes. In the El Nino hydrologic years of 1976 and 1992 years, the estimated sediment

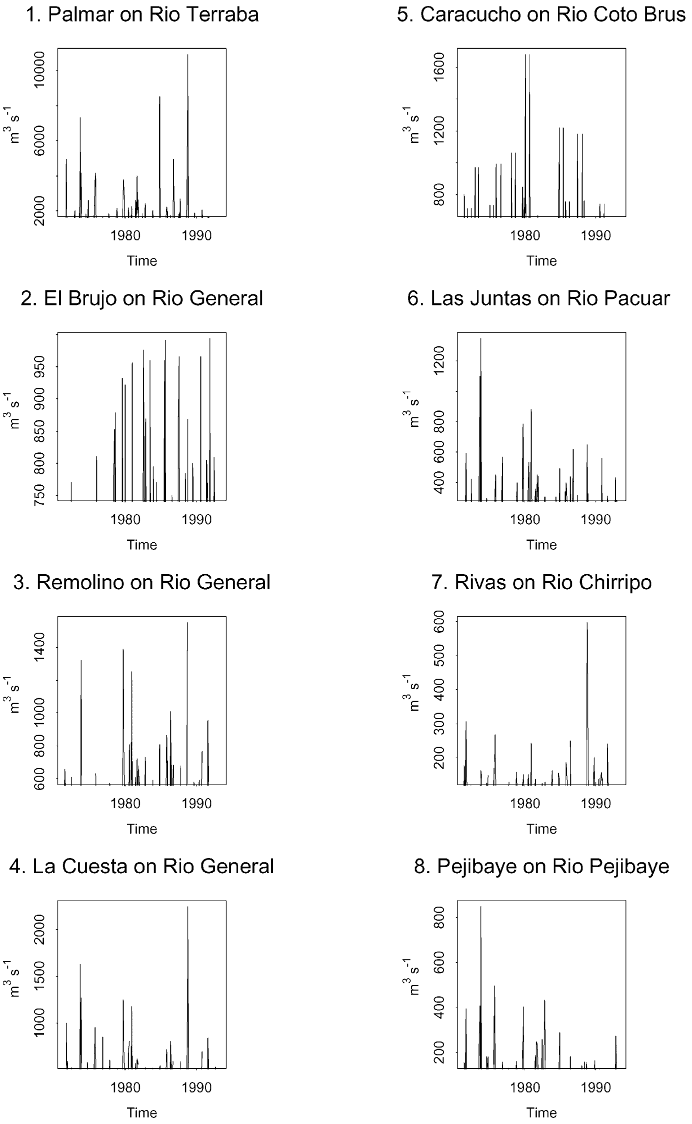

1. Palmar on Rio Terraba
5. Caracucho on Rio Coto Brus
2. El Brujo on Rio General
6. Las Juntas on Rio Pacuar
3. Remolino on Rio General
7. Rivas on Rio Chirripo
4. La Cuesta on Rio General
8. Pejibaye on Rio Pejibaye

Fig. 6. Trends in peak flows (>90 quantile) recorded at gauging stations. Note the decreasing trends at Pejibaye, Las Juntas and La Cuesta. At El Brujo, frequency and magnitude of peak flows increased in the 1980s.

yield from the basin was 100 and 79 tons km^2 yr^{-1}, respectively, while the median values for 22 hydrologic years from 1971–1992 was 261 tons km^2 yr^{-1}. In 1988, the year of hurricane Juan, the estimated yield was 704 tons km^2 yr^{-1}.

Although annual rainfall has apparently declined throughout the basin, the time-series of peak flows exceeding the 90-quantile value for Palmar indicates a shift towards higher magnitudes well into the 1970s (Fig. 6). In addition, unlike rainfall and average annual stream flow, the annual peak flows are not strongly linked to SOI. There was a significant positive linear relationship for five out of the eight stations ($0.12 < R^2 < 0.33$, $p < 0.1$) and none for the rest. The weaker linkage between peak stream flows and SOI is attributed to

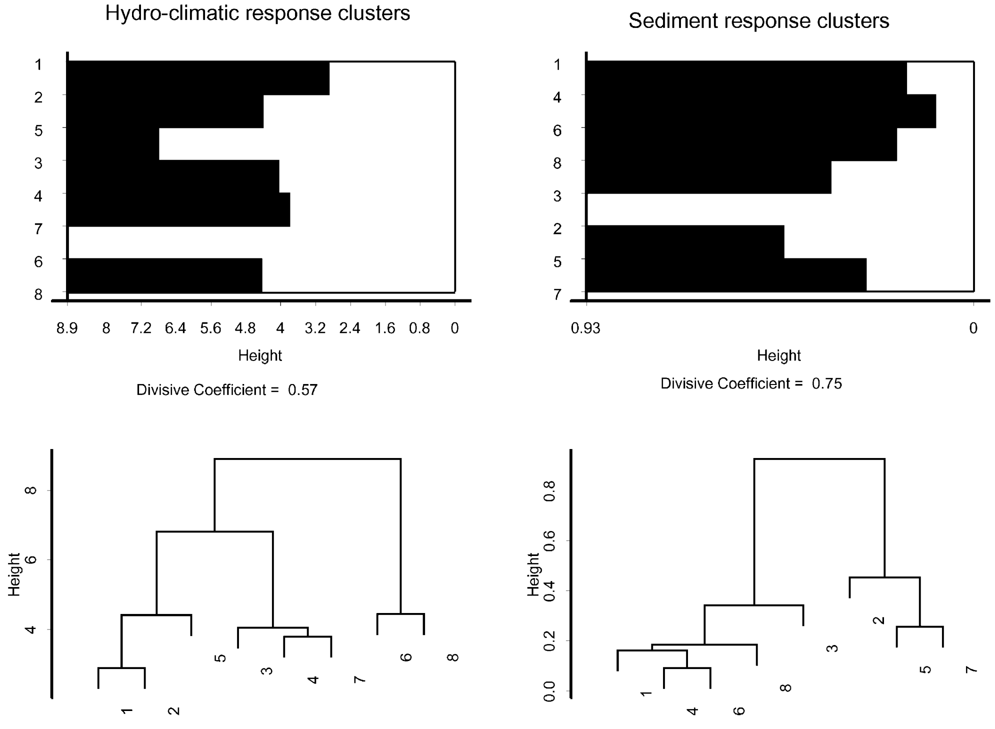


Fig. 7. Results of hierarchical divisive cluster analyses of hydro-climatic and sediment response characteristics of gauging stations/sub-basins. The two sets of analyses separate and group the stations and sub-basins on the basis of their similarity or differences in quantitative hydro-climatic and sediment response characteristics respectively. The sediment response characteristics of stations and basins is not similar to the hydro-climatic characteristics indicating a decoupling of the two. Stations 2, 5 and 7 are El Brujo (Rio General), Caracucho (Rio Coto Brus) and Rivas (Rio Chirripo), respectively. All of these had major land-surface changes during the period of study and fall in one sediment response cluster.

dominance of land-surface processes over extra-basin climatic influences.

5.2. Sedimentation dynamics in sub-basins

The time-series of the dynamic sediment concentration coefficient B_t (Fig. 3), the predicted sediment discharge (Fig. 4) and trends in peak flows for the eight stations (Fig. 6) reveal that significant changes in basin hydrologic response to intra-basin and extra-basin factors have occurred in various parts of the Terraba basin. At some stations the influence of the declining trends in annual rainfall (Fig. 5 and above) are expressed in similar trends in sediment discharge (Fig. 4). However this linkage is weaker for downstream stations that receive run-off from sub-basins undergoing major changes in land-use and land-cover.

5.3. Hydro-climatic response and sediment response

The cluster analyses of hydro-climatic and sediment response characteristic for the eight stations and sub-basins (Fig. 7) indicate the decoupling of the two. The clusters formed on the basis of hydro-climatic response parameters are very different from those based on sediment discharge response parameters. This is indicative of the strong influence of changes in intra-basin or land-surface characteristics on sediment dynamics for some sub-basins. Three stations (2, 5, 7) fall in one main sediment response cluster because all three of them had significant increases in the sediment coefficient B_t over time

(Fig. 3). These three stations/sub-basins which fall in one sediment response cluster are characterized by rapid changes in land-use/land-cover, expansion of agriculture (Tables 1 and 2) or in one case (no. 7, Rivas) possibly the lingering effects of an earthquake.

5.4. Sediment coefficient B_t and land-surface change

Two of these stations (El Brujo and Caracucho) are downstream of independent sub-basins with the highest estimated rates of deforestation (Tables 1 and 2). Interestingly, the main period of active deforestation for these two sub-basins (Tables 1 and 2) coincides with the main period of significant steady increases in the sediment coefficient B_t over time (Fig. 3). This is perhaps further evidence for the ability of the DLM method to capture actual basin sediment dynamics. In the Coto Brus sub-basin above Caracucho this was after 1979 and for the Ceibo–Volcan–Boruca sub-basin between Remolino and El Brujo it was in the 1970s–early 80s (Tables 1 and 2). This was followed by expansion of intensive agriculture.

In the case of the Rivas station on Rio Chirripo, this sub-basin was not deforested extensively (Table 1) and yet shows an increase in coefficient B_t over time especially after the early 80s (Fig. 3). In addition, the linkage between sediment response and hydro-climatic variables and SOI is weak (Table 3). Only 24–50% of the variability in sediment discharge can be attributed to these primarily extra-basin hydro-climatic factors, the rest can be assumed to be linked to changes in sediment supplies within the basin. However, there was one major event that could explain these responses independent of land-use change.

The Perez–Zeledon-Division earthquake of July 3, 1983 ($MS = 6.1$, $Z = 13$ km, $MM = 1$ X) produced the largest area of landslide destruction in Costa Rican history, covering over 175 km^2. The event reportedly led to an increased delivery of sediment (Mora, 1989). Part of the damaged area lies within the Chirripo sub-basins of the Rivas catchment. The sediment coefficient increased at a higher rate starting around 1986. These changes could be a delayed or lingering effect of the 1983 landslide, because of a favorable combination of rainfall and surface conditions. In addition, this mountainous sub-basin has the highest rainfall in the basin (Table 1). In combination with the effects of the July 1983 earthquake, it is possible that these factors led to an increase in the sediment response during the latter part of the data record. However, the sampling immediately after the event was infrequent in order to draw any firm conclusion regarding the impact of the earthquake on short term and long-term sediment dynamics. The only other sub-basin that was affected by this earthquake (no. 4, Las Juntas on Rio Pacuar) shows some evidence of increases in B_t in the 80s (Fig. 3) but it is not significant unlike the three stations in the right hand cluster of the sediment response clusters (Fig. 7). In addition, the strength of the relationship between sediment discharge and hydro-climatic variables and SOI is rather strong for this basin (Table 3).

One particular sub-basin and station stands out starkly in the apparent effect of deforestation and land-use change on surface hydrology and sediment discharge. The independent sub-basin is the 1198 km^2 Ceibo–Volcan–Boruca sub-basin defined by the El Brujo gauging station and the immediately upstream stations, Remolino and Pejibaye.

Out of all the eight stations, El Brujo is the only one in which the annual sediment discharge is weakly linked to hydro-climatologic variables and SOI (Table 3). Only 6–37% of the variability in sediment discharge is explained by regressions with these variables, and the rest can be attributed to changes in sediment supplies upstream. Flows exceeding 90 quantile (Fig. 6) were also much more frequent in the 1980–1993 period as compared to the 1970s at El Brujo downstream of this sub-basin ($n = 7$ before1980 and $n = 20$ after 1980). This period corresponds to the expansion of intensive agriculture after deforestation. The inter-annual variability in yearly peak flows is also not related to SOI ($R^2 = 0.12$, $p = 0.11$). This is primarily attributed to the growth of intensive agriculture in this basin after a period of forest conversion to pasture (Tables 1 and 2).

The Coto Brus sub-basin above Caracucho (no. 5) which also falls in the right hand cluster had significant increases in coefficient B_t corresponding to the active period of deforestation and conversion to other land-use as described earlier but is different from the other two (Rivas and El Brujo) in the right hand cluster and all the remaining ones in the left hand cluster. The annual sediment discharge is more strongly

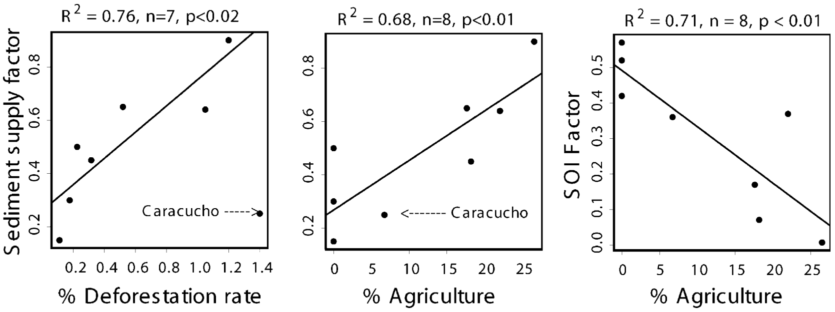


Fig. 8. Dependence of sediment supply factor on land-use change and SOI. The sediment supply factor is the $(1 - R^2)$ value obtained from the regression of annual sediment discharge as the response variable and the interaction of stream flow and rainfall erosivity as the independent variable. The SOI factor is the R^2 value with the SOI index (Table 3) as the independent variable. Caracucho on the Rio Coto Brus has the highest rate of deforestation and yet a small sediment supply factor. However, the area under intensive agriculture is smaller compared to the other basins with higher sediment supply factors.

linked to rainfall erosivity (72%) rather than stream flow (46%). This is one of the basins with no apparent negative trend in rainfall (Fig. 5).

5.5. Independent sub-basin analyses

A plot of the sediment supply factor for independent sub-basins against estimated rate of deforestation reveals a very interesting pattern (Fig. 8(a)). The sediment supply factor generally increases with the estimated deforestation rate with one major outlier. A linear model fit to the data from seven of the eight sub-basins is significant ($R^2 = 0.76$, $p < 0.02$).

There is however one major exception and outlier, the Coto Brus sub-basin above the station Caracucho. This sub-basin has the highest estimated rate of deforestation as described earlier but still has a low supply factor. Despite loss of forests (Tables 1 and 2) and increase in the sediment coefficient (Fig. 3), the supply factor was only 25%. The increase in the sediment coefficient over time especially after 1979 (Fig. 3) does however indicate a land-use effect but it is not strong enough to overwhelm the hydro-climatic control.

The sediment supply factor is however more convincingly related to the proportion of sub-basin land under agriculture ($R^2 = 0.68$, $n = 8$) as assessed in late 80s–early 90s. This indicates that the sediment supply is not just a simple function of deforestation rate but is strongly influenced by the type of land-use that follows forest conversion. The low value of the sediment supply factor for the Coto Brus sub-basin gauged at Caracucho can be attributed to the relatively small percentage of converted land under intensive agriculture as well as the other factors as described earlier. In addition, this sub-basin has large areas with Andisol soils (MAG, 1991) which are characterized by high infiltration rates and consequently lower levels of run-off even after forest conversion.

The SOI factor is strongly and negatively correlated with proportion of sub-basin land under agriculture in the late eighties (Fig. 8(c)) ($R^2 = 0.71$, $p < 0.01$). One interpretation is that inter-annual variability of sediment discharge is strongly controlled by land-surface changes such as establishment of agriculture on deforested land rather than just deforestation rates and ENSO fluctuations except for sub-basins which had relatively little change in land-use during the period of record.

5.6. Summary

To summarize, this study demonstrates the following:

1. The DLM based method is able to generate predicted sediment discharge from intermittent sediment data and continuous flow data that explicitly accounts for changes in the sediment–flow relationship over time. This is an alternative to the existing techniques that apply a single static

model to the continuous flow time-series. These static regression models applied to continuous flow data cannot be used to detect changes in sediment discharge over time, since it assumes an invariant sediment–flow relationship. On an aggregated annual basis, this dynamic sediment discharge can be directly related to extra-basin hydro-climatic factors and intra-basin land-surface factors.

2. The Bayesian DLM models in combination with graphical and simple annual regressions and cluster analyses are successful in separating the effects of land-surface changes from changes in hydro-climatology.
3. Nested time-series hydrologic and sediment data in combination with appropriate rigorous statistical approaches can be used successfully to analyze complex hydrologic systems.

6. Conclusion

The Terraba basin is an example of the complexity of the hydrologic regime of mountainous regions in the outer tropics that are characterized by the abundance of energy and moisture, high inter and intra-annual variability and high-magnitude infrequent events.

The hydrologic response of the system to rainfall inputs at relatively large spatial scales (100–5000 km$^{2)}$ is dominated by spatial and temporal patterns of hydro-climatology and rainfall regime, especially ENSO related. Land-cover and land-use changes influence basin response within the framework of this overwhelming dominance. In areas with rapid forest loss, agricultural intensification or events such as earthquakes and landslides, approximately 50–90% of the variability in inter-annual sediment discharge can be controlled by land-surface changes. Although annual rainfall declined in a large part of the basin, increases in the magnitude and frequency of >90 percentile flows were detected in sub-basins with major land-surface changes.

The current study demonstrates the value of DLM in detecting changes in hydrologic and sediment processes over time. Compared with currently used methods for detecting environmental ‘trend’, DLM is more appropriate in that it is not limited to a simple linear or log-linear trend. This feature is important because many environmental changes are triggered by few extreme events and we rarely see linear trends due to complicated interactions among many influencing factors. Although the model presented here is simple compared to many process based hydrologic models, it has fewer requirements in specification of parameters and its performance can be readily evaluated. As a result, model uncertainty is known. This needs to be applied to many long-term water quality–flow or rainfall–flow time-series data sets that have been collected in the last several decades in order to gain new insights on historic changes. Time-series data from the Terraba and other humid tropical basins elsewhere should be analyzed using the DLM methods to study changes in other hydrological processes of interest such as the rainfall–stream flow relationship.

The DLM based dynamic estimates of sediment discharge that explicitly accounts for changes in regression parameters over time will significantly improve estimates of sediment discharge, especially in cases where intermittent sediment concentration and continuous flow data are available.

This study in particular illustrates that even complex hydrologic systems can be analyzed meaningfully using a suite of appropriate statistical and quantitative tools.

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