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FOREST IMPACT ON FLOODS DUE TO EXTREME RAINFALL AND SNOWMELT IN FOUR LATIN AMERICAN ENVIRONMENTS 2: MODEL ANALYSIS

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Abstract

Through a systematic modelling analysis for focus basins in Costa Rica (131 km^2), Ecuador (10 km^2), Chile (0.35 km^2) and Argentina (12.9 km^2), the hypothesis is tested that, as the size of the flood peak increases, the effect of land use on the peak becomes less important. For each focus basin, a 1000-year synthetic rainfall time series was generated, representative of the current climate. This time series was used to run SHETRAN hydrological models for each basin with two contrasting land use scenarios (generally with and without a forest cover). The corresponding maximum daily discharges for the contrasting scenarios were then compared to show the extent to which the two responses converged as the size of the peak discharge increased. For a given forest basin discharge there could be a range of larger non-forest basin discharges, depending on antecedent soil moisture content. The simulations show consistently for the rainfall dominated sites that the width of this range either remains constant or narrows as discharge increases, indicating either relative or absolute convergence of the responses. The pattern is more difficult to distinguish for a snowmelt regime but a relative convergence of response still appears possible. The results therefore support the test hypothesis. However, the pattern is complicated by factors such as basin scale, soil depth, antecedent moisture content and land management. Forests may also still offer significant flood mitigation benefits for moderate (and more frequent) rainfall events and they protect against soil erosion and sediment transport for a wide range of events.

Keywords: Extreme rainfall; Forest; Floods; Hydrological model; Land use change; Latin America; Snowmelt

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1. Introduction

The impact of forest management on river basin response (in terms of water flow and soil erosion) for extreme rainfall and snowmelt events is an area in which there is considerable scientific uncertainty as well as poorly conceived policy. Currently, under the impression that forests reduce floods, large sums of money are invested by governments and agencies in reforesting headwater areas of river basins and land use controls are imposed on the (typically poor) populations living in these areas (CIFOR and FAO, 2005; Calder, 2005; Calder and Aylward, 2006). However, while forests may reduce floods for small to moderate storms, there is growing evidence that this effect is increasingly reduced as rainfall increases to more extreme levels (Thomas and Megahan, 1998; Beschta et al., 2000; La Marche and Lettenmair, 2001). The EPIC FORCE project (Evidence-based Policy for Integrated Control of Forested River Catchments in Extreme Rainfall and Snowmelt), funded by the European Commission (http://www.ceg.ncl.ac.uk/epicforce), was therefore set up to examine the impact of forest management on river basin response for extreme rainfall and snowmelt events, in the Latin American environment (Bathurst et al., 2008). A combination of field data analysis and model application was used to test the hypothesis that, as the size of the flood peak increases, the effect of land use becomes less important. The aim of the data analysis was to quantify directly the impact of land use, and forest cover in particular, on basin response to extreme rainfall or snowmelt in four specified focus areas. This work, which generally supports the hypothesis, is reported in Bathurst et al. (in preparation). It was recognized, though, that this analysis would be limited by the available data and field instrumentation and that it might not be possible to use a common analytical approach across the four areas. In particular, available data records are unlikely to include extreme rainfall and snowmelt events which, by their nature, are rare at a given location. One means of extracting as much information as possible out of existing data sets is to use them to calibrate mathematical models which are then applied to scenario events, such as extreme floods. Therefore the model applications were intended to extrapolate the data analyses to a wider range of conditions and to provide a systematic analysis of the impact of land use on flood peak discharge using a standard approach. These applications are the focus of this paper.

The hypothesis being examined is illustrated in Fig. 1, which shows the relationship between peak discharge and flood frequency (represented by return period) for basins which are identical except for the level of forest cover. In both cases, the less frequent the flood (i.e. with a larger return period), the greater is the peak discharge. For moderate floods, which are relatively frequent, the forested basin is assumed to be able to absorb more rainfall into the soil and therefore has lower peak discharges than the non-forested basin. This is because the greater interception of rainfall by the forest, combined with a higher transpiration by the trees, allows the build up of greater soil moisture deficits compared with the non-forested case. However, the effect of the deficit is expected to decrease as rainfall amounts increase. The diagram thus proposes a convergence of peak discharge response for the more extreme floods.

The paper reviews relevant literature, describes the focus sites and the data provision, presents the modelling strategy and results and discusses the effects of land use on flood peak discharge. There have been only a few modelling studies of the effect of forest cover on flood peak discharge in extreme events and the paper therefore adds to the development of the modelling approach. By considering a range of focus sites in Latin America, it also consolidates the results at a large regional scale.

For the purposes of the paper, “extreme rainfall” refers to high rainfall, generating floods, and does not include low rainfall responsible for droughts.

2. Modelling forest impacts on floods

Mathematical models can be powerful tools for providing important insights into the controls on basin response to land use change (e.g. Bultot et al., 1990; Storck et al., 1998; Lukey et al., 2000; Bronstert et al., 2002; Brath et al., 2006). This capacity arises from the ability to change the model parameters to represent different vegetation and land use characteristics, thus enabling scenario studies to be performed. Past studies have tended to concentrate on the changes in vegetation cover and the impact on interception and transpiration rather than, for example, the subsurface flow system (Blöschl et al., 2007). Typically, applications have involved periods of observed record (a few years to a few decades) and a process in which the model is calibrated for the existing land use, the parameters are then changed to represent a different land use, the revised model is run with the same input data and the simulations are compared (e.g. Lukey et al., 2000). Such applications have demonstrated the ability of models to reproduce the principal directions of change observed experimentally in the hydrological response (e.g. removal of forest cover increases annual runoff and peak discharges) (e.g. Storck et al., 1998; Cognard-Plancq et al., 2001; Ranzi et al., 2002). Only a few model studies, though, have examined whether changes in land use have the same or a different effect on peak discharges for floods of different return periods.

Using the above type of approach, Bultot et al. (1990) found that, for a 114-km^2 catchment in Belgium, land use changes have a greater effect on runoff in dry years compared with wet years; in wet years, the highest flood peaks remained almost unaffected. In general, though, basing simulations on periods of observed data is likely to restrict the range of flood response that can be considered, as the period of observation is probably not long enough to incorporate examples of the more extreme events, for example with return periods up to 100 years. Researchers have therefore resorted to some form of statistical technique to extend the range of flood return period.

One approach is to generate statistically a long (e.g. 1000 years) time series of synthetic climate data, so as to provide an appropriate statistical basis for defining catchment flood response for rainfall events with return periods of up to 100 years or so. The synthetic data are generated from the available period of observation, so, the longer that period, the more accurate the extension is likely to be. A hydrological model is then run for different land use scenarios using the same synthetic data as the input in each case and the results are compared. Typically the rainfall data are generated using a rectangular pulses model (e.g. Cowpertwait et al., 1996) calibrated on the available record. Thus Schnorbus and Alila (2004) generated a 100-year streamflow time series to obtain the frequency distribution of annual maximum peak flows for the 26-km^2 Redfish Creek catchment in British Columbia. They investigated ten forest harvest scenarios, taking into account snowmelt as well as rainfall. For hourly and daily peak discharges (affected mainly by rainfall), the increase in peak discharge following harvesting appears to be similar for both small and large events for a given scenario, at least up to a return period of 30 years. For 7-day discharges (determined largely by radiation generated snowmelt), the increase in peak discharge increased with return period, for return periods of 1.25 to 100 years. Brath et al. (2006) similarly generated 1000 years of synthetic input data and simulated the response of the 178-km^2 Samoggia catchment in northern Italy to the observed change in land use from 1955 to 1992. They found that the relative difference in discharge between the two cases decreased as discharge increased.

In an alternative approach, Candela et al. (2005) used a Monte Carlo modelling framework to synthesize derived flood distributions (with return periods of up to 100 years) with a simple hydrological model and probability distributions for the model variables. For a 53-km^2 catchment in Sicily, 30% of which was burnt in a forest fire, repeating the method for the pre- and post-fire conditions showed a distinct shift in the flood frequency curve. For a given return period the peak discharge increased for the post-fire condition. However, the ratio of the post-fire to pre-fire peak discharges decreases slightly as return period increases.

These few model studies provide some evidence in support of the test hypothesis, although there are clearly complicating factors. It is notable that the studies are limited to catchment areas between 26 and 178 km^2.

Model analysis of land use impact on the peak discharges of extreme events has advantages over field based analysis in terms of extending the range of event return period and land use scenario and providing a systematic basis for the analysis. Disadvantages arise from the typical errors and uncertainties associated with models, for example in calibration, parameter evaluation and the representation of spatially and temporally varying rainfall input data (e.g. Nandakumar and Mein, 1997; Beven, 2001). Output uncertainty could therefore mask the changes which would otherwise be detectable. It is important, therefore, to use the most appropriate modelling approach (e.g. Bronstert et al., 2002; Bronstert, 2004). For land use change studies, physically based, spatially distributed models have a particular advantage in that their parameters have a physical meaning and can be evaluated on the basis of measurements, past research and physical reasoning. Simpler models require calibration and the necessary data may not exist to represent a potential future catchment state. Bronstert (2004) also notes that many rainfall-runoff models have not been thoroughly tested for extreme runoff conditions. As a partial response to this he suggests using continuous runoff rather than event based models so as to account more realistically for the antecedent catchment conditions.

3. Focus areas

The focus areas were in Costa Rica, Ecuador, Chile and Argentina. The general characteristics are as described in Bathurst et al. (under review). For practical reasons, though, the modelling study was limited to specific, mostly small, catchments, as shown in Table 1.

The Pejibaye basin on the Pacific slopes of Costa Rica was selected to represent an area subject to hurricane rainfall: indeed the river gauging station was destroyed by a hurricane in 1996! The basin has undergone almost total deforestation since 1950 and the natural forest cover is now less than 3.5%. In partial compensation, though, from the 1980s, the area covered by coffee plantation increased to about 20%. The Ecuador focus area is characterized by a wet season in the first half of the year, which can be severely enhanced by El Niño events. The principal approach was to compare the responses of neighbouring paired basins, selected for their contrasting vegetation covers, over the same period of time. The pair used for the modelling study was the Lise (largely forested) and Panamá (largely pasture) basins. The Chile focus area is characterized by high winter and all year rainfall, with large interannual variability from El Niño effects. The forest cover consists of commercial species such as radiata pine or eucalyptus. The main test basin was La Reina, for which data were available for a full forest cover (1997-1999) and for the period following logging of the *Pinus radiata* plantation that covered 79.4% of the basin (2000-2001). The Argentina focus area was selected to incorporate snowmelt and rain-on-snow events. The main test basin was the Buena Esperanza in Tierra del Fuego, which has a native forest cover over about 36% of its area, at the lower to middle elevations, and a small glacier at its head.

4. Modelling methodology

The study was carried out using the SHETRAN modelling system (Ewen et al., 2000). This is a physically based, spatially distributed, continuous simulation modelling system for flow and sediment transport, relevant at the basin scale. It includes components for modelling vegetation interception and transpiration, snowmelt, overland flow, subsurface unsaturated and saturated flow, river/aquifer interaction and sediment yield. Full details of the equations and data needs of SHETRAN have been reported in a number of publications (e.g. Ewen et al., 2000, 2002; Bathurst et al., 1995) and are therefore not repeated here. Examples of recent applications include Bathurst et al. (2004, 2007), Adams et al. (2005), Adams and Elliott (2006) and Birkinshaw (2008).

Construction and validation of a fully representative SHETRAN model for each of the individual focus basins was not possible within the project timeframe. Therefore SHETRAN was applied generically. Models were set up to be generally representative of each focus basin in terms of vegetation cover, soil type and topography (using data supplied from the focus areas) and were then calibrated against the available outlet discharge data (typically for periods ranging from two to seven years). However, it was not expected that the models should reproduce the basins and their responses exactly: rather it was intended that they should be generally representative of the principal characteristics of the basins and their hydrological responses, particularly the range of peak discharges but also including baseflow magnitudes, seasonal variations in response and annual water balance. This was considered to be sufficient for investigating the effect of land use change on peak discharge in the general environment of the focus areas. Nevertheless, in most cases it was also possible to achieve a good agreement between the observed and simulated discharge time series.

The central aim of the modelling study was to investigate catchment response, for different land covers, to extreme rainfall events. However, it was not clear that the available records contained rainfall events with the large return periods appropriate to this study, i.e. of the order of 100 years. Further, the records were too short to provide a sound statistical basis for defining a 100-year event. As noted in the literature review, though, it is possible effectively to extend the range of return periods by statistically generating long rainfall time series from the current records. Therefore a 1000-year synthetic hourly rainfall time series was generated for each focus catchment, providing an appropriate statistical basis for defining the flood response for events with return periods of up to 100 years or so. It is emphasized that the 1000 years of data are a statistical representation of current rainfall conditions. They do *not* form a prediction of rainfall over the next 1000 years.

The statistical generation was carried out with Newcastle University's Rainsim software (Burton et al., in press) by combining monthly statistics for daily data with the variance and skew statistics for hourly data. The model uses the Neyman-Scott rectangular pulses model to simulate rainfall (Cowpertwait et al., 1996). It should be noted that, while Rainsim is able to extend the range of event magnitudes beyond those in the measured record, it does not enable the true return periods to be specified for these events. Thus it is not possible to quantify characteristic return periods for the 1000-year rainfall time series.

For the Argentinean site it was necessary to derive a temperature record also, for calculating snowmelt. This was accomplished by fitting regression relationships between daily temperature and precipitation data to give a 1000-year series of daily maximum and minimum temperatures. (The series was generated by Chris Kilsby (Newcastle University, UK) and Colin Harpham (University of East Anglia, UK) according to the procedure in Kilsby et al. (2007)). A sinusoidal curve was then fitted to produce hourly temperature data, assuming a maximum at 4pm and a minimum at 4am.

Evapotranspiration is generally rather less variable than rainfall from year to year. The same pattern of mean monthly values (determined from available data records) was therefore applied for each year of the 1000 years. For the sites in Ecuador, Chile and Argentina, the values were calculated as actual evapotranspiration from available automatic weather station data using the Penman-Monteith equation (with parameter values appropriate to the vegetation). For the Costa Rica site, potential evapotranspiration was provided and actual evapotranspiration was subsequently calculated from the ratio of actual to potential evapotranspiration varying with soil moisture content (e.g. Denmead and Shaw, 1962).

The general modelling approach for each focus basin was then as follows:

1) Calibrate SHETRAN as far as possible for the focus basin;
2) On the basis of the available rainfall data, generate a 1000-year synthetic hourly rainfall time series;
3) Apply the model to contrasting land use scenarios (generally with and without a forest cover) using the generated rainfall time series;
4) Compare the maximum daily discharges of the contrasting scenarios for each day of the 1000-year simulations;
5) Investigate the extent to which the contrasting responses converge as the size of the flood peak increases.

By comparing the maximum daily discharges, the simulations allow a more detailed study of the response to land use than earlier modelling studies (e.g. Schnorbus and Alila, 2004; Candela et al., 2005) which considered only annual floods.

5. Model applications

The SHETRAN grid meshes and elevations for the four catchments are shown in Fig. 2. The river links run along the edges of the squares. Table 2 provides information on model characteristics and data availability and Table 3 provides the values of the key model parameters, to which the simulations are most sensitive. Figures 3 and 4 show the model calibrations. Figure 5 shows the results of the 1000-year simulations.

5.1 Costa Rica

The simulation period was 1/1/91-31/12/93, for which hourly rainfall data are available and which includes the hurricane event of 14/9/93, in which 331.5 mm was measured in 13 hours. A single raingauge record was used (at Bolivia in the middle of the catchment). Actual evapotranspiration was calculated from the ratio of actual to potential evapotranspiration varying with soil moisture content (e.g. Denmead and Shaw, 1962). However, measured daily potential values were available only for the Bolivia station. The resulting inability of the method to account explicitly for differences in potential evapotranspiration between vegetation types (e.g. as a function of aerodynamic resistance) was allowed for by increasing the maximum ratio of actual to potential evapotranspiration for forest relative to grassland cover (based on past experience). A single silty loam soil was assumed. Comparison of the measured and simulated daily discharges (Fig. 3a) showed a tendency to overestimate the peak values but the general pattern was well represented with a Nash-Sutcliffe efficiency value of 0.85. The extreme event of 14/9/93 was also well represented. Subdaily measurements of discharge are available only as monthly maxima (i.e. instantaneous maxima). The simulated values both over- and under-estimate these levels: for the extreme event the simulated value is 985 $m^3 s^{-1}$ while the measured value was 1373 $m^3 s^{-1}$. However, the simulated and measured annual mass balances are in excellent agreement for all three years. Sources of error in the modelling include the use of a single meteorological station in a catchment where there could be significant spatial variability and a relatively coarse representation of vegetation-dependent effects such as evapotranspiration. It is unknown what errors may exist in the measured data.

The 1000-year time series of precipitation data was generated using a 25-year record of daily precipitation data from the Bolivia site (for 1971-2005) and the available three years of hourly data from the same site. The Pejibaye catchment was then simulated with its current vegetation cover and with a hypothetical complete forest cover, in each case with the same 1000 years of input data. The maximum daily discharges for the two vegetations are compared in Fig. 5a. Points representing the start of the wet season in June lie further from the line of equality than points for the end of the wet season in November. For the largest ten events (discharges exceeding 1000 $m^3 s^{-1}$) the difference is around 100 $m^3 s^{-1}$ or less.

5.2 Ecuador

For the Panamá catchment the calibration period was 6/5/2005 (when the measured discharge record begins) to 25/5/2006. For the Lise catchment the calibration period was 5/3/2005 to 25/5/2006 (although there are some missing discharge data). Evapotranspiration was modelled with the Penman-Monteith equation: the main difference in the model between the forested (Lise) and pasture (Panamá) vegetations is then the lower aerodynamic resistance for the forest relative to the pasture (10 vs 30 s m^{-1}), which promotes higher evaporation. The main soil types are Umbrisol and Leptosol (Panamá) and Umbric Leptosol (Lise). However, as the measured data are not such as to justify differences between the soils, the same parameter values are applied to all the soils. The lower layers have remarkable water-holding properties and can sustain long hydrograph recessions and baseflows.

For the Panamá calibration, an excellent correspondence between the simulated and measured discharges was achieved (Nash-Sutcliffe efficiency = 0.92) and, in particular, the shape of the recessions following precipitation events is well captured (Fig. 3b). The total annual measured (399 mm) and simulated (400 mm) runoffs are almost identical, giving annual evaporation rates of around 562 mm. For the Lise calibration the Nash-Sutcliffe efficiency was 0.81. The main problem was an inability to reproduce accurately the observed steep recession of the last major event of the 2005 wet season and the subsequent almost constant baseflow throughout the entire dry season (Fig. 3c). The simulation shows a slower recession and then the baseflow falling to almost nothing by the middle of the dry season. However, the study focused on the peak discharges and these are reasonably well simulated. Gaps in the measured discharge record in the 2006 wet season prevent a full comparison. The total annual measured (265 mm) and simulated (241 mm) runoffs are similar, giving measured and simulated annual evaporation rates of 528 mm and 552 mm respectively. Possible sources of error include the representation of the remarkable lower layer soils and unknown errors in the measured data.

The 1000-year time series of precipitation data was generated using a 23-year record of daily precipitation data from the Compud site, 6 km from the middle of the Panamá catchment, (including the El Niño periods of 1982-1983 and 1997-1998) and the existing measured hourly data from 2005-2006. The Panamá catchment was then simulated with its current vegetation cover and with a hypothetical full forest cover, in each case with the same 1000 years of input data. For the forest case the parameter values were as calibrated for the Lise catchment. Figure 5b compares the corresponding maximum daily discharges for each day of the two simulations. Points representing the start of the wet season in January lie further from the line of equality than points for the end of the wet season in May.

5.3 Chile

Model calibration was carried out for the periods 1997-1999, when the basin was forested, and 2000-2001 when the basin had been logged and then replanted. The only difference in parameter values between the two periods was for the vegetation (e.g. aerodynamic resistances of 3.5 and 40 s m^{-1} respectively for the forest and logged cases): the values were based on previous simulations in the UK (Dunn and Mackay, 1995) and measured values from other basins Breuer et al. (2003), with some minor calibration. Evaporation was simulated using the Penman-Monteith equation with the measured hourly meteorological data, the aerodynamic and canopy resistance values being 3.5 and 100 s m^{-1} respectively for the forest and 40 and 65 s m^{-1} respectively for the logged condition.

For the forested condition (1997-99), agreement between the measured and simulated discharges is good (Nash-Sutcliffe efficiency = 0.81) and importantly for this work the peaks are reasonably well captured by the simulation (e.g. for the major 1997 event simulation = 0.314 m^3 s^{-1} and measurement = 0.349 m^3 s^{-1}, while for the major 1999 event simulation = 0.263 m^3 s^{-1} and measurement = 0.24 m^3 s^{-1}) (Fig. 3d). The simulated discharges during the dry year in 1998 are relatively high, although this is not considered to be a major problem given the focus on flood events. The measured and simulated annual mass balances agree well for 1997 and 1999 but differ for 1998.

For the logged condition (2000-2001), no run-in period was provided and therefore there is a discrepancy between the measured and simulated discharges for the first two months of the simulation period (Fig. 3e). (Most of the other simulations were preceded by a run-in period of months to a year to allow the effect of the initial conditions to dissipate.) Overall, though, the correspondence is excellent (Nash-Sutcliffe efficiency = 0.89) and again the peaks are well captured. There is similarly excellent agreement between the measured and simulated annual mass balances. The reduction in interception and consequent increase in runoff compared with the forested condition are well represented by the simulation.

The 1000-year synthetic rainfall record was developed using a seven-year hourly rainfall record for La Reina catchment and a 45-year daily rainfall record for the Isla Teja gauge at Valdivia. Isla Teja is in the same general region as La Reina and has a similar annual and monthly rainfall distribution. Nevertheless it is not local to La Reina and its record therefore had to be correlated with La Reina's record before it could be used. Relationships were developed between the two stations using monthly statistics for rainfall and proportion of dry days, for a six-year period. La Reina catchment was then simulated with its forested and with its logged covers, in each case with the same 1000 years of input data. Figure 5c compares the maximum daily discharges for each corresponding day of the simulations. The difference between the two cases is least in the winter and greatest in the summer.

A more detailed description of the modelling is given by Birkinshaw et al. (in preparation).

5.4 Argentina

The calibration period was 1/11/05 to 30/4/07, which includes hourly data for rainfall, temperature and discharge. Hourly precipitation was taken from the Aerosilla gauge (at 500 m elevation within the catchment) and distributed spatially using a calibrated altitude factor. However, this raingauge is not suitable for snow collection and so precipitation in the winter is underestimated. Daily precipitation data (and some hourly data) for rain and snow were taken from the Ushuaia record (at sea level). Temperature was distributed altitudinally based on hourly measurements at Ushuaia and the Martial glacier (1000m elevation). Snowmelt was modelled with the degree-day formula (Ohmura, 2001; Hock, 2003). Using data from Ushuaia a temperature of 4ºC was used to define the transition between rainfall and snowmelt. From a combination of literature review (Kuusisto, 1980; Braun et al.,1993; Pomeroy and

Brun, 2001; Hock, 2003; Talbot et al., 2006) and calibration, degree-day factor values were set ranging from 4.3 mm $^{o}C^{-1}$ day^{-1} (pine forest) to 6.9 mm $^{o}C^{-1}$ day^{-1} (logged) and from 5.2 mm $^{o}C^{-1}$ day^{-1} (deciduous forest) to 7.8 mm $^{o}C^{-1}$ day^{-1} (logged) and were set at 13.0 mm $^{o}C^{-1}$ day^{-1} for rock debris at high elevation. Discharge is available for the Buena Esperanza outlet and its Martial and Godoy sub-catchments (areas 4.8 and 1.5 km^2 respectively), with some gaps. The main difference between the forest and non-forest vegetations was the interception/transpiration parameters and the degree-day factor. Evapotranspiration was modelled using the Penman-Monteith equation. Soils were modelled as peat over compacted till or as rock debris.

Calibration yielded Nash-Sutcliffe efficiencies of 0.83 (outlet), 0.78 (Martial sub-catchment) and 0.76 (Godoy sub-catchment), an approximate match of measured and simulated peak discharges (both over- and under-estimates) and a good agreement for the base flows (Fig. 3f). Discharge is derived from snowmelt events, rainfall events or a combination of the two. The annual mass balance shows that the total measured and simulated discharges are very similar in both years. Possible sources of errors include the use of estimated altitudinal variations of meteorological inputs and the degree-day method. The interaction of vegetation with snow accumulation and melt is represented solely by the degree-day factor; there is no allowance for such effects as snow interception or the influence of vegetation on snow redistribution by wind.

A separate calibration was carried out for the rain-on-snow event of 5/11/54, which caused major flooding in Ushuaia with a peak discharge of around 13 m^3 s^{-1}. This used hourly precipitation (disaggregated from daily data), discharge and temperature data from Ushuaia. The simulated discharge is very similar to the measured discharge with a similar peak value and a similar shape (Fig. 4).

The 1000-year time series of precipitation and temperature data was produced using a 36-year record of daily precipitation and maximum and minimum temperatures from Ushuaia (for 1970-2005). The available hourly data consisted of six years of hourly precipitation data in the summer and two years in the winter. The Buena Esperanza catchment was then simulated with its current vegetation cover (about 40% forest cover) and with a hypothetical case of the forest completely logged, in each case with the same 1000 years of input data. The maximum daily discharges for the two vegetations are compared for the 1000-year simulation in Fig. 5d. The point with the largest discharge in the figure corresponds to the result of a separate scenario comparison carried out for the observed 1954 event, i.e. a repetition of the calibration run but with the two vegetation scenarios.

5.5 Impact of non-vegetation model parameters

Although a systematic analysis of the sensitivity of the above result to model parameters other than for interception and transpiration was not carried out, two additional tests arose from the calibration process. The first considered (for the Pejibaye catchment only) the effect that a change of land use might have on the overland flow resistance. The natural forest in the catchment supports a thick leaf litter which, presumably, causes a high flow resistance. In the coffee plantations which have replaced the forest in around 20% of the catchment, the management techniques maintain a healthy leaf litter which should have a similar effect. However, areas converted to pasture are likely to have a lower flow resistance, especially where cattle have worn paths and compacted the soil. The 1000-year Pejibaye forest simulation was therefore repeated with the Strickler overland flow coefficient reduced from 4 to 1, to create a higher flow resistance. Comparison was then made with the current land use scenario results, for which the coefficient retained a value of 4 (Fig. 6).

For La Reina catchment in Chile, the 1000-year scenario simulations were repeated with hypothetical soil depths both shallower (0.5 m) and deeper (10 m) than originally modelled (2.5 m). The results are shown in Fig. 7.

5.6 Sediment transport

The impact of land use change on erosion and sediment transport for large rainfall events was simulated for La Reina catchment. The SHETRAN sediment transport model was set up and tested, first for the 1997-1999 period with forest and then for the same period with forest removed, i.e. as if logged. The simulations were driven by the calibrated water flow models and used the following soil erodibility coefficients (see Wicks and Bathurst (1996) and Ewen et al. (2002) for details): raindrop erodibility coefficient 0.05 J^{-1}; overland flow erodibility coefficient 2×10^{-8} kg m^{-2} s^{-1}. The important difference between the two model realisations is the areal extent of forest cover, which acts in the model to reduce raindrop impact erosion and overland flow transport. There is a significant increase in sediment yield from 3 t ha^{-1} yr^{-1} for the forested catchment to 13 t ha^{-1} yr^{-1} for the logged catchment. The forest value is in good agreement with an initial analysis based on limited sediment transport measurements for 1997-1998 which gave yields of 3.9-11.1 t ha^{-1} yr^{-1} depending on the technique used to derive continuous suspended sediment concentration (Menke de la Peña, 1999). The difference in yield is also in line with other studies which show that clearing of forests produces an increase in catchment sediment yield, although the increase varies depending on the vegetation types and the climate (Bosch and Hewlett, 1982; Stednick, 1996; Bruijnzeel, 2004).

As with the water flow, long term (100-year) sediment transport simulations were then run for the logged and forested cases, using the basic sediment transport models. Figure 8 compares the maximum transport rates for each day for the two cases.

6. Discussion

6.1 Land use impact on flood peak discharge – rainfall events

This section considers the results for the Pejibaye, Panamá and La Reina applications. In all these cases the only difference between the model parameterizations for the two scenarios was the values of the vegetation parameters affecting interception and transpiration. Overall, the forested catchment generates more evaporation and so a greater soil moisture deficit and a lower discharge than the non-forested catchment. However, the effect is not constant and the plots in Fig. 5 show that there can be a range of “non-forested” peak discharges for a given “forested” discharge. In some cases there is a difference, in others there is hardly any. Even for low to moderate events it is possible for the difference in peak discharge magnitude to be small, i.e. for the effect of land use to be negligible. If the soil under the forest is very wet, the response is similar to the non-forested case. Thus for the Pejibaye and Panamá sites, which have distinct wet seasons, the difference is greater at the start of the season, when the soils are dry, than at the end, when the soils are wettest. For La Reina catchment the difference is least in winter and greatest in the summer (when the trees have the least and greatest effects respectively on soil moisture). It appears, then, that antecedent soil moisture conditions determine the response and that it needs to have rained heavily before the actual date of comparison if similar responses are to occur.

Given this pattern, it is proposed that any change in the impact of land use on peak disharge as discharge varies should be evident in a change in the width of the response ranges shown in Fig. 5. Narrowing of the range as discharge increases would indicate a convergence of responses between the two scenarios, supporting the study hypothesis. The assessment can be carried out visually. In all cases the range increases rapidly as discharge increases from zero to low magnitudes. Different patterns appear, though, as discharge increases to moderate and high magnitudes. For the Pejibaye catchment (Fig. 5a), there is a tendency for the range certainly to stabilize and perhaps to narrow slightly at the more extreme flows. This suggests an absolute convergence of response. For the Panamá catchment (Fig. 5b), the range is largely constant but again narrows at the highest flows. This suggests at least a relative convergence in which the absolute difference in peak discharges remains similar, but the percentage difference decreases (i.e. as a percentage of the discharge). A very similar pattern of a constant difference between the Panamá and Lise catchment responses is shown by the field data analysis (Bathurst et al., in preparation). A notable feature of Fig. 5b is that, for most of the discharge range, the non-forested responses all lie a significant distance above the line of equality. This is probably a consequence of the model parameterization required to represent the unusual soil properties of the catchment. It appears that the high soil conductivities used in the simulation (Table 3) result in water draining from some of the soil columns faster than it arrives from precipitation. These columns therefore always have some soil storage capacity and this is greater under forested conditions (as there is higher interception evaporation). Consequently the simulations always show higher discharges under the current vegetation than under forested conditions.

For La Reina catchment (Fig. 5c), there is a tendency for the range to be constant over the moderate to high flows, suggesting relative convergence of response. Again this is consistent with the field data analysis, which indicates that the impact of the logging is proportionately less for the higher peak discharges than for the lower peak discharges (Bathurst et al., in preparation).

A more detailed study of the model analysis for La Reina catchment is reported by Birkinshaw et al. (in preparation), who propose the following mechanism for the convergence of peak discharge response between land use scenarios at high discharges: a) the wetter the antecedent conditions, the less is the difference in soil moisture deficit between the two cases and the smaller is the difference in discharge for a give rainfall input; b) higher discharges tend to occur only when the antecedent conditions are wet; and therefore c) the difference in response decreases as discharge increases. It seems likely, though, that this mechanism is overridden in truly extreme rainfall events, when, even if the soil moisture deficit is high, it is still negligible compared with the quantity of rain falling. This may explain the more obvious tendency for absolute convergence of response apparent for the hurricane rainfall environment of the Pejibaye catchment than for the other two.

An important outcome of the simulations is that, whatever the level of convergence for extreme rainfall events, forested catchments can significantly reduce flood peaks at more moderate floods. Such floods can still have adverse impacts on human activities and, as they occur more frequently than extreme events, the mitigating influence of forests should not be considered negligible.

6.2 Land use impact on flood peak discharge – combined rain and snowmelt events

This section considers the result for the Buena Esperanza catchment. The only differences between the model parameterizations for the two scenarios were the vegetation parameters affecting interception and transpiration and the degree-day factor for snowmelt. Figure 5d shows, as for the other three catchments, that there can be a range of “non-forested” (i.e. logged) responses for a given “forested” (i.e. current vegetation pattern) discharge.

On an annual scale, the simulated discharge for the logged catchment is considerably higher than for the current vegetation, owing to the lower evaporation once the forest has been removed, producing drier soil and a greater ability to store precipitation. However, the pattern for individual events is more complex. In the spring, when the entire basin in both cases is covered by snow, the discharge is higher for the logged basin. This is due to the higher degree-day factor in the logged area, which produces greater snowmelt. However, in later events, driven by snowmelt and precipitation, this pattern may be reversed. In the simulation with the current vegetation, snow still remains within the forest and its melt contributes to the discharge. By contrast, for the logged simulation the snow has already completely melted from this part of the basin and so cannot contribute to the discharge. The corresponding points can be seen below the line of equality in Fig. 5d. The timing depends on the amount of snow that accumulates over the winter and the temperatures during the spring snow melt. Once the snow has finished melting under the forest the pattern reverts back to the case of higher discharges in the logged catchment than for the catchment with the current vegetation.

The relative pattern in the Buena Esperanza catchment is complicated by the snow accumulation and melt. However, from January through to April there is no difference in discharge between the “logged” and “current” cases as a result of snowmelt (there is still snow high-up in the basin but this is the same in both simulations). The situation in these months is therefore similar to the other three catchments. Under these conditions there is little indication of a convergence of peak discharge response between the logged and forested cases for the bigger events. However, the forests are simulated as lying on top of a 10-m deep soil column. With this depth there are always some squares which do not saturate. These columns therefore always have some soil storage capacity and this is greater under forested conditions (as there is higher interception evaporation). Consequently the simulations always show higher discharges under the current vegetation than under forested conditions.

The point with the largest discharge in Fig. 5d is not derived from the 1000-year simulation but represents the observed 1954 event. The difference in peak discharge for this event is similar to those for the points in the moderate discharge range, suggesting that there may be relative convergence of response for extreme events. It may also be noted that the 1954 event has a magnitude considerably larger than those obtained from the 1000-year simulation. This suggests that the statistical generation of long rainfall time series may still struggle to attain observed extreme conditions if those conditions do not form part of the data record used in the generation process.

6.3 Impact of non-vegetation model parameters

The effect of representing differences between scenarios with more than just the vegetation parameters affecting interception and transpiration is shown in Fig. 6 for the case of the Pejibaye catchment. Increasing the overland flow resistance for the forest scenario reinforces the tendency for lower peak discharges in the forest case, producing a strong divergence of response. The percentage difference remains similar as the event size increases.

The effect of soil depth on the role of soil mositure deficit in generating differences between the scenario responses is shown in Fig. 7 for the case of La Reina catchment. The shallow soil reduces the influence of soil mositure deficit on runoff generation, allowing absolute convergence of the scenario responses. The deeper soil accentuates the differences in soil moisture deficit, producing a divergence of response.

These tests suggest that there may be circumstances in which a change in land use or land management can affect flood peak response for extreme rainfall events as much as for smaller events.

6.4 Land use impact on erosion and sediment transport

The effect of forest cover on soil erosion and sediment transport is illustrated for La Reina catchment (Fig. 8). The logged case always has a higher transport rate than the forested case. In contrast then to the complexities of land use impact on flood peak discharge, the conclusion is unequivocal. For all the conditions simulated at La Reina catchment, forest cover protects the soil from erosion and therefore reduces the sediment transport in the river in comparison with the logged case.

6.5 Simulation reliability

Between the focus catchments the simulation results are generally similar, indicating a high level of self consistency. It could be argued, though, that this is not so surprising since the difference between the two model scenarios is the same in each case, i.e. the model parameters determining transpiration and interception (and the degree-day factor for the Argentinean site). It is important to be confident, therefore, that the model is not simply predisposed to deliver the same result without accounting for real differences between the sites. Several points are relevant:

- as the scenarios represent change of only the vegetation cover (and not such factors as forest roads or the effect of forest activities on soil compaction), there should in fact be some degree of consistency between the sites;
- the models *do* account for the real differences in rainfall characteristics, topography and soil characteristics between the sites;
- the differences in the interception and transpiration parameter values between scenarios correspond to experimental measurement and physical

understanding; e.g. the aerodynamic resistance is higher for grassland than for forest (Table 3);

- the calibrations, with Nash-Sutcliffe efficiencies generally exceeding 0.8, indicate an ability to represent the characteristic responses of the individual sites; this is especially so for the Chile site, for which good calibrations were achieved for the pre- and post-logging periods that form the modelling scenarios;
- the extreme rainfall events, and the range of rainfall events generally, are provided by the statistical generation of the 1000-year time series, a consistent and objective means of extrapolating from the available data record that accounts also for differences between sites;
- where direct comparison with the field analysis is possible, the agreement in terms of pattern is excellent, i.e. for the Ecuador and Chile catchments.

Confidence in the results is therefore be considered sufficient to allow overall conclusions on the model analysis of the test hypothesis to be drawn, relevant to a range of Latin American environments.

7. Conclusions

The hypothesis that, as the size of the flood peak increases, the effect of land use becomes less important, has been tested through a model analysis, complementing a field data analysis. A systematic approach was used, involving the same approach across the four focus sites and an extension of the rainfall magnitudes beyond those of the available record. The method of extension, through the generation of 1000-year rainfall time series, is an objective approach in line with other recent studies. A consistent result was obtained, with the simulations supporting the hypothesis overall, in agreement with the field data analysis. Loss of forest cover raises annual runoff totals and flood event peak discharges. However, as the peak discharge increases to extreme levels, the overall difference in peak discharge between the forest and non-forest scenarios decreases either absolutely or relatively. In catchments with snowmelt regimes, forest cover can both increase and decrease peak discharges relative to the unforested case and it is difficult to perform a clear test of the hypothesis. It should be noted also that the interaction of vegetation with snowmelt was represented in a limited way in the simulations, solely on the basis of the degree-day factor method. Nevertheless the analysis suggests a relative convergence of response. Thus the results support the hypothesis across a range of Latin American environments from Costa Rica (hurricane regime), through Ecuador (high altitude and El Niño events) and Chile (temperate rain forest) to Tierra el Fuego, Argentina (rain and snowmelt events).

The model analysis is limited to small catchments (0.35 to 131 km^2) but the field data analysis shows that, at least in certain cases, the hypothesis is still recognizable at scales of 1000 km^2 (Iroumé et al., 2007). However, the pattern is complicated by a number of factors. The convergence of response at high flows is not necessarily absolute but may be relative. This means that forest cover may moderate the flood peak discharge for high rainfall events, even though the relative effect is less noticeable. Further, the effect of the forest cover depends on more than the size of the rainfall event: factors such as soil depth, antecedent moisture content and season also play a role. Other anthropogenic impacts and climate changes may have greater effects and so drown out the forest signal. A limitation of the study is that it has considered the effect of a change only in vegetation cover. It has not considered the effect of the practices used in that removal, including logging technique and road building (e.g. La Marche and Lettenmair, 2001; DeWalle, 2003). The provision of forest roads, for example, may effectively increase stream network density and contribute to an increase in flood levels. The single test of an altered overland flow resistance (Fig. 6) shows that a change in land management could conceivably have a significant impact on flood peak discharge for extreme events.

The implication for land management is that reforesting a catchment to prevent extreme floods may not be very effective. A more appropriate approach is likely to be downstream zoning and land use control to reduce the impact of the flood. Nevertheless, forests still offer significant benefits: they reduce the impact of moderate but more frequent floods and they provide a good level of protection against soil erosion and sediment transport for a wide range of events. The management issues associated with reforestation are discussed in detail in Mintegui and Robredo (2008).

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Table 1
The focus catchments for the modelling study

Costa Rica	Ecuador	Chile	Argentina
Pejibaye, (131 km^2)	Panamá (10 km^2) and Lise (2.3 km^2), sub-basins of the Rio Chanchán (1409 km^2)	La Reina (0.35 km^2)	Buena Esperanza (12.9 km^2)

Table 2
Focus catchment data availability for model application

Catchment	Grid resolution (m)	Vegetation cover	Soil types	Rainfall record	Evaporation record	Outlet discharge record	Extreme event
Pejibaye	500	Cultivated land, grassland, forest	3 soils (silty clay, silty loam, sandy loam). Depth (2 m)	3 daily gauges from 1970. 1 hourly gauge 1991-93 (Bolivia)	Daily PE at Bolivia from 1972	Daily 1971-96; max monthly values	Hurricanes 22/10/88, 14/9/93, 26/7/96
Lise / Panamá	80 / 150	Panamá: 73.5% pasture, crops, grassland, 16.5% forest. Lise: 69.2% forest.	3 soils (Umbrisol, Leptosol, Umbric Leptosol). Depth 0.4-m top layer, 1.2-m lower layer, except Leptosols (0.3 m thick).	6 hourly gauges 11/2/05-1/6/06	Daily PE at Namza Lise 3/6/05-1/6/06	Panamá hourly 6/5/05-25/5/06. Lise hourly 11/2/05-1/6/06	El Niño 1982-3, 1997-8 2007-8
La Reina	50	Radiata pine and native trees to January 2000; logging followed by replanting	Sand 47.6%, silt 33.8%, clay 18.6%. Depths 0.5-1.9 m.	1 hourly gauge 1996-2003 at catchment	Hourly meteorological data 1996-2003	Hourly 1996-2003	Rain 12/10/02
Buena Esperanza	180	Natural pine and deciduous forest, grassland, rock debris, glacier	Peat over compacted till (total depth 10 m); rock debris	Hourly gauge (Aerosilla) 1/5/05-30/4/07	Hourly temperature at Ushuaia and glacier 1/5/05-30/4/07	Hourly at outlet and internal sites 1/5/05-30/4/07	Rain and snowmelt 6/11/54

Table 3
Values of the principal SHETRAN parameters for the focus catchments

Parameter	Pejibaye	Lise/Panamá	La Reina	Buena Esperanza
Strickler overland flow resistance coefficient ($m^{1/3}$ s^{-1})	4[a]	0.1[a]	0.1[a]	0.08-0.12[a]
Actual/potential evapotranspiration ratio at soil field capacity: forest	0.7	-	-	-
pasture	0.4	-	-	-
Aerodynamic resistance (s m^{-1}): forest	-	10	3.5	3.5
logged or pasture	-	30	40	40
Canopy (stomatal) resistance at field capacity (s m^{-1}): forest	-	50	100	70
logged or pasture	-	50	50	50
Soil depth (m)	2	0.3-0.4 / 1.2[b]	2.5	8-0.5 / 2-9.5 / 0.6-1.2[c]
Soil porosity (m^3 m^{-3})	0.45	0.6 / 0.8[b]	0.44	0.95 / 0.35 / 0.4[c]
Soil residual moisture content (m^3 m^{-3})	0.093	0.1 / 0.1[b]	0.096	0.3 / 0.15 / 0.05[c]
Van Genuchten exponent α for soil moisture content/ tension curve (cm^{-1})	0.052	0.01 / 1.0[b]	0.008	0.012/0.006/0.8[c]
Van Genuchten exponent n for soil moisture content/ tension curve (-)	1.7	1.8 / 1.1[b]	1.4	1.5 / 1.5 / 1.1[c]
Saturated zone conductivity (m day^{-1})	10[a]	1 / 30[a, b]	1[a]	10[d]-2[e] / 0.3 / 5[a, c]

[a]Calibrated; [b]upper/lower horizon; [c]organic topsoil/compacted till/rock debris, values obtained by combination of measurement and calibration; [d]vertical flow; [e]horizontal flow

Figure captions

Fig.1. The hypothesis that, as the size of the flood peak increases, the effects of land use become less important.

Fig. 2. SHETRAN mesh and elevations for the catchments (with grid resolutions): a) Pejibaye (500 m); b) Panamá (150 m); c) Lise (80 m); d) La Reina (50 m); e) Buena Esperanza (180 m), also showing the Martial (4.8 km^2) and the Godoy (1.5 km^2) subcatchments. The stream channels run along the edge of the grid squares.

Fig. 3. Comparison of simulated and measured discharges at the catchment outlets: a) Pejibaye, January 1991 – December 1993; b) Panamá, 2005-2006; c) Lise, 2005-2006; d) La Reina, 1997-1999; e) La Reina, 2000-2001; f) Buena Esperanza, with Aerosilla precipitation, August 2005 – April 2007. (Pejibaye, mean daily; all others, hourly.)

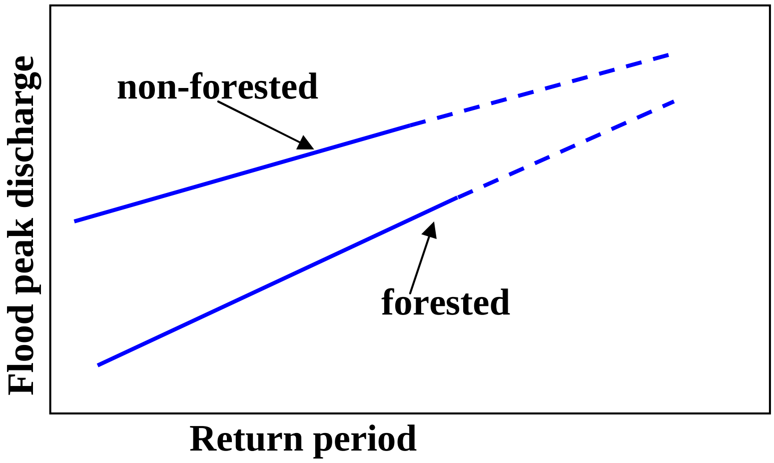
Fig. 4. Measured and simulated discharges at the Buena Esperanza catchment outlet for the major event of November 1954.

Fig. 5. Comparison of corresponding maximum daily discharges (m^3 s^{-1}) from 1000-year SHETRAN simulations of catchment scenarios for: a) Pejibaye basin, current vegetation and forest; b) Panamá, current vegetation and forest; c) La Reina, forest and logged; d) Buena Esperanza, current vegetation and logged, including the 1954 event. Line is line of equality.

Fig. 6. Comparison of corresponding maximum daily discharges (m^3 s^{-1}) for current vegetation (with unchanged flow resistance) and forested conditions (with increased flow resistance) from 1000-year SHETRAN simulations of the Pejibaye basin. Line is line of equality.

Fig. 7. Comparison of corresponding maximum daily discharges (m^3 s^{-1}) for the forested and logged conditions from 1000-year SHETRAN simulations of La Reina catchment for three different soil depths. Line is line of equality.

Fig. 8. Comparison of corresponding maximum daily sediment discharges (kg s^{-1}) for the forested and logged conditions from 100-year SHETRAN simulations of La Reina catchment. Line is line of equality.



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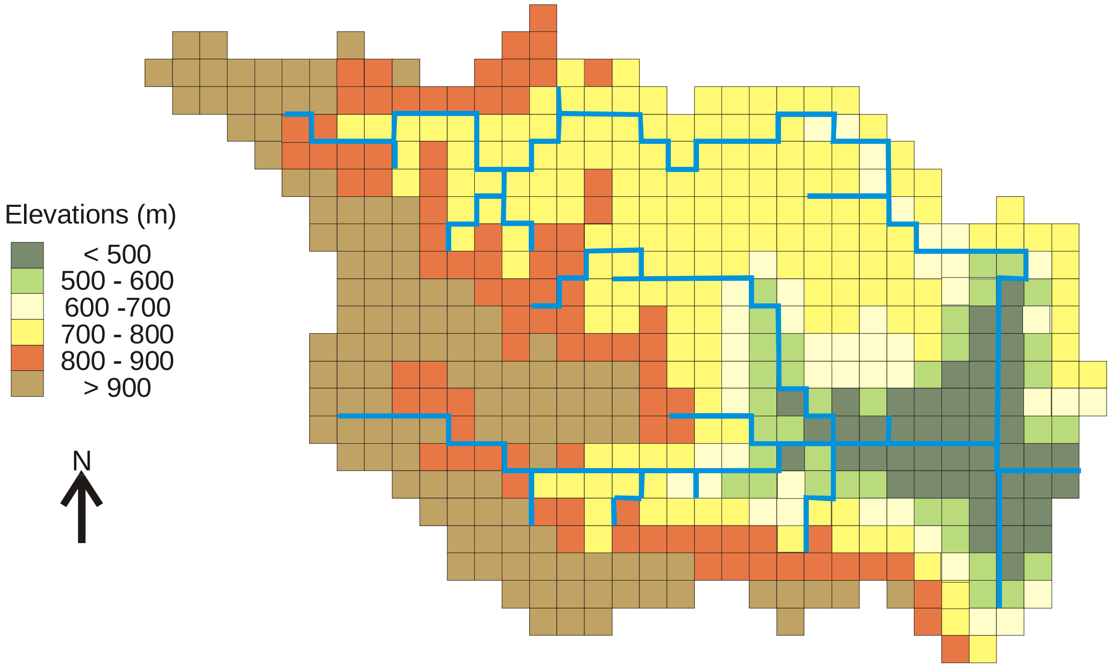


Fig. 2a. SHETRAN mesh (500-m grid resolution) and elevations for the Pejibaye catchment. The stream channels run along the edge of the grid squares.

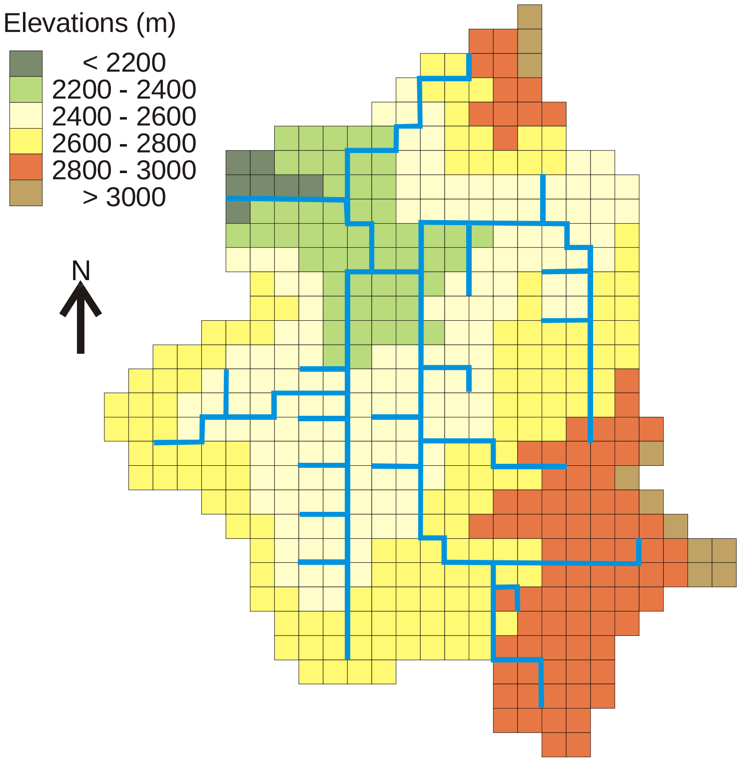


Fig. 2b. SHETRAN mesh (150-m grid resolution) and elevations for the Panamá catchment. The stream channels run along the edge of the grid squares.

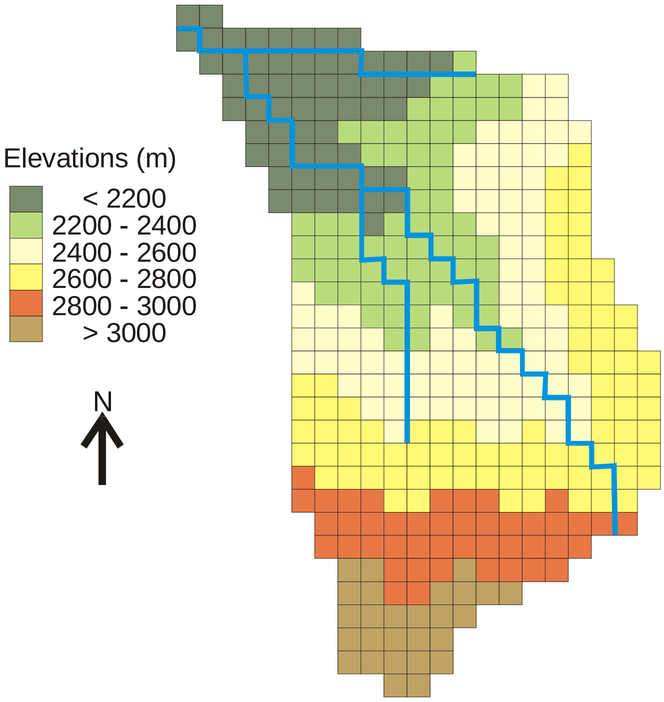


Fig. 2c. SHETRAN mesh (80-m grid resolution) and elevations for the Lise catchment. The stream channels run along the edge of the grid squares.

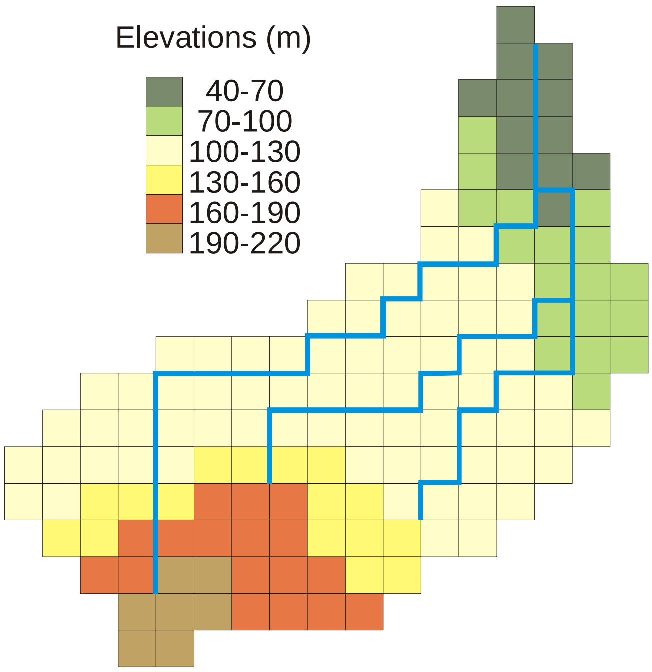


Fig. 2d. SHETRAN mesh (50-m grid resolution) and elevations for La Reina catchment. The stream channels run along the edge of the grid squares.

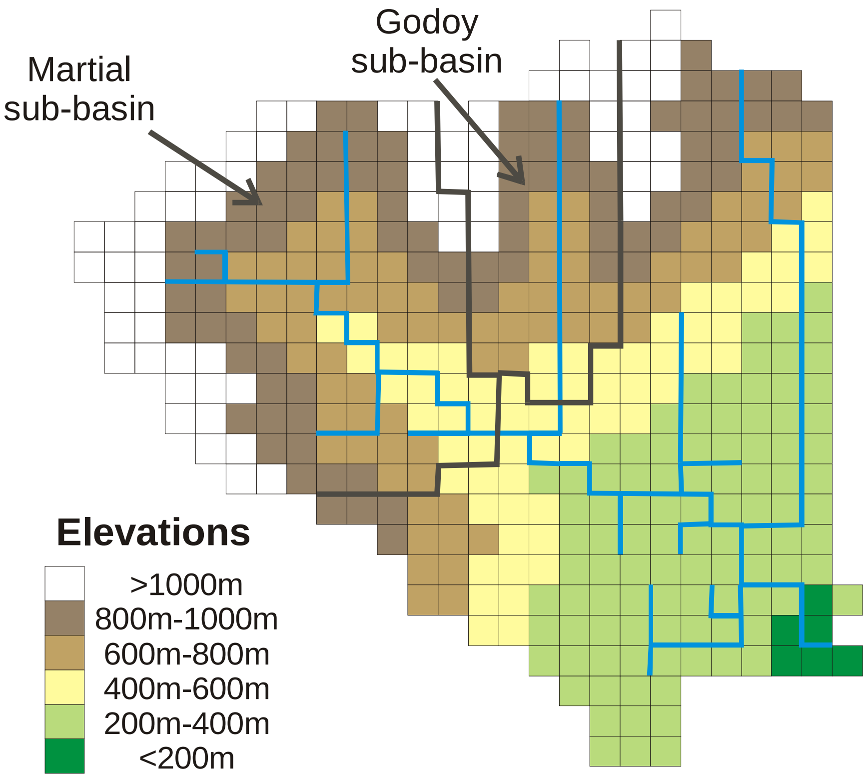


Fig. 2e. SHETRAN mesh (180-m grid resolution) and elevations for the Buena Esperanza catchment. The stream channels run along the edge of the grid squares. The Martial (4.8 km^2) and the Godoy (1.5 km^2) subcatchments are also shown.

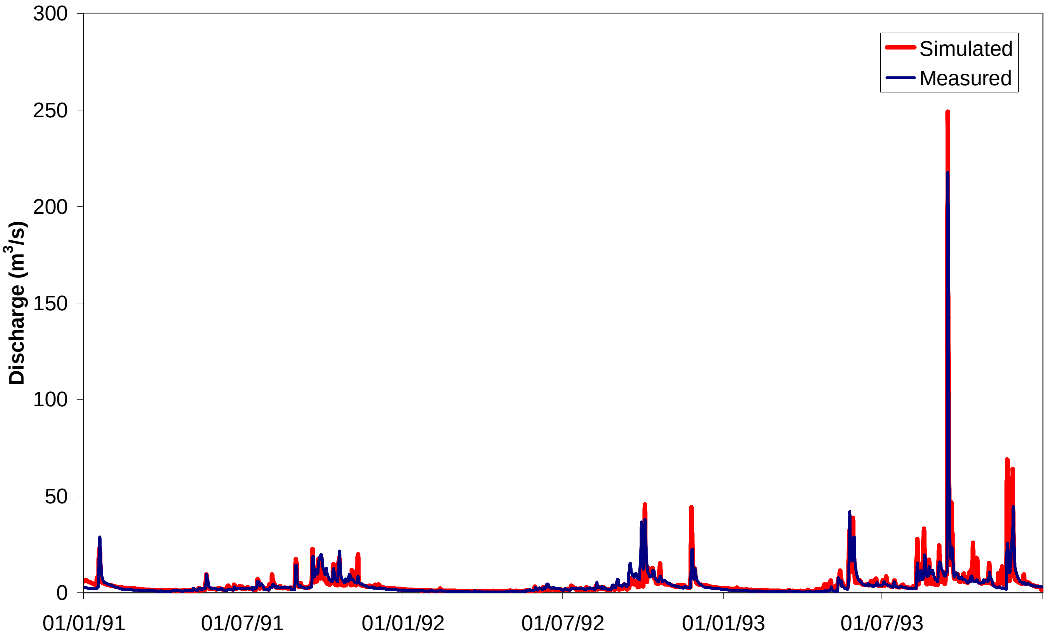


Fig. 3a. Simulated and measured mean daily discharges at the Pejibaye catchment outlet, January 1991 – December 1993.

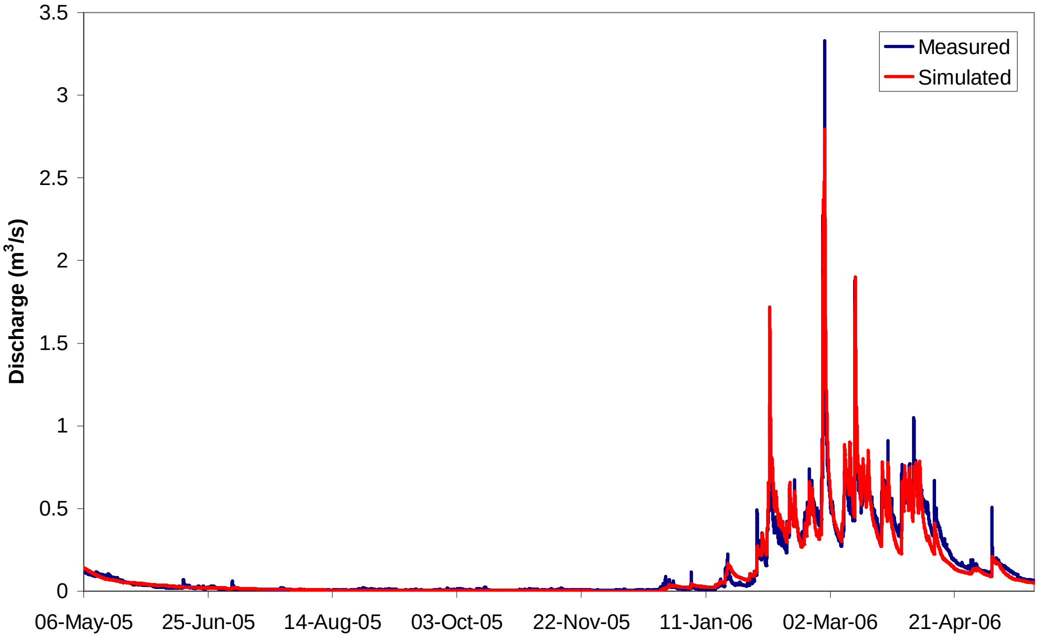


Fig. 3b. Measured and simulated hourly discharges at the Panamá catchment outlet for 2005-2006.

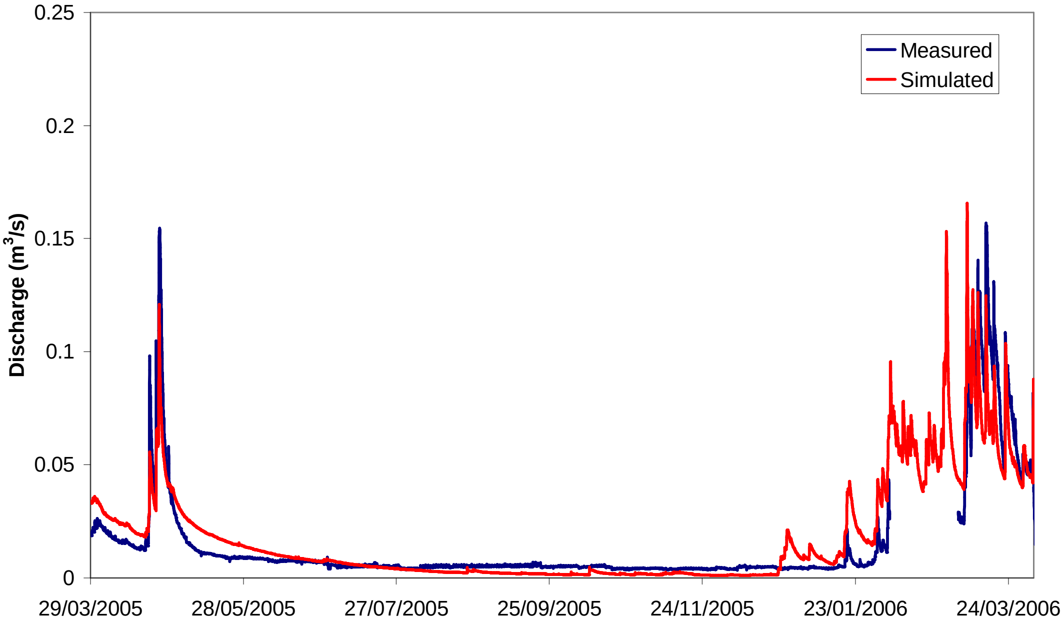


Fig. 3c. Measured and simulated hourly discharges at the Lise catchment outlet for 2005-2006.

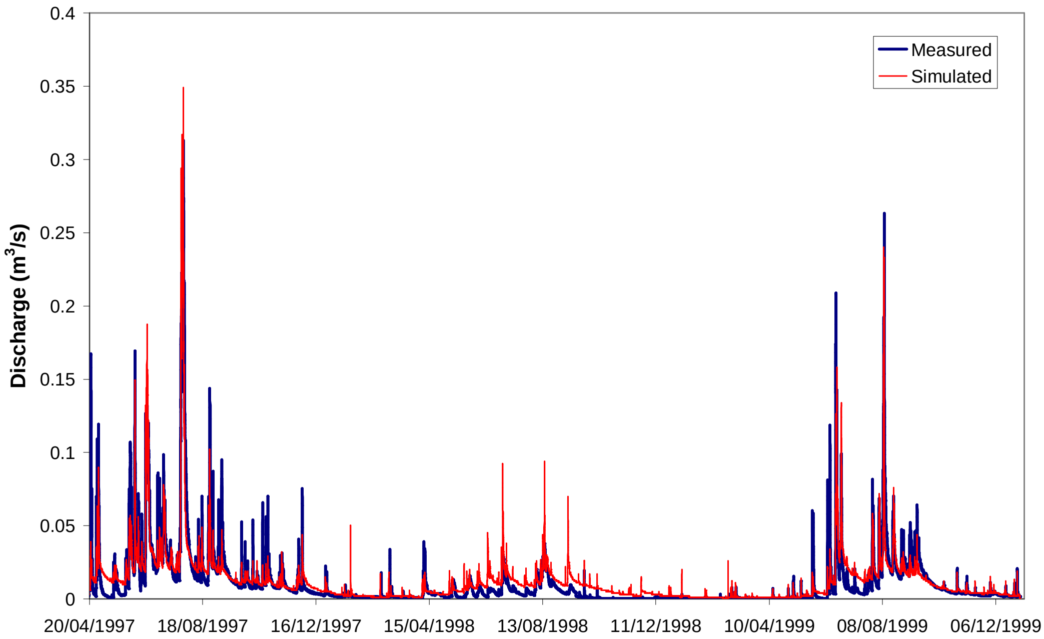


Fig. 3d. Measured and simulated hourly discharges at La Reina basin catchment for 1997-1999.

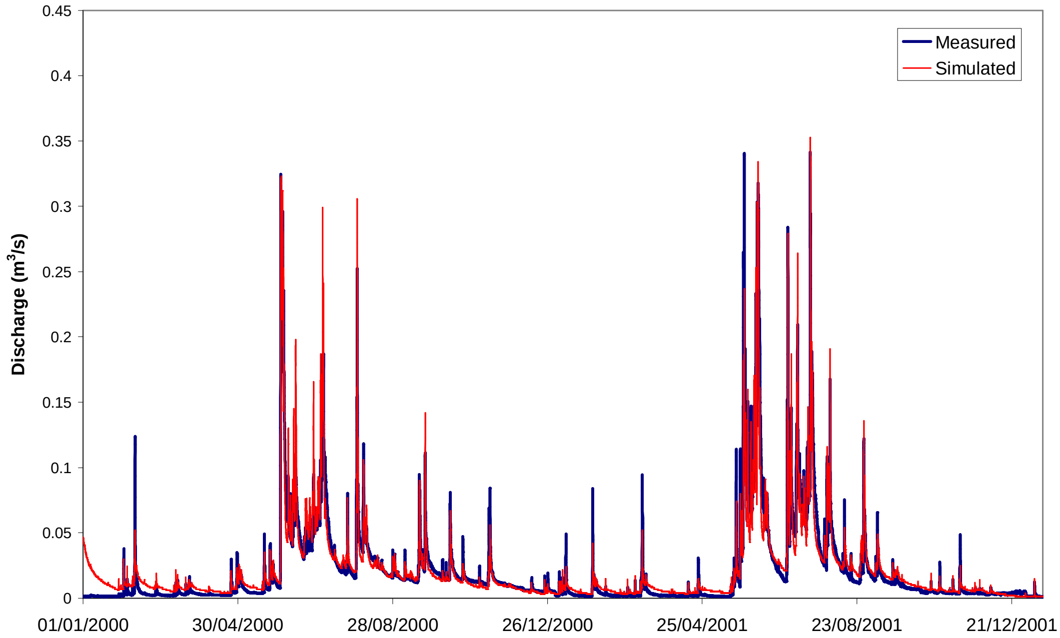


Fig. 3e. Measured and simulated hourly discharges at La Reina catchment outlet for 2000-2001.

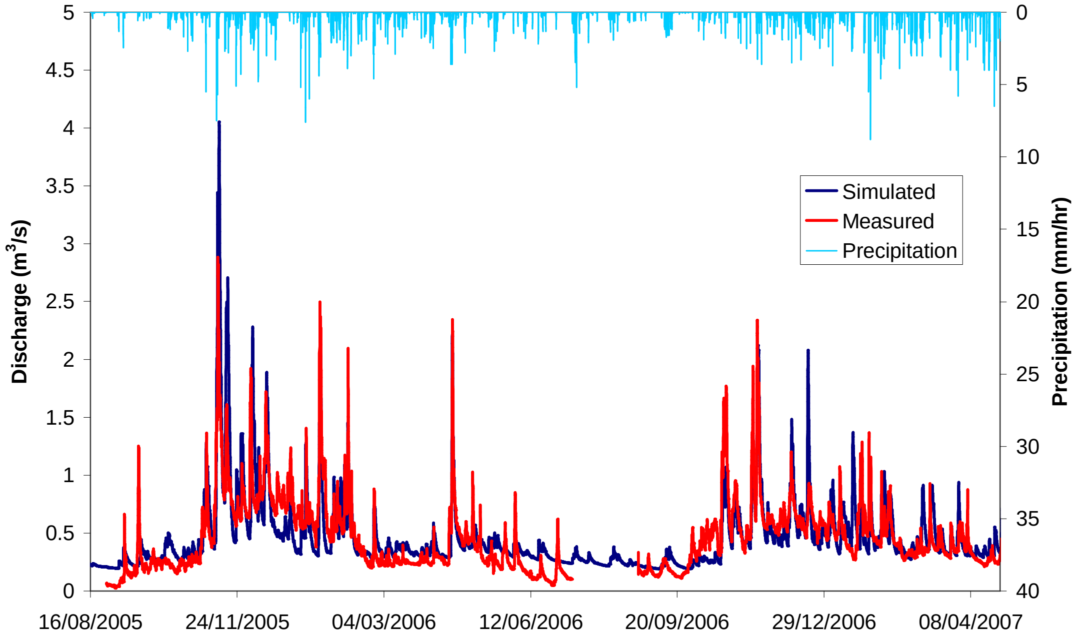


Fig. 3f. Measured Aerosilla precipitation and measured and simulated hourly outlet discharges for the Buena Esperanza catchment, August 2005 – April 2007.

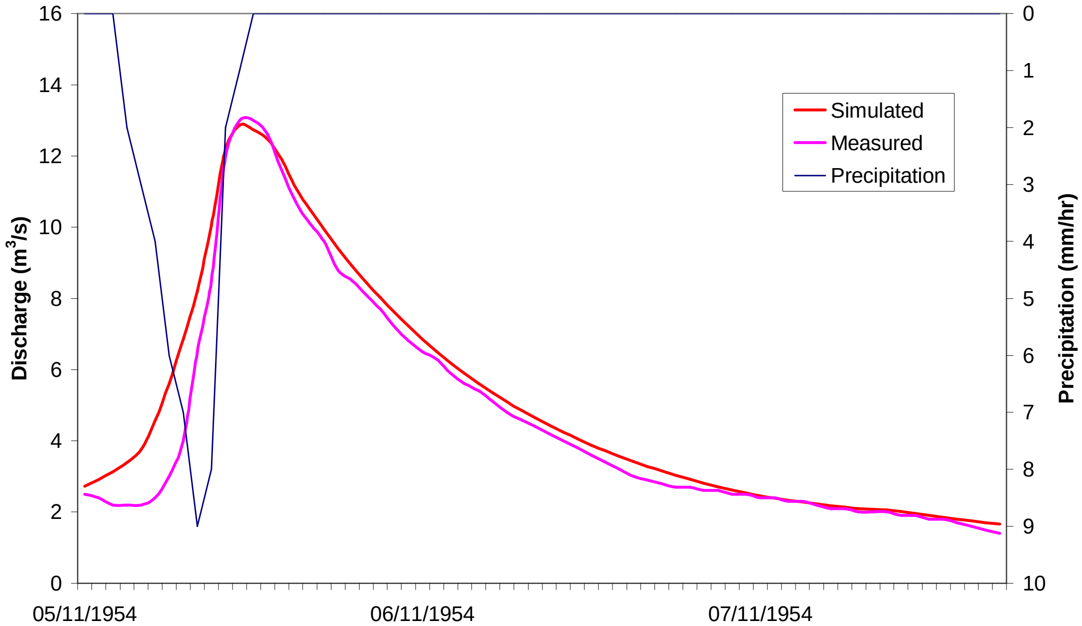


Fig. 4. Measured and simulated hourly discharges at the Buena Esperanza catchment outlet for the major event of November 1954.

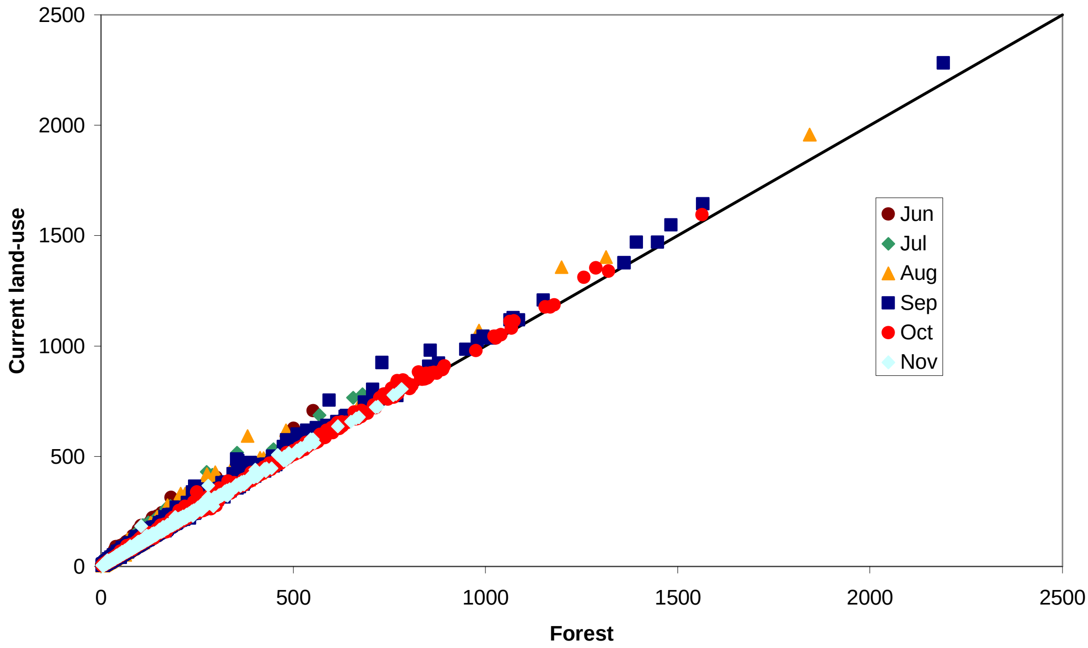


Fig. 5a. Comparison of corresponding maximum daily discharges (m^3 s^{-1}) for current vegetation and forested conditions from 1000-year SHETRAN simulations of the Pejibaye catchment. Line is line of equality. There are no major events from December through to May.

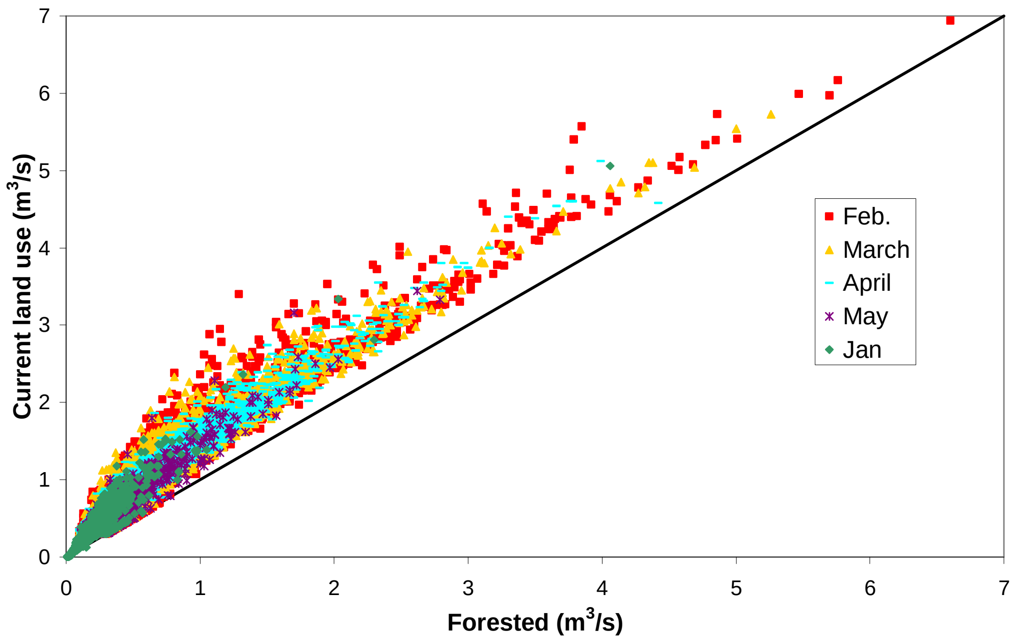


Fig. 5b. Comparison of corresponding maximum daily discharges (m^3/s) for current vegetations and forested conditions from 1000-year SHETRAN simulations for the Panamá catchment. Line is line of equality. There are no significant events from June to December.

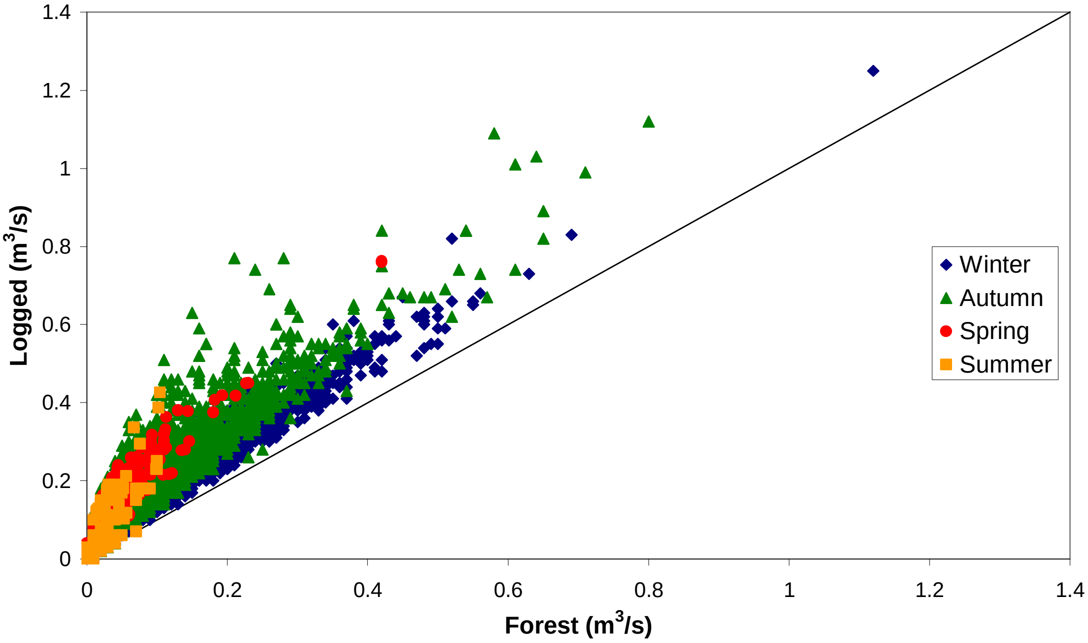


Fig. 5c. Comparison of corresponding maximum daily discharges ($m^3\ s^{-1}$) for forested and logged conditions from 1000-year SHETRAN simulations of La Reina catchment. Line is line of equality.

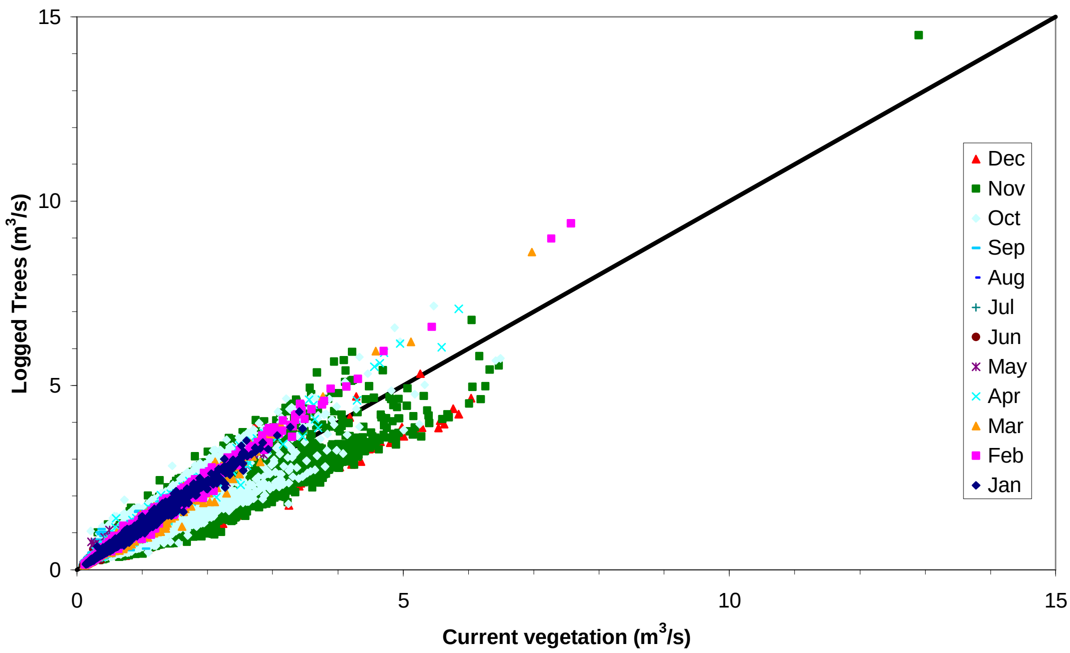


Fig. 5d. Comparison of corresponding maximum daily discharges ($m^3\ s^{-1}$) for current vegetation and logged conditions from 1000-year SHETRAN simulations of the Buena Esperanza catchment, including the 1954 event. Line is line of equality.

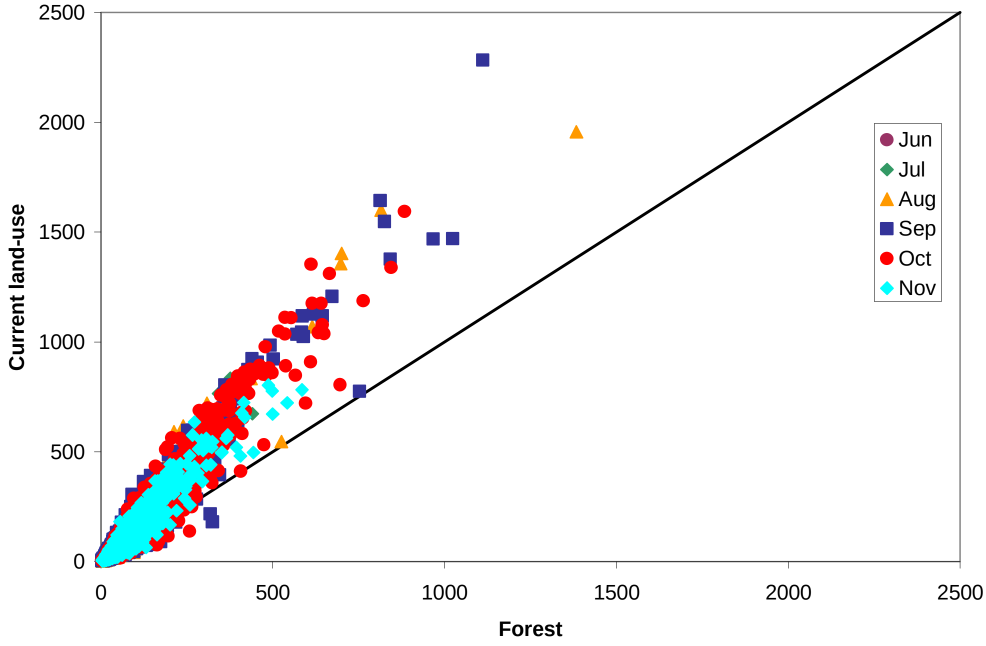
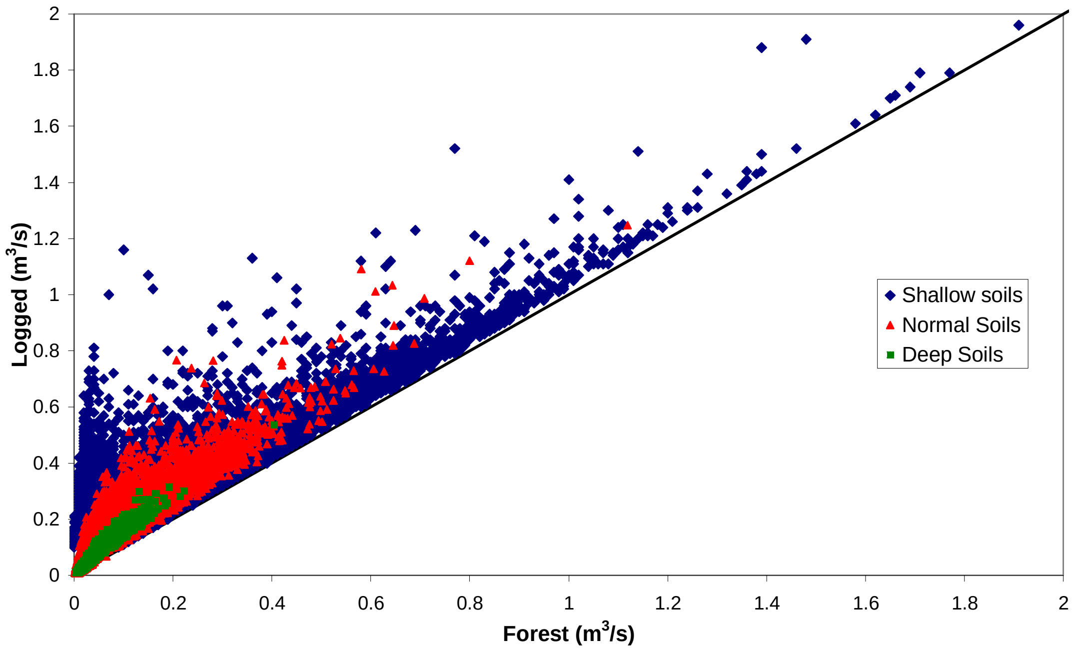


Fig. 6. Comparison of corresponding maximum daily discharges (m^3 s^{-1}) for current vegetation (with unchanged flow resistance) and forested conditions (with increased flow resistance) from 1000-year SHETRAN simulations of the Pejibaye catchment. Line is line of equality. There are no major events from December through to May.



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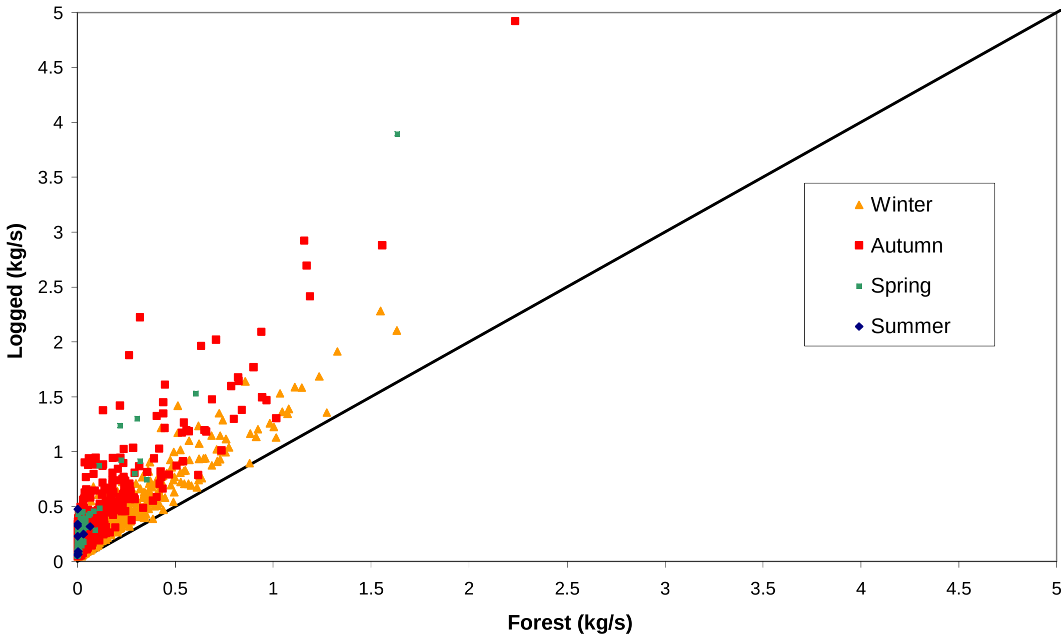

Fig. 8. Comparison of corresponding maximum daily sediment discharges (kg s^{-1}) for the forested and logged conditions from 100-year SHETRAN simulations of La Reina catchment. Line is line of equality.