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The effect of forest cover on peak flow and sediment discharge—an integrated field and modelling study in central–southern Chile

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Abstract:

An integrated field and modelling study was carried out on the 35-ha La Reina catchment, Chile, to test the hypothesis that the effect of forest cover on flood peaks becomes less important as the size of the hydrological event increases. Meteorological and discharge data were measured at the catchment before and after the pine plantation that covered 80% of the catchment area was logged. Analysis of the measured response of the catchment provides support for the hypothesis but is not conclusive. Therefore, modelling of the catchment using 1000 years of generated rainfall data representative of the current conditions was carried out for the forested and logged states. The simulations show that the absolute difference in discharge between the two cases remains approximately constant as the discharge increases: thus as a percentage of discharge it decreases. This relative convergence appears to become significant at return periods of greater than approximately 10 years. Tests with different hypothetical soil depths for the forested and logged catchments show an absolute convergence in discharge between the two cases for shallow soils and no convergence for deep soils. Sediment transport simulations show that forest cover provides a clear benefit in protecting the soil from erosion. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS peak flow; flood frequency; distributed models; forest harvesting; SHETRAN; sediment yield

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INTRODUCTION

Deforestation and logging are regularly blamed for exacerbating the disastrous effects of floods generated by extreme rainfall. Government and development agency water resources policies therefore tend to adhere to this perception, for example, imposing plantation programmes and logging bans to reduce flooding. However, there is a lack of scientific evidence to support such policies.

Over the long term (i.e. annual scale), there is good understanding of the effect of forest cover on water yield and quality (Bosch and Hewlett, 1982; Andréassian, 2004; Brown *et al.*, 2005; Chang, 2006; Sun *et al.*, 2006). Deforestation tends to generate higher flows, net erosion and nutrient losses. Afforestation tends to reduce groundwater recharge and net water availability because the trees intercept part of the precipitation and, owing to their deeper root systems, transpire more water than grasses during the drier periods. In contrast to the understanding of long-term effects, though, the impact of forest management on river catchment response for extreme rainfall events is an area in which there is still considerable scientific uncertainty. Some researchers have found a general increase in peak flows after timber logging (Fahey, 1994; Jones and Grant, 1996). However, many have reported increases in peak flows only for events with return periods smaller than 10 years (Whitehead and Robinson, 1993; Thomas and Megahan, 1998; Ziemer, 1998; Beschta *et al.*, 2000; La Marche and Lettenmaier, 2001; Caissie *et al.*, 2002). Smith (1987), on the other hand, found that timber logging affects runoff even for storms of 100-year return periods. It appears that the magnitude and duration of post-logging effects on base and peak flows depend on soils, morphology and geology of the catchment, on rainfall characteristics and pattern, on the extent and type of forest operations and the sort of the vegetation established after the logging. There is scope, therefore, to investigate the effect further and to extend the investigations to climate and forest regimes beyond those reported in the literature, i.e. the Pacific Northwest of the United States, the United Kingdom and New Zealand.

This study is focussed on the effect of forest cover on peak flow and sediment discharge in the 0·35-km^2 La Reina catchment in the temperate region of central–southern Chile. In this region, a large amount of forest has been planted in recent decades, most of it on land that had previously been deforested for decades (CORMA, 2007). This study analyses the effect of the clear-cutting of the mature pine forest in early 2000, firstly by analysing the discharge data from 1997 to 2006 and, secondly, by carrying out a modelling study using the physically based spatially distributed SHETRAN catchment model. The aim is to test the hypothesis that

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the effect of forest cover on flood peaks becomes less important as the size of the hydrological event increases.

The above-mentioned studies of peak flow responses have tended to rely mainly on data analysis and therefore have been limited by the availability of the data. Even cases for which there are long datasets [Jones and Grant (1996) have three decades of post-harvest data], rare and extreme events are poorly represented. In Chile, with fast growing plantations and very short rotations, the availability of data is more problematic. For example, Iroumé *et al.* (2010) showed that the post-harvesting effect is clearly noticeable for the first 3 years after the forest intervention before runoff shows a recovery trend towards pre-harvesting conditions. This fact generates a limitation on field studies as the post-harvesting period is very short and the data representing this period are restricted. Model application can complement such studies by extending the range of events and providing a systematic basis for the analysis. A few studies have begun to demonstrate the contribution which modelling can make to topic (Bultot *et al.*, 1990; Schnorbus and Alila, 2004; Candela *et al.*, 2005; Brath *et al.*, 2006). This study extends that work through model analysis of a clearly defined logging episode.

LA REINA CATCHMENT

La Reina is a 0·35-km^2 catchment in Region X, 41 °S, in Chile (Figure 1). Until October 1999, a commercial Monterey Pine (Pinus radiata D. Don) forest planted in 1977 covered 79·4% of the catchment (with deciduous trees in the remainder). The entire catchment was logged from October 1999 to February 2000 and, during June–July 2000, it was replanted with Eucalyptus nitens (H. Deane & Maiden). The logging was carried out with rubber-tired Skidders in the areas with gentle slopes and cable logging on the steeper slopes. Soils are mainly well drained and around 0·5–2 m deep. The mean annual precipitation is approximately 2500 mm, mostly from frontal rainfall in the winter (June–August). The annual potential evaporation is approximately 1000 mm.

This analysis uses data from the intensive monitoring of La Reina catchment carried out between June 1996 and December 2006 (Table I). These data include hourly discharge from the flume at the catchment outlet and hourly meteorological data from a site at the edge of the catchment. The data are generally of good quality, although some infilling of the meteorological data has been necessary (especially from June to September 2002 because of problems with the precipitation measurements). There is also a long period of missing data in 2004 and 2005 (Table I). Some suspended sediment sampling has been performed at the outlet but not sufficiently to allow calibration of a sediment transport model. Forty-five years of daily precipitation data were available for the Isla Teja weather station at Valdivia, 60 km from La Reina and this data was used to supplement the shorter precipitation record at La Reina.

SHETRAN MODEL

SHETRAN (www.ceg.ncl.ac.uk/shetran/) is a physically based, spatially distributed modelling system for water flow and sediment and solute transport in river catchments (Ewen *et al.*, 2000; Birkinshaw *et al.*, 2009). It includes components for vegetation interception and transpiration, snowmelt, overland flow, variably saturated subsurface flow, river/aquifer interaction and sediment yield. Solutions to the governing, physics-based, partial differential equations of mass and momentum

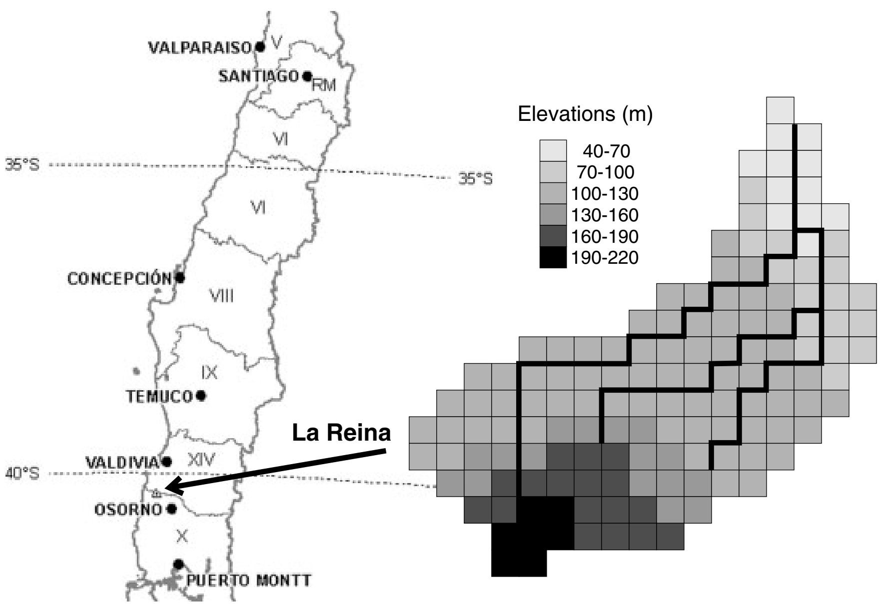

Figure 1. Location of the La Reina catchment (Roman numerals show national regions) and SHETRAN mesh and elevations; the stream channels in SHETRAN run along the edge of the grid squares

Table I. Data availability (hourly) at La Reina up to December 2006

Data type	Data period	Notes
Weather station	June 1996–December 2006	Underestimated precipitation data for June–September 2002. No precipitation data for January 2004–December 2004
Discharge	April 1997–December 2006	No data for November 2003–June 2005

are achieved on a three-dimensional grid using finite-difference equations. Application of SHETRAN to simulate the effect of land-use change on runoff and sediment yield has been demonstrated by Lukey *et al.* (2000) for a catchment in France. Other examples of recent applications include Adams and Elliot (2006) and Birkinshaw (2008).

The most convenient way of visualizing SHETRAN is as a representation of the catchment as a set of vertical columns, with each column divided into finite-difference cells. The lower cells contain aquifer materials and groundwater, higher cells contain soil and soil water and the uppermost cells contain surface waters and the vegetation canopy. The mesh follows the topography of the catchment with channels specified around the edge of the finite-difference cells. The parameters of the physical laws vary from square to square on the mesh, thus allowing representation of the spatial heterogeneity of the physical properties of the rocks, soils and vegetation cover. The coupled surface/subsurface representation allows overland flow to be generated by rainfall excess over infiltration and by upward saturation of the soil column. Soil erosion is modelled as a function of raindrop impact and overland flow (Wicks and Bathurst, 1996)

SHETRAN is described as being physically based as it solves the fundamental physics-based equations of mass, momentum and energy conservation. The model parameters therefore have physical meaning and can be evaluated from field measurements and physical reasoning. It is spatially distributed, which means that the input meteorological data, the model parameters and the output variables can vary between soil columns. The physically based approach is important in this study as it allows the change in forest cover to be modelled by changing the vegetation parameter values to represent the forest and logged conditions using physical reasoning. The spatially distributed nature of the model is also important as the effect of land-use on soil moisture in individual grid squares can be studied.

DATA ANALYSIS

Iroumé *et al.* (2006b) have previously investigated the effect of logging at La Reina. They analysed data for January 1997–December 2002 and found a 110% increase in mean annual runoff as a result of the logging. This analysis is extended as follows. Flow duration curves (Figure 2) were calculated from the daily discharge for each of the pre- and post-logging years (1997–1999 and 2000–2003, respectively). The curves show the expected response on an annual scale with, in general, higher flows post-logging than pre-logging, although there is some variability between the years depending on the precipitation. For example, 1997 was a very wet year and so the flow duration curve is higher than that for many post-logging years. From Figure 2, it can be seen that there is a definite upward 'shift' of the Q10% value in the post-logging years, with a maximum Q10% value of 8000 m^3 day^{-1} occurring in 2000 compared with a minimum Q10% value of 2000 m^3 day^{-1} in 1998.

Iroumé *et al.* (2006b) also analysed the relationship between the size of the rainfall event and the peak discharge and, from this analysis, estimated a 32% increase in mean peak flows as a result of logging. Peak flows were analysed by separating them into categories based on rainfall event volume ('small' rainfall events from 5 to 10 mm, 'medium' events from 10 to 50 mm, and 'large' events with rainfall depths greater than 50 mm) for the pre-logging and post-logging period (up to 2003) (Primrose, 2004; Iroumé *et al.*, 2006a). *In the pre-logging period, there were 41 small events, 95 medium events and 37 large events. In the post-logging period, there were 89 small events, 190 medium events and 87 large events.* These data show an increase in mean peak discharge for small, medium and large events as a result of logging. However, the percentage increase for the 'small' event category (189% increase) is greater than that for both the 'medium' (74% increase) and 'large' (62% increase) event size categories, suggesting that the larger the event, the less is the effect of land-use. The post-logging data are plotted separately for each year in Figure 3; the data for 2005 and 2006 are also plotted to show the pattern beyond the immediate post-logging period. The figure shows that, in spite of the development of the new plantation established in the year 2000, peak discharges registered in the sixth year after logging are still significantly higher than those of the pre-logging period. They do not show an initial post-logging increase followed by a gradual diminution tending towards the peak discharge levels of the pre-logging condition, a pattern that might typically be expected.

In an attempt to examine peak flows in detail, further consideration was given to the pre- and post-logging peak flow values arising from extreme rainfall events exceeding 100 mm in total precipitation (the upper portion of the 'large' event size category). In total, across the period of data analysis (June 1996 to December 2003), only 25 precipitation events exceeded this rainfall total; 9 in the pre-logging period and 16 in the post-logging period. Figure 4 compares the relationship between these extreme events and the resultant peak discharge values

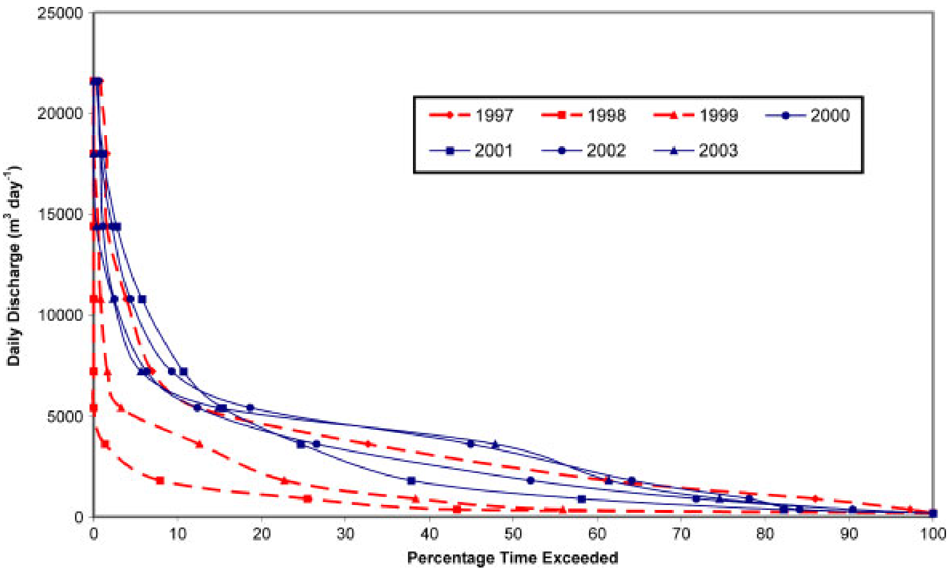

Figure 2. Flow duration curves for each of the pre- and post-logging years (period 1997–2003)

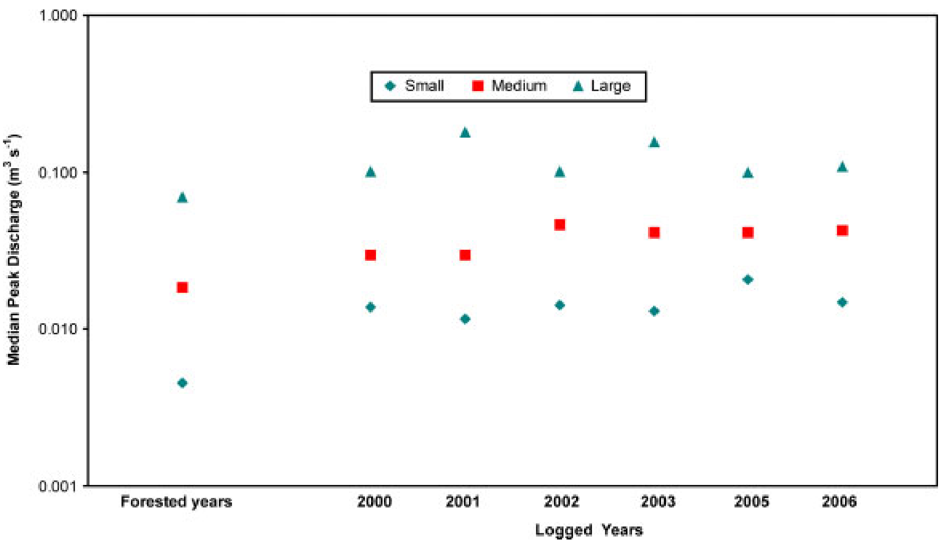

Figure 3. Trends of median peak flow values for small, medium and large events for the forested years and each of the post-logging years, La Reina catchment

for the two periods. The trends from Figure 4 suggest a convergence of peak flows for the pre- and post-logging periods for extreme rainfall events, but the trends are very sensitive to the two extreme points.

It would be helpful to quantify the return period for the peak flows above which there appears to be convergence of response. The highest instantaneous flows measured at La Reina outlet during 1997–2006 were 0·342 m^3 s^{-1} on 17 July 2001 and 0·337 m^3 s^{-1} on 12 December 2002. However, the data from La Reina (Table I) are insufficient to provide statistical reliability for the return periods for these events. The analysis was therefore extended to regional raingauges and discharge gauging stations with longer records. Frequency analysis of rainfall data for Isla Teja (Valdivia—60 km from La Reina) and Remehue (Osorno—40 km from La Reina) give return periods of 2·6 and 15 years for a maximum of 24-h rainfall in 2001 but for different dates from that of the peak La Reina discharge. In other words, the highest recorded La Reina discharge occurred for a rainfall event that did not contain particularly extreme rainfall regionally. In 2002, the return periods for the maximum 24-h rainfall at the two stations were 22 and 12 years, respectively, the Isla Teja value (22 years) being for the same event as the peak La Reina discharge (12 December 2002). Data for six river gauging stations (on the Collileufu, Inñque, Crinces, Damas, Negro and Santo Domingo rivers, areas 127–2318 km^2) show return periods for mean daily peak discharges of 1·2–3·5 years for various events in 2001 (including 2·6 years for the Negro for the same event as the peak La Reina discharge). For 2002, the same stations show return periods of 4·3–16·4 years, all for the same event as the peak La Reina discharge (12–14 December 2002). The large difference in area between the catchments of La Reina and the other gauging stations and the use of mean

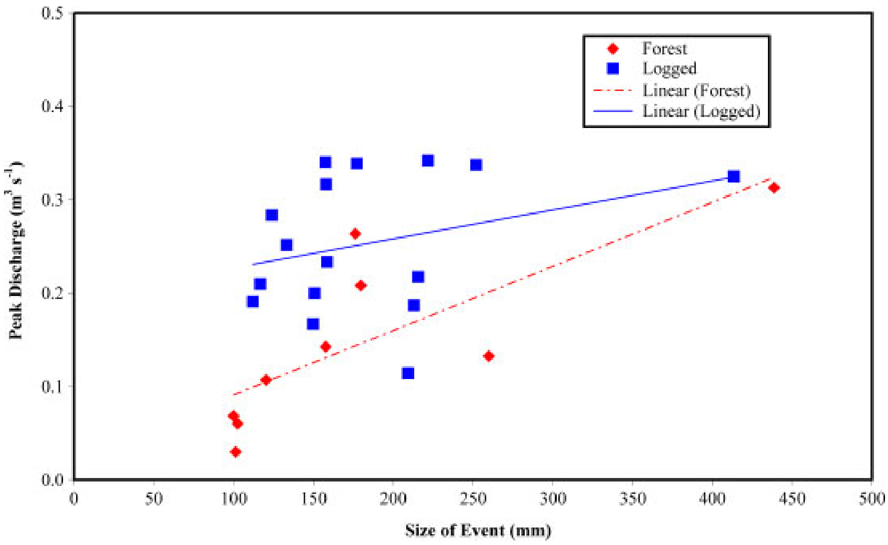

Figure 4. Pre- and post-logging relationship between precipitation events greater than 100 mm and the resultant peak discharge

daily peak flows, rather than instantaneous peak flows characterizing La Reina, must be noted. Nevertheless, it is concluded from the regional analysis that the return periods of the measured peak La Reina discharges are 4–16 years, of the order of 10 years on average.

It is clear from the above analysis that there is considerable scatter in the data (Figure 4), probably due, at least in part, to the variation in the antecedent soil moisture conditions for each event. Although the data analysis suggests that forest cover has a lesser effect on peak discharge for larger events, the data are not sufficient to provide conclusive support for the hypothesis that the effect of forest cover on flood peaks becomes less important as the size of the hydrological event increases. A complementary modelling study was therefore carried out, providing both an extension in the range of events and a systematic approach to comparing peak flows for the forested and logged conditions over that range.

MODELLING METHODOLOGY

To achieve the extension of the data analysis work, SHETRAN was used to compare the flood responses of the La Reina catchment in its forested and logged conditions for the same rainfall events. The following procedure was carried out:

1. Model set-up and calibration of the forested catchment from 1997 to 1999 and the logged catchment from 2000 to 2001.
2. Generation of 1000-year rainfall time series based on measured data at La Reina and the nearby Isla Teja site.
3. Water flow simulation of forested and logged catchments using 1000-year time series and the calibrated parameters from the 1997 to 2001 simulations.
4. Scenario testing with 1000-year time series for shallow and deep soil.
5. Sediment transport simulation with 1000-year time series.

Model set-up and calibration

The SHETRAN mesh for La Reina catchment uses 141 50 m × 50 m grid squares and 53 river links (3 m wide) that run along the edges of the grid squares (Figure 1). The grid elevations can be seen in Figure 1. Calibration of the model was carried out for two periods: for 1997–1999, when the catchment was forested and, for 2000–2001, when the catchment had been logged and then replanted but there was little growth. Rainfall data are available from June 1996 but the discharge record starts in April 1997. The forested simulations were therefore started in June 1996, with the first 10 months forming a settling-down period but not forming part of the main simulation period. It was not possible to model 2002 because of missing precipitation data from June to September 2002. Rainfall was provided on an hourly basis. It is important to note that the simulations for the two periods used exactly the same soil parameters but different vegetation parameters, i.e. representing the altered land cover. This characterization is considered in more detail in the section on Discussion and Conclusions.

The measured soil depths of between 0·5 and 1·9 m were used in the model. The shallower soils were found near the outlet with most of the catchment having the deeper soil. A mean saturated conductivity of 4·18 m day^{-1} was obtained from five infiltration tests (1·3, 2·2, 2·7, 5·3 and 9·3 m day^{-1}). However, the modelled conductivity was calibrated at 2 m day^{-1}, well within the measured range. Soil samples collected from three soil pits (two samples in each pit) by the Corporación Nacional Forestal give mean sand–silt–clay percentages of 47·6%, 33·8% and 18·6% respectively. The other soil parameter values used (based on these measurements and not calibrated) are given in Table II. The Strickler overland flow resistance coefficient was calibrated at 0·1 m$^{1/3}$ s^{-1}. This value is lower than is often

Table II. Parameters used in the SHETRAN simulation of La Reina

Parameter	Pine	Native forest	Logged
Canopy drainage—C_K (mm s^{-1})	1·9E−5	1·9E−5	1·9E−5
Canopy drainage—C_b (mm^{-1})	3·7	3·7	3·7
Canopy storage (mm)	1·5	2·0	0·5
Rooting depth (m)	1·8[a]	1·8[a]	0·1
Aerodynamic resistance (s m^{-1})	3·5[b]	3·5[b]	40[b]
Leaf area index (−)	6	6	1
Canopy resistance (s m^{-1})	100[b]	100[b]	65[b]
Saturated conductivity (m day^{-1})	2[b]	2[b]	2[b]
Saturated water content (−)	0·44	0·44	0·44
Residual moisture content (−)	0·096	0·096	0·096
Van Genuchten alpha (m^{-1})	0·8	0·8	0·8
Van Genuchten *n* (−)	1·4	1·4	1·4
Strickler overland flow ($m^{1/3}$ s^{-1})	0·1[b]	0·1[b]	0·1[b]
Raindrop impact erodibility (J^{-1})	0·05	0·05	0·05
Overland flow erodibility (kg m^{-2} s^{-1})	2E−8	2E−8	2E−8
Ground cover fraction (−)	0·95	0·95	0
Height of leaf drip (m)	2	2	0·5

The canopy drainage parameter C_K is the rate of drainage when the canopy is at its storage capacity and C_b is used in an exponential function to describe how the drainage rate falls as the canopy dries (Rutter *et al.*, 1972). Canopy resistance is the value at field capacity: in the model it increases with soil moisture tension. See Wicks and Bathurst (1996) for an explanation of the terms, raindrop impact and overland flow erodibility.
[a] Rooting depth is reduced if the soil depth is less than 1·9 m
[b] Parameter was calibrated.

used in SHETRAN but the calibration is constrained by the measured, or otherwise physically reasonable, values of the other key parameters. The vegetation parameters used for the interception and transpiration calculations for the two periods are also given in Table II. These were based measured values from other catchments collated by Breuer *et al.* (2003). Evapotranspiration was simulated using the Penman–Monteith equation with the measured hourly meteorological data. The aerodynamic and canopy resistance values were calibrated but are well within measured ranges and show physically realistic differences (Table II) (e.g. aerodynamic resistance for the forest = 3·5 s m^{-1} and for the cleared ground = 40 s m^{-1}). These values have a particularly important effect on the results; this is discussed in the next section. In general, it may be noted that the simulation area is well defined, the model parameters are firmly based on measured property data and the input data are provided with a good temporal resolution.

The soil samples collected from the soil pits were represented by the following particle-size distribution in the SHETRAN sediment component, with the percentages shown in brackets: 0·1 mm (60%), 0·37 mm (20%), 0·89 mm (10%), 1·59 mm (5%), 2·25 mm (3%) and 3·5 mm (2%). The distribution was selected from a library of distributions derived for SHETRAN. Sediment transport simulations were carried out using the 1997–1999 meteorological data with forest cover and then with the forest logged. The simulations determine soil erosion by raindrop impact and overland flow and the resulting sediment yield. This allows for leaf drip in the forested case and the lack of vegetation protection associated with bare soil in the logged case. The simulations are driven by the calibrated water flow models and the parameters used are given in Table II.

Generation of 1000-year synthetic rainfall time series

On the basis of the available rainfall data (from La Reina and Isla Teja), a 1000-year synthetic hourly rainfall time series was generated using Newcastle University's RainSim model (Burton *et al.*, 2008), which is a stochastic rainfall field generator based on the Neyman–Scott rectangular pulses model. The basic procedure was to calculate appropriate rainfall statistics for each month (e.g. daily precipitation, daily variance, daily skew, proportion of dry days in a stated period, hourly precipitation and hourly skew), fit the Neyman–Scott parameters for each month to these statistics and then generate the 1000-year synthetic time series from the Neyman–Scott parameters.

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. Although RainSim can extend the range of event magnitude beyond their current measured record, the lack of data means that events of this magnitude cannot be validated. Thus, it is not possible to quantify return periods for the largest events within the 1000-year time series, but the generation of 1000 years of data provides an appropriate statistical basis for defining the catchment flood response for events with return periods of up to 100 years or so. For smaller events within this time series, comparisons of the measured rainfall at La Reina at nearby sites is possible and so return periods can be quantified (hence the discussion in the Data Analysis section).

The use of a long-time series generated statistically from the current record that effectively extends the range of return periods has already been demonstrated by other researchers (Schnorbus and Alila, 2004; Brath *et al.*, 2006). The longer the current record, the more accurate that extension is likely to be. In this case, the 7-year record for La Reina catchment was not considered sufficient, and the 45-year daily rainfall record for Isla Teja, 60 km away in Valdivia, was used. Isla Teja has an annual and monthly rainfall distribution similar to La Reina, but its separation from the latter catchment required that its record be correlated with La Reina's before it could be used.

Within the 7 years of hourly data at La Reina, there are six complete years with full rainfall records at both

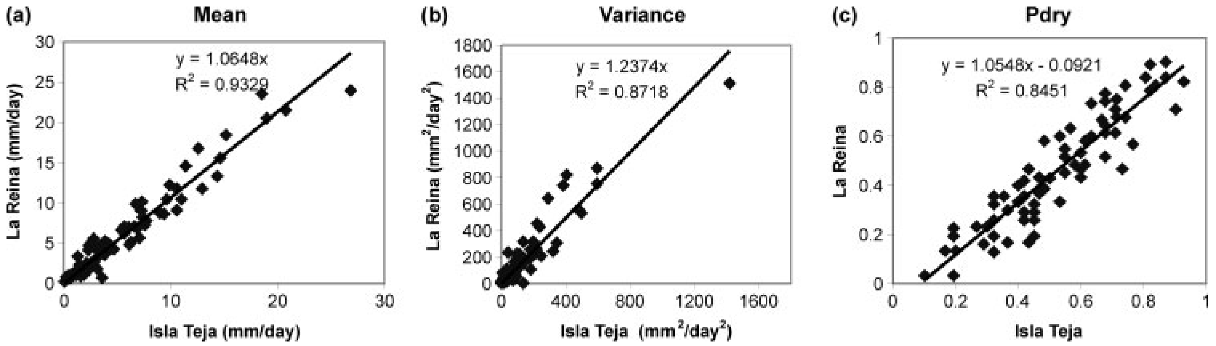

Figure 5. Comparison between La Reina and Isla Teja for each month of a 6-year period for (a) mean daily precipitation, (b) variance in precipitation and (c) proportion of dry days

Table III. Annual measured and simulated totals (mm) in the SHETRAN simulation of La Reina

Years	Precipitation	Measured discharge	Simulated discharge	Measured evaporation	Simulated evaporation
1997–1999	2286	917	1015	1369	1270
2000–2001	2604	1835	1904	769	700

La Reina catchment and Isla Teja. Therefore, for these 6 years, monthly statistics of corresponding daily data for the two stations were compared for mean, variance and proportion of dry days (Figure 5). These show a high correlation, with the mean and proportion of dry days at La Reina being slightly higher than that at Isla Teja and a greater variance at La Reina compared with that at Isla Teja. Using these relationships, the statistics of 45 years of daily Isla Teja data were modified to be appropriate for La Reina daily rainfall. For example, for each month, the mean daily precipitation at Isla Teja was multiplied by 1·0648, the daily variance by 1·2374 and the proportion of dry days by 1·0548. In this manner, 45 years of daily statistics corresponding to La Reina were obtained. These modified statistics of daily data were combined with the variance and skew statistics for the hourly La Reina data. RainSim was then used to generate a 1000-year time series of hourly rainfall with daily and hourly statistics corresponding to those found at La Reina. The mean monthly evapotranspiration was calculated with the Penman–Monteith equation (with parameter values appropriate to the vegetation) and automatic weather station data. The same values were used for each year of the 1000 years.

RESULTS

Calibration for forested conditions 1997–1999

The comparison between the simulated and measured discharges for 1997–1999 can be seen in Figure 6. Overall, the correspondence is good (Nash–Sutcliffe efficiency = 0·84), and importantly for this work the peaks are reasonably well captured by the simulation. The simulated discharge for the major event on 28 July 1997 is 0·36 m^3 s^{-1} compared with the measured peak of 0·31 m^3 s^{-1}, while for the major event on 9 August 1999 the simulated peak is 0·23 m^3 s^{-1} compared with the measured value of 0·26 m^3 s^{-1}. The main discrepancy with the observation is that the simulated discharges during the dry year in 1998 are too high, although this is not considered to be a major problem given the focus on flood events. A comparison of the measured and simulated mass balance also shows an excellent match (Table III).

The standard potential evaporation rate for this part of Chile is around 1000 mm. [This value was calculated from the site data and corresponds to short grass cover. The annual pan evaporation has been measured nearby by Iroumé and Huber (2002) at around 800 mm.] However, measured data from La Reina from 1997 to 1999 and from two other nearby catchments give actual evaporation totals that can be considerably larger than this. For example, in 1997 at La Reina the measured evaporation was over 1500 mm. The reason that the measured evaporation is larger than the standard potential evaporation is a result of large interception losses of water from forest canopies, which, as shown by Calder (2005), are expected with low intensity rainfall in temperate climates and are a result of the lower aerodynamic resistance of the forest. Huber and Iroumé (2001) and Huber *et al.* (2008) studied interception losses in detail for a range of forest types at nine sites in temperate Chile. Overall, interception losses accounted for between 10% and 40% of precipitation depending on the type and age of the trees. Iroumé and Huber (2002) also show that similar interception losses and wet evaporation rates from the canopy of up to 1 mm h^{-1} can take place even in winter. These high interception losses have also been found by other researchers (Dykes, 1997; Schellekens *et al.*, 1999; Waterloo *et al.*, 1999). The simulated losses from interception can be seen in Figure 7, with losses of around 30% of the precipitation in 1997, 1998 and 1999 and wet evaporation rates of up to 2 mm h^{-1} in summer.

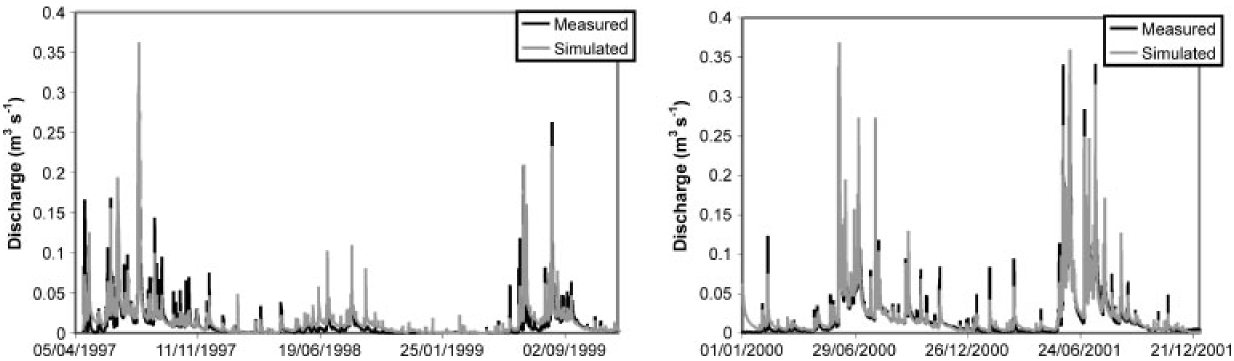

Figure 6. Measured and simulated discharge at La Reina outlet before logging 1997–1999 and after logging 2000–2001

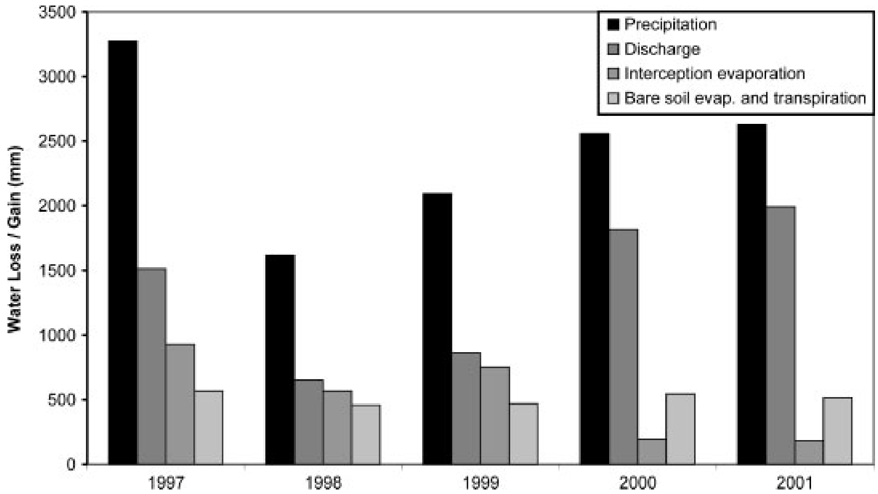

Figure 7. Simulated mass balance (including evaporation losses) for La Reina 1997–2001

These results were obtained using the Penman–Monteith equation with a low aerodynamic resistance for the forest cover, and it is encouraging that the simulated results correspond with what is known about evaporation losses from experimental data.

Calibration for logged conditions 2000–2001

The comparison between the simulated and measured discharges for 2000–2001 can be seen in Figure 6. No settling-down period was provided and therefore there is a discrepancy between the measured and simulated discharges at the very start of the simulation period. Overall, though, the correspondence is excellent (Nash–Sutcliffe efficiency = 0·91) and, importantly for this work, the peaks are well captured by the simulation. The comparison of the measured and simulated mass balance also shows excellent agreement (Table III).

The 110% increase mean annual runoff found at La Reina by Iroumé *et al.* (2006b) agrees with the trend found at other sites (Bosch and Hewlett, 1982; Stednick, 1996; Bruijnzeel, 2004). The main reason for this is the reduction in interception caused by the removal of the trees. This is shown clearly in Figure 7 with the simulated interception evaporation decreasing considerably in 2000 and 2001 compared with that in the years before logging. The simulated bare soil evaporation and transpiration are altered very little as a result of the logging.

1000-Year simulation results

SHETRAN simulations were carried out for the forested and logged cases using the 1000-year synthetic hourly rainfall time series. The standard method of showing the effect of logging on discharge (Schnorbus and Alila, 2004) is to compare the annual maximum discharges from the forested and logged cases on a Gumbel plot. Figure 8 shows that these discharges are always greater for the logged than for the forested conditions. The difference between the two increases for bigger events up to a return period of about 100 years when the lines are parallel to each other. This means that the difference between the two as a percentage of discharge is actually decreasing for bigger events. However, there are limitations associated with this method. Firstly, the annual maximum discharges for logged and forested conditions may come from different rainfall events and so should not be compared directly. Secondly, in this method, a vast amount of information is not being used, for example, for major events that do not produce an annual maximum.

Another method of analysing the effect of land-use on flood peaks, which avoids the above disadvantages, is shown in Figure 9. The figure compares the maximum daily discharges for each corresponding day of the 1000-year simulations for the forested and logged cases and shows that there can be a range of 'logged' responses

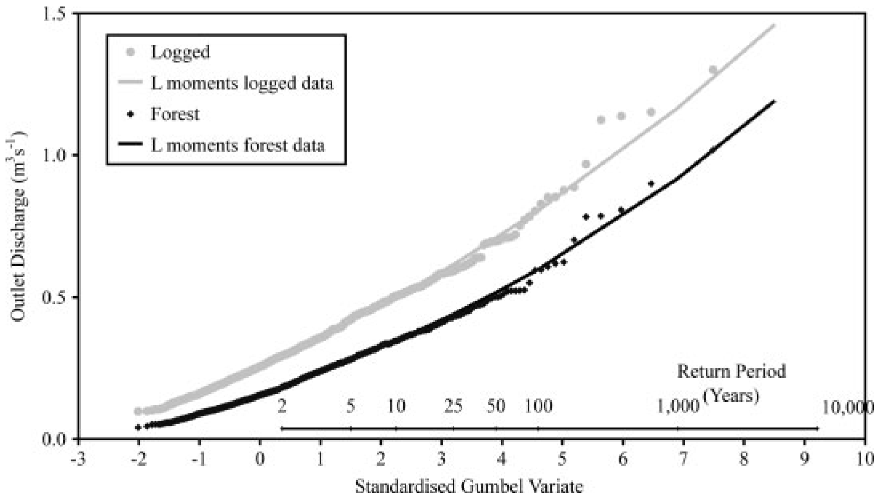

Figure 8. Gumbel plot of annual maximum discharge (m^3 s^{-1}) for the forested and logged conditions from the 1000-year SHETRAN simulations of the La Reina catchment

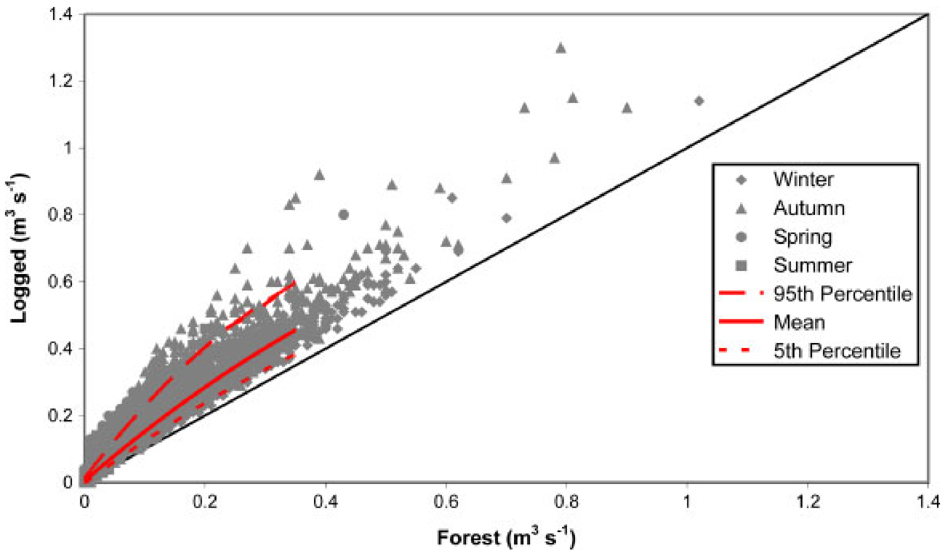

Figure 9. Comparison of maximum daily discharges (m^3 s^{-1}) for forested and logged conditions from the 1000-year SHETRAN simulation of the La Reina catchment. Line is the line of equality

for a given 'forested' discharge, i.e. for a forested discharge of say 0·2 m^3 s^{-1}, the logged discharges vary between 0·2 and 0·7 m^3 s^{-1}. In some cases, there is little difference between the two discharges, in others there is; if the soil under the forest is very wet, the response is similar to that in the logged case. The data are identified by season, showing that the difference between the two cases is least in winter and greatest in summer/autumn (when trees have the least and greatest effects respectively on soil moisture). Whatever the discharge, the range of 'logged' discharges for a given 'forested' discharge remains similar, so, as a percentage of the discharge, the range decreases as the discharge increases, i.e. in agreement with the test hypothesis. This is confirmed by the 95th percentile line in Figure 9, which becomes parallel to the line of equality for the larger events (there are insufficient data to extend the lines any further). It appears that a combination of antecedent soil moisture conditions and rainfall event characteristics determine the response. This is confirmed by two further sets of simulations that were carried out to explore the impact of firstly antecedent soil moisture and secondly the rainfall event size and type.

To assess the impact of the antecedent soil moisture, a single rainfall event was run with 36 different antecedent conditions. First, a 3-year simulation was run for each vegetation case (using La Reina rainfall data for 1997–1999). From the results, soil moisture conditions were selected from the end of each month (a total of 36 with a mixture of wet and dry conditions). The conditions were different for the forested and logged cases but were from the same points in the respective simulations. Second, a daily event was selected from the 1000-year series, corresponding to the largest discharge difference between the logged and forested cases. The event was then run for each of the 36 soil moisture conditions. The results (Figure 10A) confirm that, the wetter the soil, the greater is the discharge. The results also show that there is

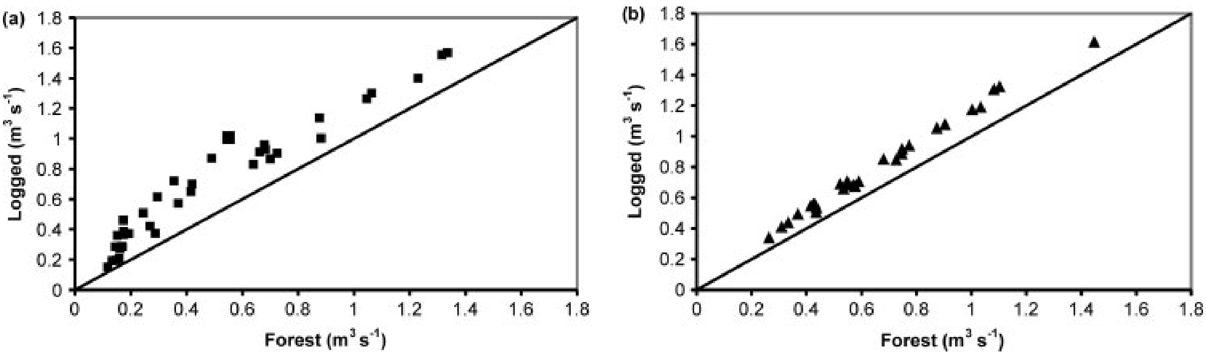

Figure 10. Comparison of maximum discharges (m^3 s^{-1}) for forested and logged conditions from the SHETRAN simulations at La Reina for (a) the same rainfall event with 36 different antecedent soil moisture conditions. (b) The same initial conditions with 30 different rainfall events. The enlarged data point in (a) shows the event used in Figure 11. Line is the line of equality

still a range (albeit more limited) of 'logged' discharges for a given 'forested' discharge. They also show a slight convergence of the forested and logged cases as discharge increases, in correspondence with wetter soil. It is very clear, though, that the difference between the forested and logged cases decreases as a percentage of discharge as the discharge increases. As a check, this analysis was repeated for the two daily rainfall events with the next largest difference between the logged and forested cases, with very similar results (not shown here). Overall, it can be seen that the antecedent moisture conditions affect both the magnitude of the discharge and the percentage difference between the logged and the forested case.

To assess the impact of rainfall event type and size, a single antecedent soil moisture condition was selected and run with 30 different rainfall events. The antecedent soil moisture condition selected was the wettest of the 36 different antecedent conditions analysed above. The antecedent conditions were different for the forested and logged cases but were based on the same meteorological data. The rainfall events were selected to give a range of type of events and size including the event that produced the largest discharge. The results (Figure 10B) show a very small range of 'logged' discharges for a given 'forested' discharge. Unlike the analysis for the antecedent conditions, the percentage difference between the forested and logged cases remains nearly constant as a percentage of discharge as the discharge increases, i.e. the data almost form a straight line diverging slightly from the line of equality. As a check, this analysis was repeated for the two different antecedent conditions, with very similar results but lower discharges (not shown here). Overall, it can be seen that the rainfall event type and size affect the magnitude of the discharge. However, the percentage difference between the logged and the forested cases remains very similar. Having considered both the antecedent soil moisture and the rainfall event separately, it can be seen that the combination of both is needed to produce the full range of responses seen in Figure 9.

A spatially distributed model such as SHETRAN enables the different responses in different parts of the catchment to be analysed in more detail. For the rainfall event and the antecedent conditions that produce the discharge shown by the enlarged point in Figure 10A, the soil moisture storage at the start of the event and during the peak flow were considered. The ranked soil moisture deficit for the soil column at each grid square is shown in Figure 11. Throughout the catchment in the forested simulation, the soils have less stored water at the start of the rainfall event, which is a result of higher evaporation losses. This means that the forested soils can store more rainfall before saturation of excess overland flow occurs than can the logged soils. The difference between the curves for the logged and forested storages is the additional water storage that would need to be added to the forested catchment for the outlet discharges to be the same. During the rainfall event, more of the catchment saturates for both the logged and forested simulations. However, the saturated area is always greater for the logged simulation, so by the time of the peak of the rainfall event occurs, the area saturated for the logged simulation (90 out of the 141 grid squares) is greater than that for the forested simulation (60 squares). The outlet event discharge is produced mainly as a result of saturation excess overland flow and so the difference in saturated area produces the difference in peak outlet discharge between the two simulations (1·011 m^3 s^{-1} for the logged simulation and 0·548 m^3 s^{-1} for the forested simulation).

Scenario testing

The above simulations were carried out for measured soil depths of 0·5–1·9 m (mostly 1·9 m). To investigate the influence of depth, they were repeated with shallow (0·5 m) and deep (10 m) soils. The results (Figure 12) for the same 1000-year precipitation time series show that, as expected, the shallow soil has bigger peak discharges than the standard and deep soils. With the shallow soils, the extra storage capacity of the forested case is minimized, so that the runoff response resembles that of the logged case more clearly, especially for large events. Thus, there is an absolute convergence of the logged and forested responses at higher discharges. In contrast, for the deep soil, the difference between the forested and logged conditions as a percentage of discharge seems to remain similar whatever the size

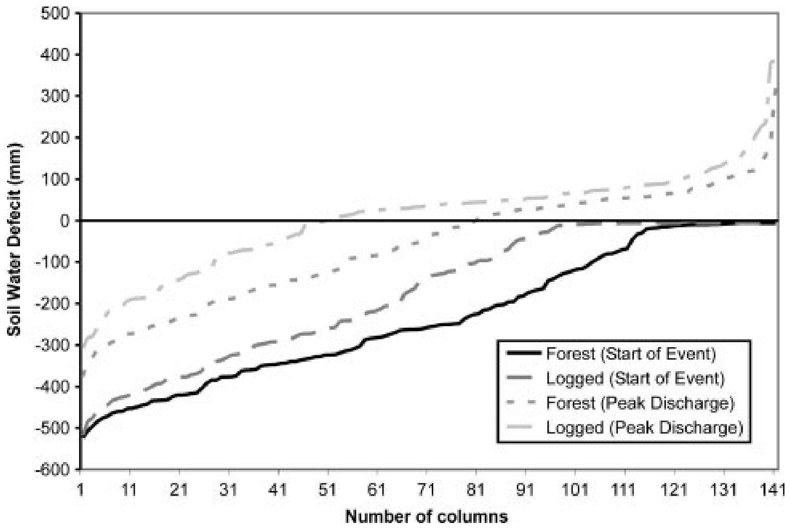

Figure 11. Ranked water storage in the soil column at each grid square for forested and logged conditions from the SHETRAN simulations of La Reina. Curves are shown for the start of the event and for the peak discharge for the data point highlighted in Figure 10. A positive soil water deficit implies that the soil column is saturated and the value is the depth of surface water

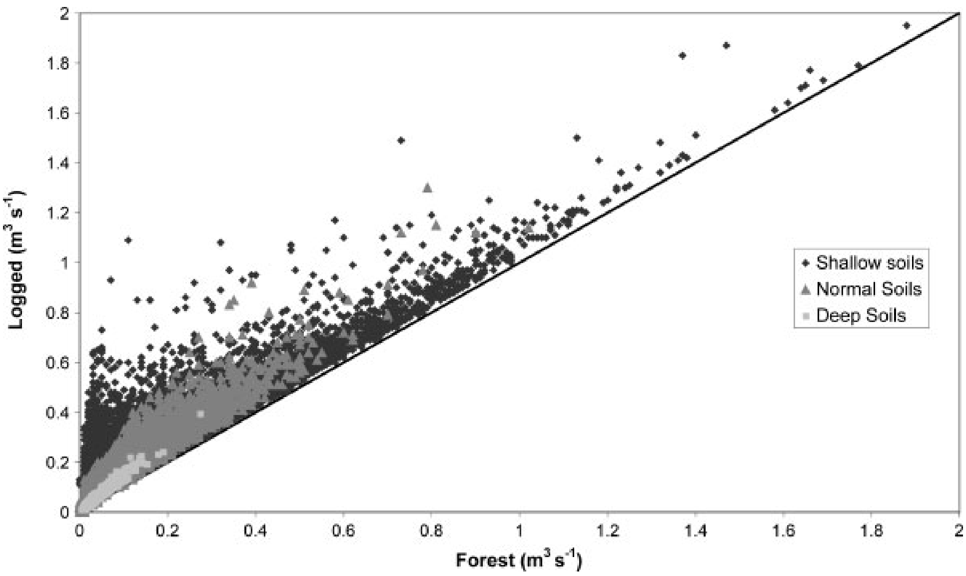

Figure 12. Comparison of maximum daily discharges (m^3 s^{-1}) for forested and logged conditions from the 1000-year SHETRAN simulation at the La Reina catchment for three different soil depths. Line is the line of equality

of the discharge event. The soils for the forested case are much less likely to saturate and retain a permanent advantage over the logged condition in being able to absorb more rainfall, even for large events. Hence, the runoff responses diverge.

Following the procedure used for the standard soil depth, additional simulations were carried out to examine the effect of the antecedent conditions. Figure 13A shows the results for the shallow soils for the same rainfall event with 36 different initial conditions. This shows that, the wetter the initial conditions, the less is the difference between the forested and logged cases, so that under very wet antecedent conditions their discharges are almost the same. The same procedure for the deep soils (Figure 13B) shows the opposite response: the wetter the initial conditions, the larger is the difference between the forested and logged cases. In this case, the difference as a percentage of discharge remains similar as the discharge increases.

Sediment transport

Sediment transport simulations were carried out using the 1997–1999 meteorological data with forest cover and then with the forest logged. Table IV shows the annual mass balance for the two vegetation cases. There is a significant increase in sediment yield from 3·6 t ha^{-1} $year^{-1}$ for the forest to 8·3 t ha^{-1} $year^{-1}$ for the logged catchment. The forest value is in good agreement with an initial analysis based on limited sediment transport measurements for 1997–1998 (corresponding to the forested state), which gave yields of 3·9–11·1 t ha^{-1} $year^{-1}$ depending on the technique used to derive continuous suspended sediment concentration (Menke de la Peña, 1999). Comparison is also possible against measurements

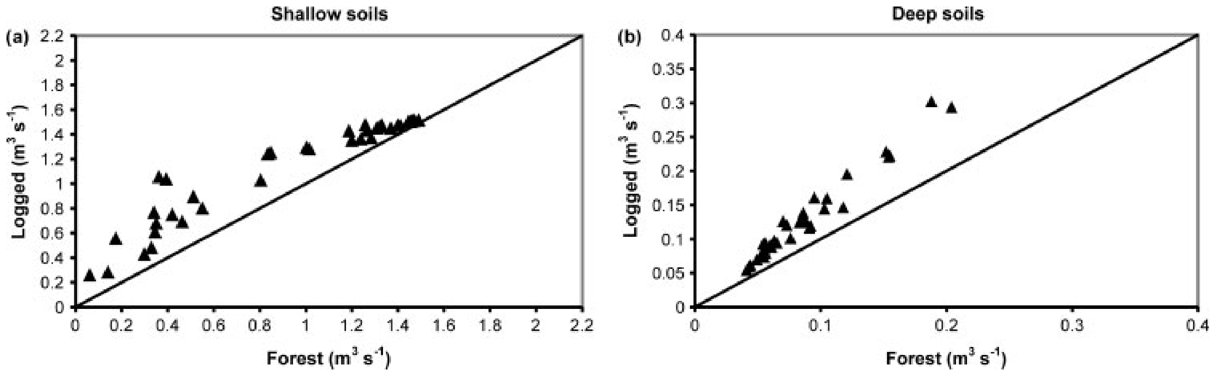

Figure 13. Comparison of maximum discharges (m^3 s^{-1}) for forested and logged conditions from the SHETRAN simulations at La Reina with a (a) shallow (0·5 m deep) soil and (b) deep soil (10 m deep) for the same rainfall event with 36 different antecedent soil moisture conditions. Line is the line of equality

Table IV. Simulated annual water discharge and sediment yield at La Reina 1997–1999 for forested and logged cases

	Forest	Logged
Water flow (mm year^{-1})	1015	1582
Sediment yield (t ha^{-1} year^{-1})	3·6	8·3

from other sites. Bosch and Hewlett (1982), Stednick (1996) and Bruijnzeel (2004) have all reviewed the effect of vegetation on sediment yields. Clearing of forests produces an increase in catchment sediment yield, although the increase varies depending on the vegetation types and the climate. A review of small catchment and plot measurements in southern Chile (Niklitschek and Gayoso, 2006) shows mean yields of 27 t ha^{-1} year^{-1} for bare soil and 0·08–2·2 t ha^{-1} year^{-1} for forest plantations with different treatments. However, the plantation yields are averaged over a 20-year period, so may not reflect the relatively high values typically observed in the year or two following logging. Likewise, plot data from southern Chile suggest that soil loss after logging is approximately 2–5 t ha^{-1} year^{-1} for sites where the forest residue is burnt and the soil has no cover, is around 0·5–2 t ha^{-1} year^{-1} for sites where the forest residue is retained and is less than 0·1 t ha^{-1} year^{-1} for control sites with no logging (Gayoso and Iroumé, 1989; Oyarzún and Peña, 1995). The SHETRAN simulations are supported by the limited field data but are generally high compared with certain plot measurements. As with the water flow, long-term sediment transport simulations were run for the logged and forested cases using the basic sediment transport models. Thousand-year simulations were run and the maximum transport rates for each day for the two cases were compared (Figure 14). The logged case always has a higher transport rate than the forested case, indicating a clear benefit from forest cover in terms of protection against erosion.

DISCUSSION AND CONCLUSIONS

The 0·35-km^2 La Reina catchment, Chile, is an excellent case study as the entire catchment was logged between October 1999 and February 2000. The result of this logging is shown by the 110% increase in annual water yield (Iroumé *et al.*, 2006b). Data analysis suggests that

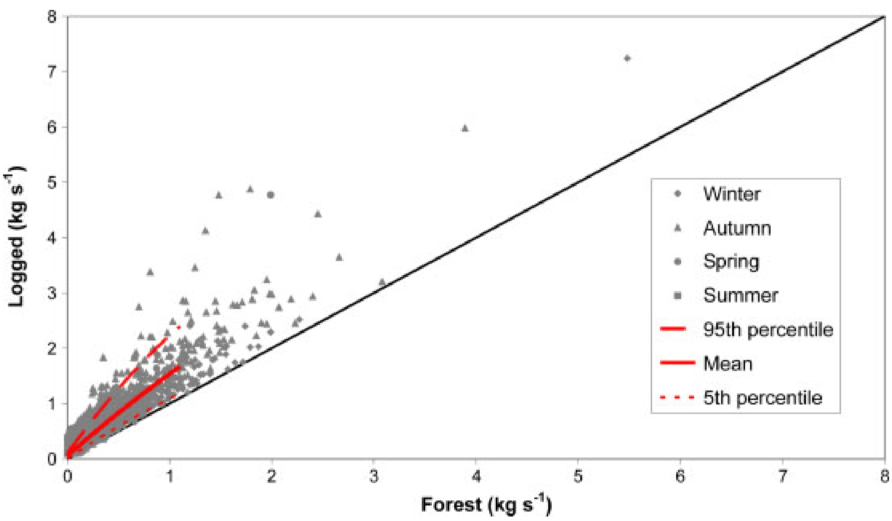

Figure 14. Comparison of corresponding maximum sediment discharges (kg s^{-1}) for the forested and logged conditions from the 1000-year SHETRAN simulations of the La Reina catchment. Line is the line of equality

logging of the catchment also increases the peak flow but that there is a lesser effect on peak discharge for larger events. However, the data are not sufficient to provide conclusive support for the hypothesis that the effect of forest cover on flood peaks becomes less important as the size of the hydrological event increases. A complementary modelling study was therefore carried out, providing both an extension in the range of events and a systematic approach to comparing peak flows for the two land-use conditions (forest and logged) over that range.

Physically based, spatially distributed modelling was carried out for both the forested conditions (1997–1999) and logged conditions (2000–2001) using SHETRAN and an excellent comparison was achieved between measured and simulated discharges. In the simulations, the difference between the forest and logged conditions was produced entirely by appropriate changes in the vegetation parameters, while keeping the soil and overland flow resistance characteristics the same. Confidence that the calibrations represent the two land covers in a physically plausible manner is therefore high. A 1000-year synthetic rainfall time series was generated, representative of the current climate at the La Reina catchment. With the series as input, simulations were run with the calibrated models for both the logged and forested cases. Comparison of the corresponding maximum daily discharges for the two cases shows that there can be a range of 'logged' responses for a given 'forested' discharge, depending on season, type of event and antecedent soil moisture conditions. Considering the mean values of 'logged' and 'forested' discharge (Figure 9), above a particular value the absolute discharge difference between the two remains approximately constant as discharge increases; thus, as a percentage of discharge, it decreases. This appears to become significant for discharges greater than approximately $0{\cdot}3\ m^3\ s^{-1}$ for the forested catchment and $0{\cdot}4\ m^3\ s^{-1}$ for the logged catchment, which, using the data in Figure 8 and the return period for specific events at La Reina (discussed in the Data Analysis section), suggests a return period of approximately 10 years. The reasons that land-use becomes less important for larger discharges are as follows: (1) the wetter the antecedent conditions, the smaller is the difference in discharge between the forested and logged cases, at least as a percentage of discharge; (2) higher discharges occur only when the antecedent conditions are wet; and therefore (3) the difference in response decreases as discharge increases.

Simulations with different soil depths show different results because depth affects how much water can be stored in the soil column before saturation occurs and runoff is generated. Thus, with a shallow soil there is absolute convergence while with a deeper soil there is no convergence of response. The sediment transport simulations show that forest cover provides a clear benefit in protecting the soil from erosion and therefore reducing the sediment transport in the river in comparison with the logged case.

La Reina is well drained so there appears to be little or no infiltration excess runoff. Thus, the discharge response is a function of saturation excess runoff and subsurface stormflow. Therefore, the discussions here are not relevant to those catchments where infiltration excess runoff is important. La Reina is also a small catchment (35 ha) and so the results discussed here are relevant only to similar-sized catchments. Additional work would need to be carried out to see if the same conclusions can be drawn on a larger scale. Conventionally, it might be expected that the impacts of forest cover change would become attenuated on the larger scale, owing, for example, to non-uniform rainfall and a greater heterogeneity of land-use. However, analysis of data records in Chile suggests that a response similar to that simulated at La Reina can in fact be found in catchments of up to 1500 km^2 (Bathurst *et al.*, 2010). This is probably due to the industrial scale of the felling and planting that takes place in these catchments, whereby substantial proportions of a catchment's area are treated almost simultaneously.

As mentioned previously, the change in land-use is represented in the model by changes to only the vegetation parameters. It is known that practices used in the removal of trees may also affect parts of the catchment through soil compaction and reduced surface roughness (Beschta *et al.*, 2000). However, no information was available on the form or location of any such changes and they were therefore not taken into account in this study. It would be of interest, though, to investigate the sensitivity of the simulations to such changes as further research takes place.

Overall, this study demonstrates the contribution that physically based modelling can make to understanding hydrological processes, especially when combined with field analysis. The field analysis supported the test hypothesis but was not conclusive. The modelling study was able to extend the range of events, provide a time series long enough to allow a statistically reliable representation of long return period events and allow a systematic analysis unimpeded by lack of data. This analysis agreed with the field data analysis, giving strong support to the test hypothesis. The application reinforces the use of modelling to extend field data analysis for investigating the impact of land-use change on flow response.

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