HYDROLOGICAL PROCESSES
Hydrol. Process. **17**, 1291–1306 (2003)

Changes in the surface water hydrologic characteristics of an endoreic basin of northern Mexico from 1970 to 1998

D. Viramontes[1] and L. Descroix[2]*
[1] *Instituto Mexicano de Tecnología del Agua (IMTA), Paseo Cuauhnáhuac 8532, CP 62 550 Jiutepec, Morelos, Mexico*
[2] *Institut de Recherche pour le Développement (IRD), Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE), BP 53, 38 041 Grenoble cedex 9, France*

Abstract:

The western Sierra Madre is the main water-providing area of northern Mexico. However, most of this mountain range has suffered a progressive degradation of soils and vegetation due to overgrazing and deforestation, for four or five decades. The objective of this study is to determine the impacts of these changes on water balance and hydrodynamic basin behaviour.

The hydrological data of two basins (the Sextin basin, 4660 km^2 and the Ramos basin, 7130 km^2) of this area were analysed. Annual runoff coefficients have not changed. Therefore, other indices were used to determine changes in the streamflow regime:

- an index of irregularity of daily discharge;
- the separation of flood flow and base flow;
- the lag time of the watersheds;
- the baseflow recession index;
- the two-day recession index.

Some changes were noticeable at the basin scale in the water balance of the catchments:

- the ratio of the flood runoff coefficient to the base runoff coefficient increased from the 1970s to the 1990s;
- the basin lag time decreased 2·1% in the Ramos basin and 6·1% in the Sextin basin;
- the two-day recession index and the baseflow recession index increased, reflecting a more rapid decrease of streamflow after the peak flow;
- the mean annual runoff coefficient and the irregularity as estimated by the index used here showed no significant evolution.

The convergence of such observations confirms that dramatic changes in the evolution of water resources in the near future in this area are to be expected, if the current land use is not strongly modified. Water management and dam operation would also be seriously affected. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS hydrograph separation; response time; base flow index; overgrazing; crusted soils; runoff; overland flow; western Sierra Madre

INTRODUCTION

The impact of land use changes on the hydrological behaviour of watersheds is currently one of the main problems of water management. The building of dams or hydraulic devices can rapidly modify river regimes. Overgrazing, deforestation and developing urbanization can also influence catchment water balances, but

---

* Correspondence to: L. Descroix, Institut de Recherche pour le Développement (IRD)–Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE), BP 53, 38 041 Grenoble cedex 9, France. E-mail: descroix@hmg.inpg.fr

Received 25 March 2002
Accepted 20 July 2002

their action is more progressive and not so strong as that of dams. The effects of urbanization were recently studied in Georgia (Rose and Peters, 2001), where it appears that annual runoff coefficients are not significantly modified by urbanization; the main changes are observed on the low flows and on the recession pattern of streamflow.

The linkage between vegetation and catchment hydrological behaviour is so obvious that in some countries the forest administration is named the 'Water and Forest' service. The impact of forest harvesting on runoff has for a long time been a matter of scientific research; the experimental catchments of Wagon Wheel Gap (Colorado, USA) have been dedicated since 1909 to the study of the hydrological influence of land use (Hewlett *et al*., 1969).

Experimental studies on river discharge and runoff coefficient need to compare data and evolution on several similar watersheds in order to reveal possible statistical trends or evolution of the water balance. Nevertheless, most of the previous published researches were based on the total discharge evolution of the basins. Their main goal was to define whether a physically modified area produces more or less runoff.

Hibbert (1967) made one of the first syntheses of experimental data collected under different climates. From 39 watershed data sets, he concluded that:

- reduction of forest cover leads to an increase in discharge;
- re-vegetating of bare soils reduces runoff.

Based on 94 experimental watersheds, the results presented by Bosch and Hewlett (1982) interestingly completed these observations:

- the runoff response to changes in the vegetation cover is significantly higher under wet climates;
- the vegetation pattern also has a strong impact on runoff, conifers significantly reduce runoff, while bushes have a lower influence;
- considering the entire data set, they observed that the correlation between forest cover rate and runoff reduction is not very obvious.

More recently, a great number of studies were dedicated to this item, in tropical rainy areas (Fritsch, 1990) as well as in temperate climate areas (Cosandey, 1995; Caugant, 1998; Andréassian, 1999). Some of them criticized the great dispersion of points in the trends observed by Bosch and Hewlett (1982), but none considered such a voluminous data set. Stednick (1996) updated these observations, and specified that harvesting effectively leads to an increase in streamflow discharge (however, grassland destruction seems to have a significantly lower influence), but mainly if at least 20% of the catchments are concerned. This author concluded: '*the variable responses of annual water yield to harvesting suggest both complex and perhaps non-linear responses*.' Braud *et al*. (2001) reported unexpected results from an arid area of the Andes region: a catchment which exhibits larger shrub cover and smaller average slope produces more than twice the runoff (and 10 times more sediment) than another catchment with lower vegetation cover and steeper slopes. In the same area, they had previously demonstrated that '*rainfall and soil type spatial variability were one order of magnitude more influential on runoff generation than vegetation cover spatial variability*' (Braud *et al*., 1999). At the methodological level, Tallaksen (1995) proposed a review of base flow recession indexes which allow us to make comparisons between catchments and to study the evolution of their hydrological behaviour even if the average discharge is similar.

CHARACTERISTICS OF THE STUDY AREA AND PROBLEMATICS

The western Sierra Madre is a massive mountainous range composed of Tertiary acid volcanic rocks. It represents the biggest ignimbritic continuous bedrock cover system in the world (Demant and Robin,

Table I. Climatic characteristics of the study area

Station	Altitude (m)	Annual rainfall[a]		Annual mean temperature (°C)
		Mean (mm)	CV[b]	
El Cuije	1100	190	0·42	21
Tepehuanes	1800	463	0·17	16
La Cienega de Escobar	2100	610	0·21	14
El Tarahumar	2850	971	0·17	10·5

[a] Rainfall is mean annual rainfall (1960–1990).
[b] CV is coefficient of variation.

Table II. Annual rainfall and runoff characteristics of the upper Nazas watersheds (Ramos basin from 1970 to 1998 and Sextin basin from 1971 to 1997)

Catchment	Parameter	Rainfall[a] (mm)	Runoff depth (mm)	Runoff coefficient (%)	Runoff deficit (mm)
Ramos	*Mean*	*654*·23	*81*·38	*11*·97	*572*·85
	Std. dev.	111·64	46·20	5·55	84·88
	Var. coeff.	0·17	0·57	0·46	0·15
	Min. value	442·75	18·07	3·64	370·08
	Max. value	886·66	213·05	24·03	730·41
Sextin	*Mean*	*612*·37	*120*·12	*17*·92	*499*·28
	Std. dev.	121·83	90·84	11·00	76·03
	Var. coeff.	0·20	0·76	0·61	0·15
	Min. value	404·00	7·50	1·75	382·28
	Max. value	871·19	419·86	51·20	646·59

[a] Rainfall depth calculated from data of 42 climatologic stations by krigging.

1975). The maximum elevation is around 3300 m and the bottom of the valleys lie between 1500 and 2000 m. Soils are generally shallow to moderate (less than 100 cm thick). They have a weak water storage capacity (100 to 120 mm on average for 50-cm thick soils) (Viramontes, 1995). Given the latitude (25 °N), the climate is dry subtropical. The rainfall annual amount ranges from 450 mm in the valleys to 900 mm at top altitudes. Table I gives some general climatic values of the study area, located in the northern part of Durango State, in the upper Rio Nazas basin (Figure 1), and is compared with El Cuije station, located in the Chihuahuan desert, near Torreon (Coahuila State). Annual cumulative rainfall increases with altitude (0·32 mm/100 m). Furthermore, it can be noticed that the interannual rainfall variability increases with a decrease of annual rainfall amount (Descroix *et al.*, 2002), the coefficient of variation of annual rainfall ranges from less than 0·2 at the wettest stations to more than 0·42 at the driest ones, around the Chihuahuan desert. Moreover, the climatic station of La Cienega de Escobar presents on average 100 annual days of frost. In the Rio Nazas upper basin, catchments of 5000 km^2 (Rio Ramos and Rio Sextin basins, Figure 1) have annual runoff coefficients of about 0·15 (Table II) but the coefficient of variation is high (CV = 0·63). Nevertheless, flow in the Rio Nazas reaches the arid endoreic area of La Laguna, and provides irrigation for an area of more than 1000 km^2.

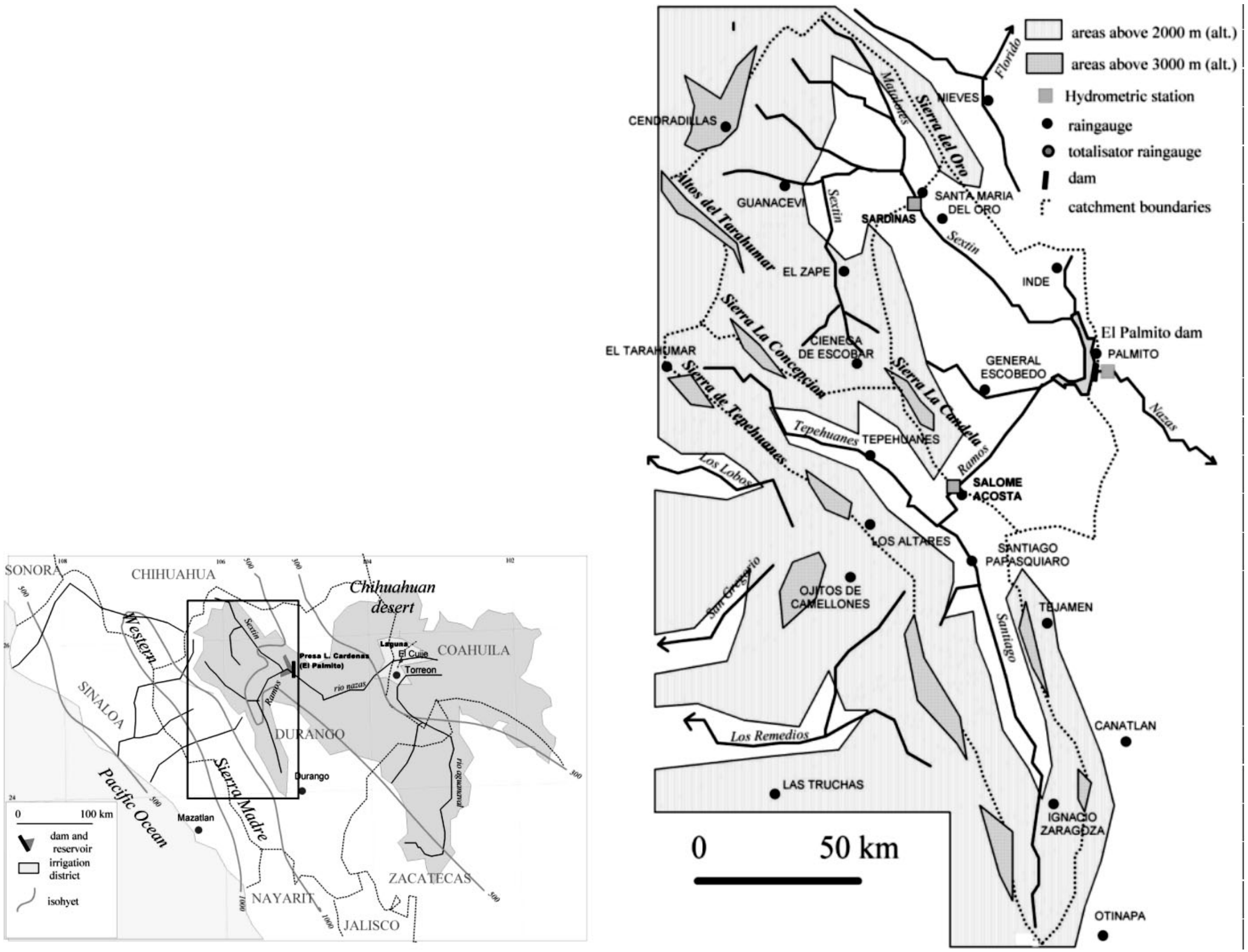

Figure 1. Map of the study area in the Sierra Madre range (north west of Mexico). The two studied experimental watersheds (Ramos and Sextin basins) with the location of hydrometric stations, rain gauges are shown in the inset

In the western Sierra Madre (which includes the upper Nazas basin), cattle rearing is the main economic activity. However, the livestock density is often four times higher than desirable according to the grassland theoretical capacity (Table III). The effects of overgrazing on the landscape can be observed in the whole pasture zone (from 1800 to 2400 m of elevation):

- an increase of ligneous (principally small pines) and other unpalatable species and a decrease of the graminaceous ones (Viramontes, 1995)—Boutrais (1994) has called this process 'green degradation of grassland';
- a pavement of hillslopes with blocks left behind by the removal of fine particles in the early erosional stages;
- the formation of small terraces on slopes steeper than 25% (Poulenard *et al.*, 1996)—this process, which consists of a network of cattle trails on hillslopes, has previously been described by Serrate (1978) in both the French Alps and the Peruvian Andes.

Forestry theoretically has an extensive form in the western Sierra Madre and would not result in wide deforested areas. Nevertheless, non-authorized harvesting and strong market demand for wood lead to overexploitation. According to a study carried out by Rodriguez (1997) in the Tepehuanes and Guanacevi (Durango State) forestry districts, which involve the Sextin and Ramos watersheds, a severe deforestation occurs in these regions. In this study, remote sensing data were used to assess changing land use; forested areas are decreasing, and pasture and bare soil (including tilled soils) areas are increasing. From 1972 to 1992 (Table IV), forest cover appears to be threatened in the short term by overexploitation, due to clandestine harvesting.

Results of research carried out from 1994 to 1998 (Descroix and Nouvelot, 1997; Descroix *et al.*, 2001) at the plot scale (1 m^2 to 50 m^2) suggest the following observations:

- overgrazing results in an extension of crusted soil areas, mainly on gentler slopes;

Table III. Need and availability of pasture surface (hectares/bovine unit) in two rural communities of the western Sierra Madre (total area 20 000 hectares)

Name of rural community	Available pasture area, 1994	Necessary pasture area, 1994	Available pasture area, 1997	Necessary pasture area, 1997
Posta de Jihuites	2·25	10·50	3·75	9·67
Boleras	3·95	19·40	5·26	17·14
Pooled data	3·38	16·34	4·83	14·64

Table IV. Evolution of surface cover in the western Sierra Madre from 1972 to 1992; forestry districts of Tepehuanes and Guanacevi (Landsat MSS images, Rodriguez, 1997)

Vegetation pattern	1972 (km^2)	1992 (km^2)	Evolution (%)
Dense forest (pines)	662	220	−66
Intermediary forest	1537	672	−54
Deciduous forest	1967	1203	−39
Tree savannah	1417	1805	+27
Pasture	1591	1614	+0·2
Bare and tilled soils	758	905	+19

- on steeper zones, erosion causes the removal of fine size particles and the formation of a stone pavement—in the long term the pavement is self-limiting, because the soil is protected from kinetic energy by stoniness;
- in forest (Table V) and tree savannah areas, tree felling increases the splash effect and soil sealing, inducing a runoff rise and a reduction of hydraulic conductivity;
- a decrease in hydraulic conductivity of soils is also noticeable on crusted and trampled soils (Table VI);
- runoff and erosion have an aerial form—gullies appear only in a few cases, on gentler slopes, located at the bottom of the grabens;
- oaks cover is more efficient than pines against erosion and runoff yield;
- on pasture and tree savannah, an overgrowth of pines is observable—pines take over the oaks but induce a degradation of pasture quality and a soil acidification.

At the plot scale, some of these observations lead to an increase of the runoff coefficient and soil loss values, as a consequence of overgrazing and deforestation (Tables V and VI).

Given the increased density and area of livestock rearing and increased forest clearing, the western Sierra Madre has suffered a progressive environmental degradation, which could have local and regional consequences. On an experimental scale, previous studies showed that human activities had a strong impact on vegetation, soils and runoff yield. The upper Rio Nazas basin is controlled at El Palmito dam (watershed area 19 000 km^2, Figure 1); it supplies 87% of the surface water of the entire Rio Nazas basin, though it represents only 20% of the total area (92 000 km^2). These figures emphasize the significance of this region, as well as the whole Sierra Madre range for the future of the surrounding arid areas of northern Mexico. Therefore, it is necessary to study whether changes at the plot scale (modifications due to overgrazing and deforestation) can lead to water balance changes. Degradation of the soil–vegetation reservoir may affect the basin response to rainfall, such as increasing the flood risk, increasing the severity of drought, and decreasing the annual water supply.

The main aim of this paper is to determine whether changes in hydrological behaviour of watershed occurred due to degradation in the environment.

MATERIALS AND METHODS

Data employed in this study includes daily streamflow for two main tributaries of the Rio Nazas: the Rio Ramos basin (7130 km^2 at the stream gauging station of Salomé Acosta) and the Rio Sextin basin (4660 km^2

Table V. Influence of deforestation on runoff and erosion in forest, on plots of 50 m^2 (one plot in each case)

	With trees	Without trees but with litter	Under trees
Runoff coefficient (%)	23	8·5	2·8
Erosion (g/m^2)	133	30·5	1·11

Table VI. Influence of cow trampling on runoff, erosion and soil properties. Average of eight plots of 1 m^2 located in pasture lands

	Trampled	Not trampled
Runoff coefficient (%)	43	8·3
Erosion (g/m^2)	90	7
Apparent density (g/cm^3)	1·38	1·31
Hydraulic conductivity (mm/s)	0·0035	0·008

at Sardinas station) (see Figure 1) from 1970 to 1998. The precipitation amount was recorded at 42 stations (daily values) during the same period, managed by the Comisión Nacional del Agua (CNA), the Mexican water management public service. The measurement network density is quite poor, but stations are adequately located except for the crests and upper hillslopes where very few stations were located. Spatial fields of daily rainfall depths were krigged to derive basin input.

Firstly, the daily rainfall, daily runoff and runoff coefficient were analysed to detect trends and discontinuities. Then, a set of data processing methods have been used in order to determine changes in hydrological regimes of streamflows.

Irregularity index

This constitutes the simplest index used here. It is defined as the ratio of the minimum daily discharge of the year to the maximum one. In order to improve the significance of such an index, the average of the 25 highest and the 25 lowest values in the year is taken into account:

$$\mathrm{IrI} = Q_{\mathrm{min}\,25}/Q_{\mathrm{max}\,25}$$

where $Q_{\mathrm{min}\,25}$ is the average of the 25 lowest daily discharge values, $Q_{\mathrm{max}\,25}$ being the average of the 25 highest discharge values.

Hydrographs separation

The methodology used to separate base flow and flood flow from daily mean discharge values was the Gustard algorithm (Gustard *et al.*, 1989), such as suggested by Humbert and Kaden (1994). The principle of this method is the following: '*admitting that climatic effects have been eliminated, any perceptible modification of the environment parameters has to reflect on the evolution of respective proportion of base flow and flood flow*.' An example is given in Figure 2. The calculation is based on five steps (Gustard *et al.*, 1989; Humbert and Kaden, 1994).

1. Starting from a series of daily mean discharges, the calculation period is divided into non-overlapped groups of N days (here N was taken equal to 3); then, low points of inflexion (FLi) of each group (F1, F2, ..., Fn) are determined.
2. Successive scrutinization of the groups (F1, F2, F3), (F2, F3, F4), (F$n-1$, Fn, F$n+1$)—when the central value of a group (Fn) is smaller than its flanked values, this is selected as a pivot point (FLi) for the constitution of the base flow curve; the operation is repeated (FL2, FL3, ..., FLn).
3. A linear interpolation between all FLi leads to an estimation of each daily value of base flow (BF) and flood flow (FF) (Figure 2).
4. Calculation of flood runoff coefficient (Cr-flood) and base runoff coefficient (Cr-base).
5. Then, integration of annual volumes of base flow and flood flow.

The hydrograph separation according to the Gustard algorithm allows us to obtain, for each value of mean daily discharge in the series of the two basins, a base flow (BF) and a flood flow (FF).

Lag time of watersheds

The daily discharge and rainfall data sets allow the lag times of each basin to be calculated.

For each rainfall event, the elapsed time between the rainfall in the basin and the corresponding rising of river flow was measured.

It was previously noticed in the data set that the maximum lag time of the catchments is approximately two days. Then, the following process was used.

1. Classification of daily rainfall (P) and rivers discharge (Q) data.

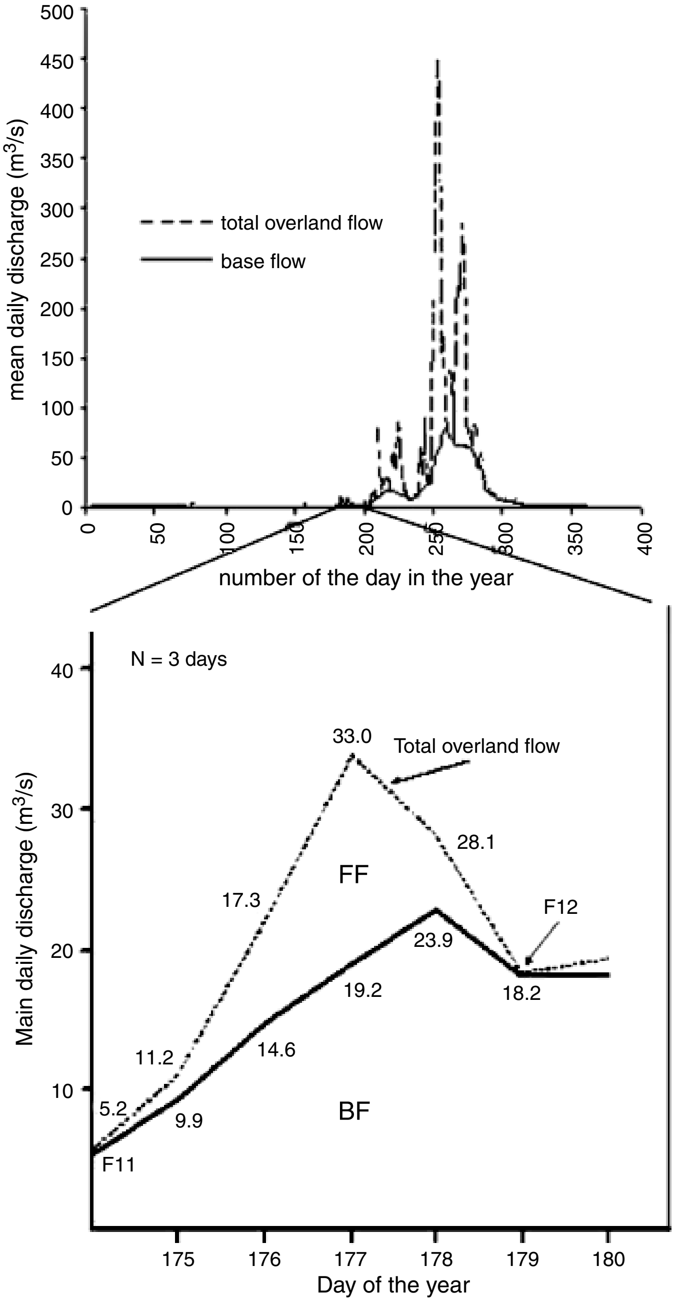

Figure 2. Example of hydrograph separation according to the Gustard algorithm: the Ramos River at Salome Acosta station (1978); BF = base flow; FF = flood flow; FL1 and FL2 are low points of inflexion of the hydrograph

2. Localization of each flood day (F_d) determined by a daily discharge enhancement ($Q_d > Q_{d-1}$), d being the day the flood occurs.
3. Localization of each rainfall event for two days before the flood (P_{d-2}, P_{d-1}, P_d).
4. The lag time is calculated as the difference (in days and fractions of days) between P_d and F_d.

In the 30-year data set of mean daily flow values, the first and last five years (in the Sextin basin) and six years (in the Ramos basin) were taken into account to calculate the respective basin response time. The low precision of discharge data (daily average) is compensated by the high number of floods taken into account (approximately 400 for each period and for each basin).

Baseflow recession index

This was defined (as baseflow recession constant) by Rose and Peters (2001):

$$k_{\mathrm{bf}} = (1/t)\ln(Qm_{\min})/Qm_{\max})$$

where k_{bf} is the baseflow recession index. In this study, $Qm_{\min}$ is the lowest monthly average discharge (taken generally in December), $Qm_{\max}$ is the highest monthly average discharge in the year (generally September), and t (days^{-1}) the time elapsed between the highest flow in September and the lowest flow in December.

Two-day recession index

Inspired by Domenico and Schwartz (1998), cited by Rose and Peters (2001), who defined it as:

$$Q_2 = \mathrm{Q_p e}^{-kt}$$

$$k_2 = (1/t)\ln Q_{\mathrm{p}}/Q_2$$

where Q_{p} is the peak discharge, Q_2 is the discharge two days after the peak, $t = 2$ days, and k_2 (h^{-1}) is the two-day recession index.

These methods have been applied to the same data set of the two subcatchments of the upper Rio Nazas basin (Figure 1). The calculation of the IrI and k_{bf} was made by comparing the highest runoff of the rainy season (generally in September) with the driest month of the winter (generally December). The recession is not easily measurable until May (the driest month in the year) because rainfall can occur in winter (the ‘warm years’ of the southern oscillation), making comparison with the recession of this kind of year impossible.

RESULTS AND DISCUSSION

Before studying the changes in streamflows due to land use changes, it is important to determine the presence of possible trends or discontinuities in the statistical data (rainfall, runoff and runoff coefficient). Figure 3 shows the evolution of the three series of annual data for the two basins. There is no visible trend in these series. A statistical research of trends or discontinuities of the three series has been performed. It is shown in Table VIIa (for the Sextin basin) and VIIb (for the Ramos one) that there is no trend or discontinuity in the rainfall series, according to most of the important tests: random behaviour (Kendall and Stuart, 1977; Chatfield, 1989); test of Buishand (1984) with the control ellipse (Bois, 1986); the Mann–Whitney test (Pettitt, 1979), the Lee and Heghinian (1977) test; and the segmentation test (Hubert *et al.*, 1989). The same tests were also performed with the annual discharge and runoff coefficient data. In all cases, the only discontinuity appeared in the tests of Lee and Heghinian; but this discontinuity is revealed in each case for different years (1993 and 1997 for rainfall in the Sextin and Ramos basins, respectively; 1991 and 1993 for runoff depth; 1992 and 1993 for runoff coefficient). This is accounted for by the sensibility of the test at the series of dry years (1992; 1994 and 1995; 1997 and 1998).

The CV of rainfall in the upper Nazas basin is close to 0·2. However, the CV of mean annual discharge at the outlet is 0·63. This is due to the great spatial variability of rainfall and of the runoff conditions. On average, 85% of the total annual rainfall occurs between June and October (Table VIII). During this rainy season, most of the rainfall events are convective storms of short duration; more than 95% of the rainfall

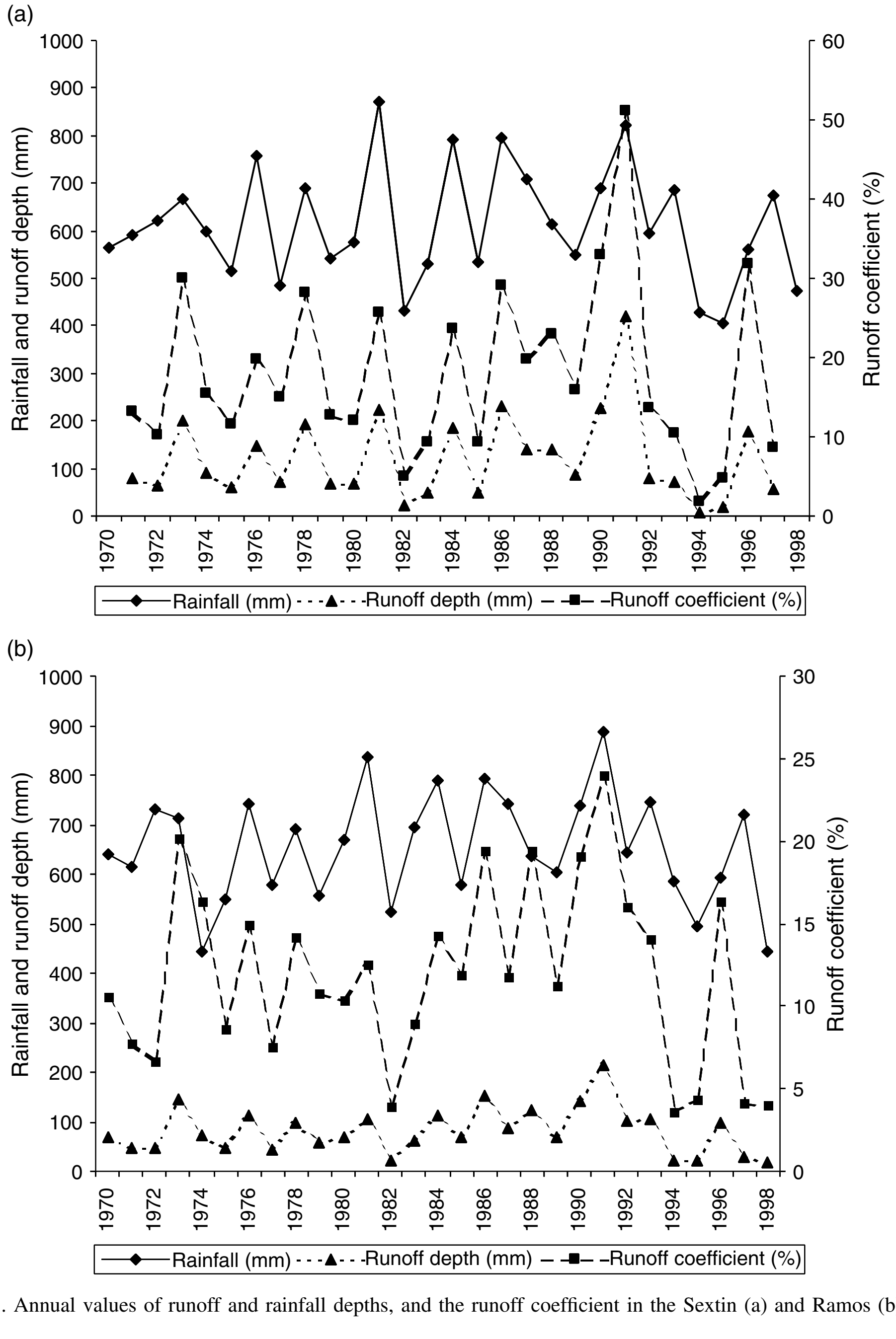

Figure 3. Annual values of runoff and rainfall depths, and the runoff coefficient in the Sextin (a) and Ramos (b) basins

events (defined as storms separated from the others by more than half an hour without rain) occur once a day, which makes easier the calculation of the response time of the watersheds.

The first index used in this study, the irregularity index IrI, did not give significant results; according to this index, there is no noticeable evolution towards an irregularity of annual discharge. Therefore, four series of results are presented here.

Table VII. Results of statistical tests of the random behaviour and detection of discontinuities in the annual rainfall data (with a confidence level of 90%) of (a) the Sextin basin and (b) the Ramos basin

Statistics test	Invalid hypothesis (absence of discontinuity)	
	Accepted	Rejected
(a) Sextin basin		
Random behaviour (Kendall and Stuart, 1977; Chatfield, 1989)	√	
Buishand (1984) and control ellipse (Bois, 1986)	√	
Mann–Whitney (Pettitt, 1979)	√	
Lee and Heghinian (1977)		√ (1997) see text
Segmentation (Hubert *et al.*, 1989)	√	
(b) Ramos basin		
Random behaviour (Kendall and Stuart, 1977; Chatfield, 1989)	√	
Buishand (1984) and control ellipse (Bois, 1986)	√	
Mann–Whitney (Pettitt, 1979)	√	
Lee and Heghinian (1977)		√ (1997) see text
Segmentation (Hubert *et al.*, 1989)	√	

Table VIII. Annual distribution of rainfall in the upper Nazas basin (% of total annual amount)

Month	J	F	M	A	M	J	J	A	S	O	N	D
	3·0	1·1	0·7	1·6	3·5	12·9	22·3	24·1	18·4	6·9	2·4	3·2

The first one considers the ratio of flood flow runoff coefficient (Cr-flood) to the base flow runoff coefficient (Cr-base). It is shown (Figure 4) that this ratio increased from the first decade (1970–1979) to the last one (1990–1998). Furthermore, it is noticeable that the coefficient of determination of each regression also increases appreciably in the last decade (this result is significant according to the Fisher test).

Thus, the following regression equations are obtained for the Ramos basin:

$$1970\text{–}1979 \quad \text{Cr-flood} = 2{\cdot}3(\text{Cr-base}) \quad (r^2 = 0{\cdot}55)$$

$$1980\text{–}1989 \quad \text{Cr-flood} = 2{\cdot}7(\text{Cr-base}) \quad (r^2 = 0{\cdot}56)$$

$$1990\text{–}1998 \quad \text{Cr-flood} = 2{\cdot}9(\text{Cr-base}) \quad (r^2 = 0{\cdot}67)$$

The proportion of base flow of the total annual runoff decreased from more than 30% in the 1970s to less than 25% in the 1990s. Inversely, the proportion of flood flow increased significantly. The temporal variability of streamflow seems to be increasing; this should be a consequence of the soil water storage reduction in the basin, due to soil and vegetation degradation. The evolution for the Sextin basin is not noticeable and is statistically insignificant.

The second series of results is based on the analysis of the watershed lag times. Around 500 and 400 rainfall events were respectively assessed in the Ramos and Sextin basins. Lag times varied markedly from the beginning of the 1970s to the middle of the 1990s (Table IX). In the Sextin basin, the lag time decreased by 6·1% during this time (this result is statistically significant according to the Student test); but in the Ramos

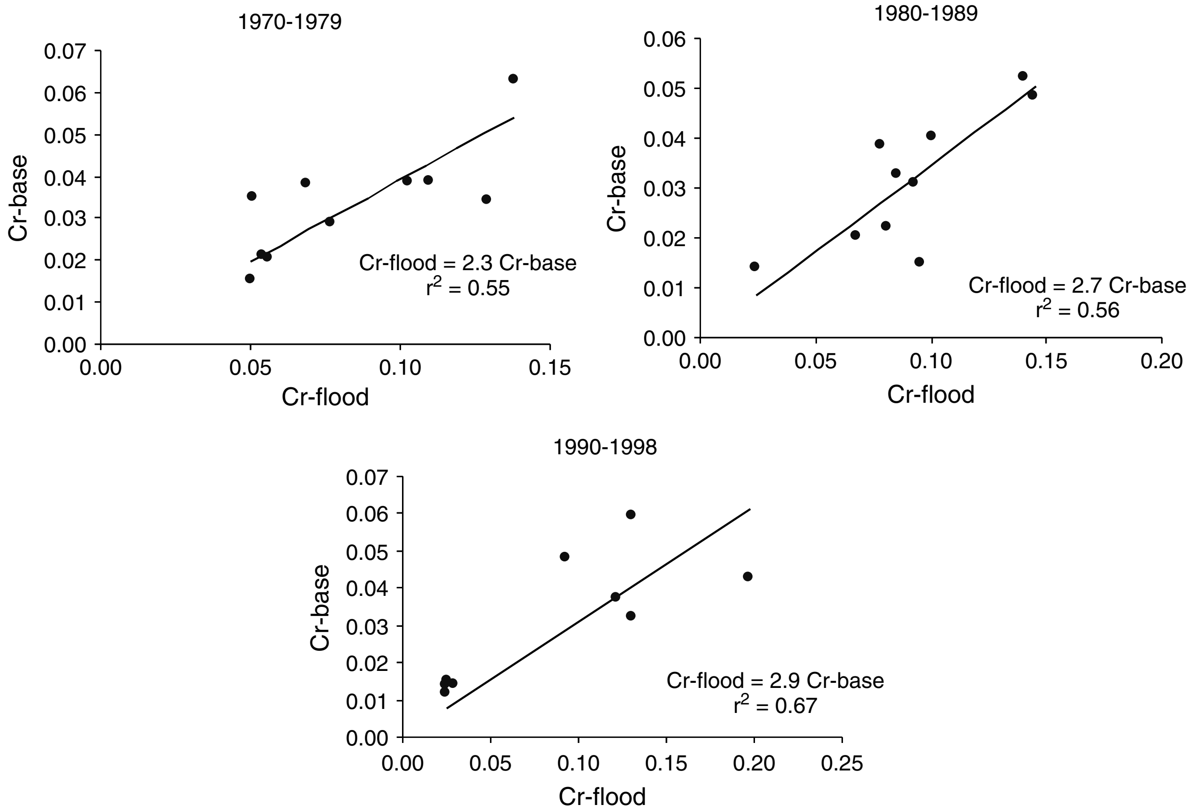

Figure 4. Evolution of flood runoff coefficient (Cr-flood) and base runoff coefficient (Cr-base) per decade in Ramos river basin from 1970 to 1998

Table IX. Statistic and temporal evolution of the lag times of the Ramos and Sextin river basins

		Period 1 1970–75	Period 2 1993–98	Evolution[a] Δ (%)	Student test (90%)
Ramos river basin	Av. (day)	1·71	1·67		
	Std. dev.	0·52	0·54	*−2·11*	
	N (events)	489	496		
		1971–75	1993–97		
Sextin river basin	Av. (day)	1·7	1·59		
	Std. dev.	0·5	0·58	*−6·1*	[b]
	N (events)	393	366		

[a] Δ is the relation evolution of the average lag time between period 2 and period 1.

[b] The evolution is statistically significant at an 80% confidence level, according to the Student test.

basin, the decrease was far less obvious and not statistically significant. The reduction of the basin response time could be a result of changes in the watershed environment, subsequently modifying soil hydraulic conductivity and soil water retention capacity.

The third set of results proposed here concerns the base flow recession index k_{bf}. This index is increasing for the Ramos basin, from 0·015 during the 1970–1984 period to 0·0195 during the 1985–1998 one. This increase is statistically significant (at an 80% confidence level, according to the Student test) and is consistent with a reduction of the basin water storage between these two periods. In the Sextin basin, change is too low and is statistically insignificant.

The last series of results is based on the two-day recession index. In the two basins, the analysis of respectively 657 and 560 events (for the Ramos and Sextin basins) highlights the increase of the index value from the 1970–1979 decade to the 1990–1998 one:

- in the Ramos basin, it increased from 0·084 days^{-1} to 0·131 days^{-1} (this rise is statistically significant with an 80% confidence level, according to the Student test);
- in the Sextin basin, the two-day index increased from 0·141 days^{-1} to 0·162 days^{-1} (but this is not statistically significant).

Changes in the hydrodynamic behaviour of slopes are easy to observe at the plot scale, but may not be significant at the watershed scale. In the western Sierra Madre, livestock trampling and deforestation induced some drastic changes on soil surface characteristics and related hydraulic properties of hillslopes. Results at plot scale are in agreement with conventional findings: vegetation loss (due to overgrazing and forest clearing) leads to an enhancement of runoff and soil losses (Fritsch, 1990; Kosmas *et al.*, 1997; Woo *et al.*, 1997). This kind of evolution is easier to prove at the watershed scale under humid climates, as has been shown by Bosch and Hewlett (1982) and Stednick (1996). Bernard-Allée and Cosandey (1991) calculated the impact of the forest clearing in the French Cevennes mountains where annual rainfall is about 1900 mm; the runoff depth increased 150 to 200 mm yearly after the cutting. Such marked evolutions are noticed in England (Hudson and Gilman, 1993) or in humid areas of North America (Bosch and Hewlett, 1982).

The increase of the two-day recession index in these basins which have suffered a strong deforestation can be compared with the results of Rose and Peters (2001) in an urbanized catchment of Georgia (USA): both deforestation and urbanization lead to an increase in impervious areas which make the hydrographs 'spikier'. The evolution of both the two-day recession index and the baseflow recession index is consistent with the observations made by Viramontes and Descroix (in press) in the same basins using the 'Nazasm' model based on the α depletion index of the API (antecedent precipitation index) as described by Descroix *et al.* (in press). This reflects the decrease in water storage of the watersheds and the higher values of peak flows (and inversely, lower values of low flows), as has also been shown in a case of forest harvesting by Caissie *et al.* (2002).

In the study area, it has been found that increasing runoff and erosion were due to the development of new soil surface features, particularly crusted soils which drastically enhance runoff. Furthermore, the most important degradation factor is overgrazing, because trampling cows make the soil bulk density increase and reduce hydraulic conductivity (Descroix *et al.*, 2001) (Table VI).

At the catchment scale, it seems difficult to prove any change in hydrological behaviour of the hillslopes in the Sierra Madre. However, some authors have found significant changes in annual runoff amount (Bosch and Hewlett, 1982; Galea *et al.*, 1993; Hudson and Gilman, 1993; Calder *et al.*, 1995; Sorriso-Valvo *et al.*, 1995). In agreement with other authors (Cosandey, 1995; Caugant, 1998; Andréassian, 1999), the runoff coefficient of the Ramos and Sextin catchments remains practically unchanged. Nevertheless, some evolutions have been noticed in the way in which runoff occurs.

Furthermore, process studies show that the soil water retention capacity is reduced in overgrazed and deforested small basins (Descroix *et al.*, in press). The same evolution seems to be verified in the larger, 5000-km^2 basins (Viramontes, 2000). Under subhumid conditions with annual rainfall amount of 600 mm, the main trend is rather a hydrological behaviour change than a runoff increase (Viramontes and Descroix, 2002).

CONCLUSION

Overexploitation of the environment in western Sierra Madre has caused a widespread degradation of vegetation and soils. The cattle trampling and forest harvesting have been found to have some consequences.

At the plot scale, obvious rises of the runoff coefficient and soil losses were observed and are related to soil sealing, a decrease in hydraulic conductivity and an increase in splash effect; this pattern does not apply to pasture areas on steep slopes where a stony pavement protects the soil from drops in kinetic energy.

At the catchment scale, the rainfall amount and runoff coefficient were not modified. It is actually well known that land use changes have more influence on the average discharge in areas where the total annual rainfall is significant, such as under temperate and equatorial climates.

After demonstrating the absence of trends and discontinuities in the annual rainfall data of the two studied basins, a set of analysis methods was used to determine whether changes occurred on the streamflow regimes. The two main methods described here are the separation of hydrographs and the lag time of the basins. Results are compared with those of other methods proposed by Rose and Peters (2001). Some slight evolutions were thus highlighted:

- the baseflow component of the annual runoff amount has been decreasing for three decades—the ratio FF/BF (flood flow/base flow) registered a 20% increase from the 1970s to the 1990s for the Ramos basin and only 2% in the Sextin basin;
- inversely, the basin lag time decrease was lower in the Ramos basin (2·1%) than in the Sextin basin (6·1%);
- the two-day recession index increased between the 1970s and the 1990s in the two basins, but results are significant only for the Ramos basin;
- the baseflow recession index also increased from the 1970–1984 period to the 1985–1998 one, but this increase is statistically significant only for the Ramos basin.

Both methods (separation of hydrographs and basin lag time analysis), as well as the baseflow recession index and two-day recession index, seem to be better evidence of an evolution in hillslope hydrodynamic behaviour than the variation of the runoff coefficient, which appears not to have changed significantly in the last three decades in the western Sierra Madre. Simultaneous observations at both the plot and the basin scales allow us to correlate the environmental degradation of the watersheds, particularly due to overgrazing and deforestation, and the evolution of the streamflow regime. Cattle trampling and timber harvesting lead to strong changes in soil surface features, triggering an evolution of runoff regime.

The variations may appear small, if each of the indices discussed above is considered apart. Nevertheless, the slight variations converge and the results are all consistent: base flows, basin water storage and lag time of the basins are diminishing and inversely peak flows are more rapid towards the end than at the beginning of the considered period.

All these relatively slight changes affect the sole wet region of the whole of northern Mexico, and their evolution may have dramatic consequences on the future water supply of extended arid areas surrounding the western Sierra Madre.

ACKNOWLEDGEMENTS

This paper is based on applications of the Gustard algorithm developed by J. Humbert and U. Kaden (CEREG, Strasbourg). We warmly thank J. F. Nouvelot (from IRD) for supplying us with other algorithms, and Dr N. Peters, who reviewed this manuscript and suggested some major improvements. We also thank L. Montoya, from Comisión Nacional del Agua (Torreón, Mexico) for providing us with hydrological and climatological data sets of the Upper Nazas basin.

REFERENCES

Andréassian V. 1999. Indicateur d'impact de l'évolution du couvert forestier sur la ressource en eau à l'echelle des bassins versants des Cévennes et de la Montagne Noire. *Programme Environnement, Vie et Société CNRS*, Rapport Final: Paris; 55.

Bernard-Allée P, Cosandey C. 1991. Conséquences d'une coupe forestière sur les bilans hydrologique et sédimentaire: le bassin-versant de la Latte, Mont Lozère. *Physio-Géo* **21**: 79–94.

Bois P. 1986. Contrôle des séries chronologiques corrélées par étude du cumul des résidus. In *Deuxièmes journées hydrologiques de l'Orstom*. Orstom Publication: Montpellier; 89–100.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**: 3–23.

Boutrais J. 1994. Eleveurs, bétail et environnement. In *A la croisée des parcours*. ORSTOM—Centre d'études africaines: Paris; 303–319.

Braud I, Fernández PC, Bouraoui F. 1999. Study of the rainfall–runoff process in the Andes region using a continuous distributed model. *Journal of Hydrology* **216**: 155–171.

Braud I, Viche AIJ, Zuluaga J, Fornero L, Pedrani A. 2001. Vegetation influence on runoff and sediment yield in the Andes region: observation and modelling. *Journal of Hydrology* **254**: 124–144.

Buishand TA. 1984. Tests for detecting a shift in the mean of hydrological time series. *Journal of Hydrology* **68**: 51–69.

Caissie D, Jolicoeur S, Bouchard M, Poncet E. 2002. Comparison of streamflow between pre and post timber harvesting in Catamaran Brook (Canada). *Journal of Hydrology* **258**: 232–248.

Calder IR, Hall LR, Bastable HG, Gunston HM, Shela O, Chirwa A, Kafundu R. 1995. The impact of land use change on the water resources in sub-Saharan Africa: a modelling study of lake Malawi. *Journal of Hydrology* **170**: 123–135.

Caugant C. 1998. *Impact de l'evolution du couvert forestier sur le comportement hydrologique de bassins versants du Massif Central*. Mémoire DEA, Géomorphologie. Université Paris 1, Cemagref: Paris.

Chatfield C. 1989. *The Analysis of Time Series. An Introduction*, 4th edition. Chapman and Hall/Kluwer Academic: Dordrecht; 241.

Cosandey C. 1995. La forêt réduit-elle l'écoulement annuel? *Annales de Géographie* **581/582**: 7–25.

Demant A, Robin C. 1975. Las fases del vulcanismo en México; una síntesis en relación con la evolución geodinámica desde el cretácico. *Revista del Instituto de Geología* **75**(1): 70–83.

Descroix L, Nouvelot JF. 1997. *Escurrimiento y erosión en la Sierra Madre Occidental*. ORSTOM-INIFAP: México; 50.

Descroix L, Viramontes D, Vauclin M, Gonzalez Barrios JL, Esteves M. 2001. Influence of surface features and vegetation on runoff and soil erosion in the western Sierra Madre (Durango, North West of Mexico). *Catena* **43**: 115–135.

Descroix L, Nouvelot JF, Vauclin M. 2002. The role of the Antecedent Precipitation Index on runoff functions: applications to the western Sierra Madre (Northwest Mexico). *Journal of Hydrology* **263**: 114–130.

Domenico PA, Schwartz FW. 1998. *Physical and Chemical Hydrogeology*, 2nd edition. John Wiley & Sons: New York; 506.

Fritsch JM. 1990. *Les effets du défrichement de la forêt amazonienne et de la mise en culture sur l'hydrologie de petits bassins-versants en Guyane française*. Thèse, Université des Sciences et Techniques du Languedoc, Montpellier, France.

Galea G, Breil P, Ahmad A. 1993. Influence du couvert végétal sur l'hydrologie des crues, modélisation à validations multiples. *Hydrologie Continentale* **8**(1): 17–37.

Gustard A, Roald LA, Demuth S, Lumadjeng HS, Gross R. 1989. *Flow regimes from experimental and network data*. FRIEND program, Institute of Hydrology: Wallingford (2 vols).

Hewlett JD, Lull HW, Reinhart KG. 1969. In defence of experimental watersheds. *Water Resources Research* **5**(1): 306–316.

Hibbert AR. 1967. Forest treatment effects on water yield. In *International Symposium for Hydrology*, Sppoer WE, Lull HW (eds). Pergamon: Oxford; 813.

Hubert P, Carbonnel JP, Chaouche A. 1989. Segmentation des séries hydrométéorologiques. Application à des séries de précipitations et de débits de l'Afrique de l'Ouest. *Journal of Hydrology* **110**: 349–367.

Hudson JA, Gilman K. 1993. Long term variability in the water balances of the Plynlimon catchments. *Journal of Hydrology* **143**: 355–380.

Humbert J, Kaden U. 1994. Détection des modifications de l'écoulement fluvial au moyen de l'indice de débit de base. *Revue de Géographie Alpine* **82**(2): 25–36.

Kendall SM, Stuart A. 1977. *The Advanced Theory of Statistics*. Charles Griffin: London; vol. 3, 585.

Kosmas C, Danalatos N, Cammerat LH, Chabart M, Diamantopoulos J, Farand R. *et al*. 1997. The effects of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena* **29**: 45–59.

Lee AFS, Heghinian SM. 1977. A shift of the mean level in a sequence of independent normal random variables, a Bayesian approach. *Technometrics* **19**(4): 503–506.

Pettitt AN. 1979. A non-parametric approach to the change-point problem. *Applied Statistics* **28**(2): 126–135.

Poulenard J, Descroix L, Janeau JL. 1996. Surpâturage et formation de terrassettes sur les versants de la Sierra Madre Occidentale (Nord-Ouest de Mexique). *Revue de Géographie Alpine* **2**: 77–86.

Rodriguez MG. 1997. *Determinación de la vegetación en la Sierra Madre Occidental para la calibración de imágenes satélite*. Tesis de licenciatura, ECF-UJED, Durango, Universidad de México, México.

Rose S, Peters NE. 2001. Effects of urbanisation on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* **15**: 1441–1457.

Serrate C. 1978. *Dynamique des versants de Haute Montagne: Andes Péruviennes—Alpes Briançonnaises*. Thèse de géographie, Université Paris VII, Paris, France.

Sorriso-Valvo M, Bryan RB, Yair A, Lovino F, Antronico L. 1995. Impact of afforestation on hydrological response and sediment production in a small Calambrian catchment. *Catena* **25**: 89–104.

Stednick JD. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* **176**: 79–95.

Tallaksen LM. 1995. A review of baseflow recession analysis. *Journal of Hydrology* **170**: 349–370.

Viramontes D. 1995. *Caracterización de los suelos y la vegetación en la parte alta de la cuenca del Nazas*. ORSTOM-INIFAP Mexico; 42.

Viramontes D. 2000. *Comportement hydrodynamique des milieux dans le Haut bassin du rio Nazas (Sierra Madre Occidentale, Mexique); causes et conséquences de leur évolution*. Thèse de Doctorat, Université Joseph Fournier, Grenoble, France.

Viramontes D, Descroix L. 2002. Modifications physiques du milieu et conséquences sur le comportement hydrologique des cours d'eau de la Sierra Madre Occidentale (Mexique). *Revue des Sciences de l'Eau* **15**: 493–513.

Woo M, Fang G, DiCenzo P. 1997. The role of vegetation in the retardation of rill erosion. *Catena* **29**: 145–149.