Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **27**, 991–1009 (2002)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/esp.388

SEDIMENT YIELD AND STORAGE VARIATIONS IN THE NÉGRON RIVER CATCHMENT (SOUTH WESTERN PARISIAN BASIN, FRANCE) DURING THE HOLOCENE PERIOD

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Received 2 January 2001; Revised 21 January 2002; Accepted 26 February 2002

ABSTRACT

In the Négron River catchment area (162 km^2), surface-sediment stores are composed of periglacial calcareous 'grèze' (5×10^6 t) and loess (21×10^6 t), and Holocene alluvium ($12{\cdot}6 \times 10^6$ t), peat ($0{\cdot}6 \times 10^6$ t) and colluvium ($18{\cdot}5 \times 10^6$ t). Seventy-five per cent of the Holocene sediments is stored along the thalwegs. Present net sediment yield, calculated from solid discharge at the Négron outlet, is low (0·6 t km^{-2} a^{-1}) due to the dominance of carbonate rocks in the catchment. Mean sediment yield during the Holocene period is 7·0 t km^{-2} a^{-1} from alluvium stores and 7·6 t km^{-2} a^{-1} from colluvium stores. Thus, the gross sediment yield during the Holocene period is about 18·7 t km^{-2} a^{-1} and the sediment delivery ratio 3 per cent. The yield considerably varies from one sub-basin to another (3·9 to 24·5 t km^{-2} a^{-1}) according to lithology: about 25 per cent and 50 per cent of initial stores of periglacial grèze and loess respectively were reworked during the Holocene period. Sediment yield has increased by a factor of 6 in the last 1000 years, due to the development of agriculture. The very high rate of sediment storage on the slope during that period (88 per cent of the yield) can be accounted for by the formation of cultivation steps ('rideaux'). It is predicted that the current destruction of these steps will result in a sediment wave reaching the valley floors in the coming decades. Subboreal and Subatlantic sediments and pollen assemblages in the Taligny marsh, where one-third of the alluvium is stored, show the predominant influence of human activity during these periods in the Négron catchment. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: sediment yield; sediment storage; Holocene; human impact; Parisian Basin

INTRODUCTION

Recent changes in the surface of continents can be studied by analysis of the relief and surface sediments resulting from the displacement of material. To determine the speed of change and the impact of environmental parameters requires quantification of the flux of matter, particularly solid material (Probst, 1992). The most widely used method consists of measuring the current flux of suspended matter, at the mouth of the river for example, in order to quantify the net rate of denudation (mm a^{-1}) or sediment yield (t km^{-2} a^{-1}) in the drainage basins of major rivers (Holeman, 1968; Milliman and Meade, 1983; Meybeck, 1988).

However, it is known that part of the flux of solid material in rivers is stored in catchment areas as alluvium and colluvium (Trimble, 1977). The larger the basin the more material is stored (Robinson, 1978; Milliman and Meade, 1983; Milliman and Syvitski, 1992). Only part of the catchment is subject to erosion, while other parts store the sediment, and some surfaces may remain unchanged (Revel and Rouaud, 1985). By quantifying sediment stores, not only can the sediment budget be assessed, but this assessment can also be extended back to previous periods. Quantification has mainly concerned material accumulated in lacustrine basins which form effective traps and have well-defined boundaries, facilitating measurement (Macaire *et al*., 1997; Bichet *et al*., 1999). Fluvial sediments are more difficult to quantify because they are spread over valley floors.

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Moreover, the proportion of gross sediment yield stored on slopes has not often been taken into account in assessing material, due to the difficulty of precise quantification over a large area. In America, data exist for sediment yield including colluvial stores on slopes, particularly those resulting from recent human activities (Haggett, 1961; Costa, 1975; Trimble, 1983). There are few data in Europe where human activities have existed for longer (Revel and Rouaud, 1985).

On the other hand, the mean value of sediment yield calculated for a catchment masks spatial variability linked to characteristics of the surface of the area concerned (relief, lithology, vegetation) and temporal variability linked to characteristics of the climate, vegetation and ground use (Ahnert, 1970; Wilson, 1973; Dietrich and Dunne, 1978; Trimble, 1983; Meade *et al*., 1990).

This study aims to attempt a sediment budget as complete as possible for the Holocene period using different approaches (quantification of present flux of solid material, of various sedimentary stores, and of rates of sedimentation), and to compare the values obtained by each approach. The mean sediment yield of the catchment will be compared to those of its various sub-basins. The sediment yield values for periods prior to and contemporary with human activities will be calculated in order to establish variations due to natural and human factors.

We chose to study a west European catchment where crop farming developed dramatically over at least a millennium and where colluvium is present but rarely considered in sediment budgets. The Négron catchment, located in the Parisian Basin, is representative of such a catchment. Its surface area (162 km^2) made it possible to obtain the data required, and is large enough for the results to be representative of the southern Parisian Basin.

THE NÉGRON CATCHMENT

The Négron catchment is located northeast of the town of Loudun (47°1′ latitude north and 0°5′ longitude east) in the southwest of the Parisian Basin (Figure 1A). It is composed of Mesozoic and Cenozoic sedimentary beds slightly tilted towards the north-northeast and cut in the north and south parts of the catchment by two faults running west-northwest (Figure 1B). These sedimentary beds induced some different geomorphological units. In the north there is an area of Turonian chalk hills (maximum elevation 120 m) covered with Senonian and Eocene sand, clay, flint and conglomerate (Alcaydé and Joubert, 1987; Alcaydé *et al*., 1989). Extending south of the hill area there is a depression (minimum elevation 40 m) cut in Cenomanian sand and marl. Further south there is an Oxfordian limestone plateau surrounded by Oxfordian marl. In the southern part of the catchment near Loudun, south of the fault, Turonian chalk and Senonian clay hills emerge.

The Quaternary formations consist of loess, colluvium, 'grèze', alluvium and peat. The loess forms thin cover, sparsely scattered on the hill-tops and the limestone plateau in the northern and southern parts of the catchment (Figure 1B). There is a small amount of colluvium stored on slopes, mostly located on the Turonian chalks at different slope levels, but also found on the Cenomanian and Oxfordian marls at the bottom of the slopes. The accumulation of colluvium sometimes forms topographical steps running parallel to the contour line, which are cultivation terraces called 'rideaux' (Bollinne, 1971).

The valleys also contain colluvium, especially in their undrained upstream stretches. Downstream, where there is intermittent or continuous drainage, the colluvium is reworked into alluvium. Calcareous grèze is found under the alluvium in the Oxfordian limestone outcrop zone. Peat interbedded with alluvium is found in the wider, downstream stretches of the valleys, notably in the Taligny marsh.

On Oxfordian limestone and marl, Turonian chalk and Cenomanian marl, soils are mainly thin and calcimagnesic (Boutin *et al*., 1990; Cam *et al*., 1992). On Cenomanian sand, soils are brown. Senonian and Cenozoic sand, clay and loess areas exhibit varied soils (brown, leached or hydromorphic).

The Négron River is a tributary of the Vienne River. It is a perennial river with a mean longitudinal slope of 0·23 per cent and a mean water discharge at its outlet of 0·42 $m^3 s^{-1}$ (for the years 1994 to 1996; Oubelkasse, 1998). It is fed by springs in Oxfordian limestone (Lebideau, 1996). Downstream, where the bottom of the valley is broader and composed of Cenomanian marl, the Négron divides into two or three channels and flows through a marshy area, the Taligny marsh. The Négron has four main perennial or intermittent tributaries:

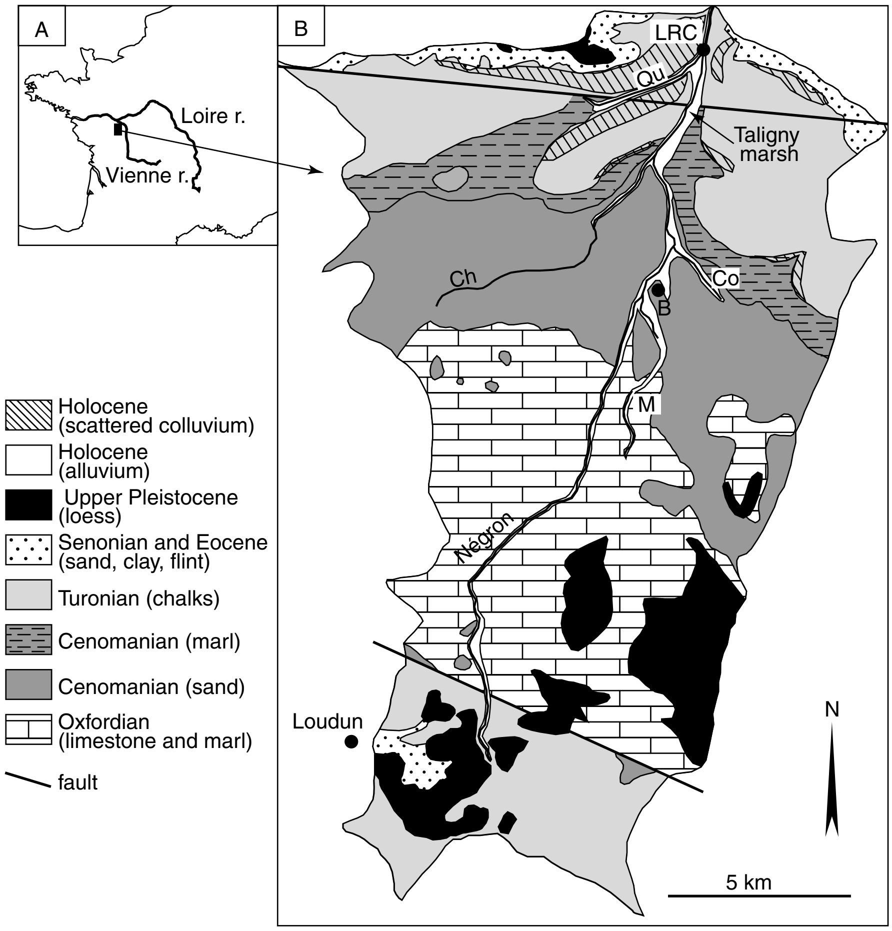

Figure 1. Location (A) and geology (B) of the Négron catchment (from Alcaydé and Joubert, 1987; Alcaydé *et al*., 1989; reproduced by permission of BRGM). LRC, La Roche-Clermault; B, Beuxes; Ch, Chavenay river; Co, Comprigny river; M, Merdelon river; Qu, Quincampoix river

the Merdelon and the Comprigny on the right bank, and the Chavenay and the Quincampoix on the left bank (Figure 1B). There are many small dry valleys, especially on the limestone plateau.

The present climate in the region is temperate with oceanic features: the average annual rainfall is 655 mm and the average annual temperature in Loudun is 11·7 °C. The main activity in this area today is farming. Crop farming (corn, maize, sunflower) accounts for 60 per cent of the catchment surface, mainly on slopes with calcimagnesic soils, while pastureland accounts for 8 per cent of the surface, mainly on brown soils in the Cenomanian depression. Woods cover 21 per cent of the surface, especially on hill-tops.

METHODS

The outcrop surface of the geological formations was determined by digitizing the geological contours on 1 : 50 000 maps (Alcaydé and Joubert, 1987; Alcaydé *et al*., 1989) and calculated using the contouring Surfer 6 program (Golden Software, Inc.; Table I).

The present flux of suspended matter was calculated from samples taken between February 1996 and May 1997 at four stations: (1) located on the Négron upstream of the Taligny marsh and (2) at the exit of the catchment, (3) on the Quincampoix and (4) on the Chavenay upstream of their respective confluences with the Négron (Figure 2). Samples of 10 litres of water were taken at each station every month and during floods,

Table I. Age, lithology, composition and quantification of the bed-rock formations and surficial sediment stores outcropping in the Négron catchment

Location	Lithology	Age	Petrographic composition*			Grain size†			Outcrop surfaces		Volume (10^6 m^3)	Volumetric mass (g cm^{-3})	Mass (10^6 t)
			$CaCO_3$	Silicates	Organic matter	Gravel	Sand	Silt and clay	(km^2)	(%)			
Négron water	Suspended matter	Present	53	47	–	0	24	76					
Surficial Sediment Stores													
On slopes	Colluvium on Turonian (with 'rideau')	Holocene whi‡	7	93	–	6	48	46	2·4		1·2	1	1·2
	Colluvium on Turonian (without 'rideau')								5·4		4·9	1	4·9
	Colluvium on Cenomanian (without 'rideau')		56	44	–	4	35	61	1·8		1·4	1	1·4
	Colluvium on Oxfordian (without 'rideau')		1	99	–	0	34	66	0·6		0·4	1	0·4
	Total colluvium								10·2		7·9	1	7·9
	Loess	Late Pleistocene	0	100	–	0	28	72	9		10·5	2	21
	Total on slopes								19·2		18·4		28·9
In valleys	Peat	Holocene	7	29	64	0	24	76	–		1·2	0·5	0·6
	Alluvium	Holocene whi‡	31	68	1	3	22	75	3·9		0·7	2	1·4
	(mainly silt)										4·1	2	8·2
	Alluvium (mainly sand and gravel)	Holocene	28	72	–	17	55	28			1·5	2	3
	Total alluvium								3·9		6·3		12·6

	Colluvium	Holocene whi[‡]	–	–	–	–	–	–	3·5		1·6	1	1·6
		Holocene	–	–	–	–	–	–	–		4·5	2	9
	Total colluvium								3·5		6·1		10·6
	Grèze	Late Pleistocene	58	42	–	27	33	40	–		2·5	2	5
	Total in valleys								7·4		16·1		28·8
	Total surficial sediments								26·6	16·4	34·5		57·7
Bed-rock	Conglomerate with flints	Eocene	0	100	–		very variable		2	1·2			
	Sand and clay with flints	Senonian	0	100	–		very variable		4	2·5			
	Yellow sandy chalk	Turonian	48	52	–	0	35	65	5	3·1			
	Micaceous chalk		67	33	–	0	24	76	12	7·5			
	Chalk with *Inoceramus*		53	47	–	0	45	55	20	12·3			
	Chalk and marl with glauconite	Cenomanian	48	52	–	0	8	92	12	7·5			
	Sand with glauconite		18	82	–	0	70	30	32	19·7			
	Limestone	Oxfordian	94	6	–	0	17	83	44·4	27·3			
	Marl		34	66	–	0	11	89	4	2·5			
	Total bed-rock								135·4	83·6			
Total bed-rock + surficial formations									162	100			

–, no analysis.
[*] As percentage of the bulk for suspended matter and surficial sediments, and as percentage of the <2 mm fraction for the bed-rock.
[†] As percentage of the bulk for suspended matter and surficial sediments, and as percentage of the <2 mm silicate fraction for the bed-rock.
[‡] whi, with human impact.

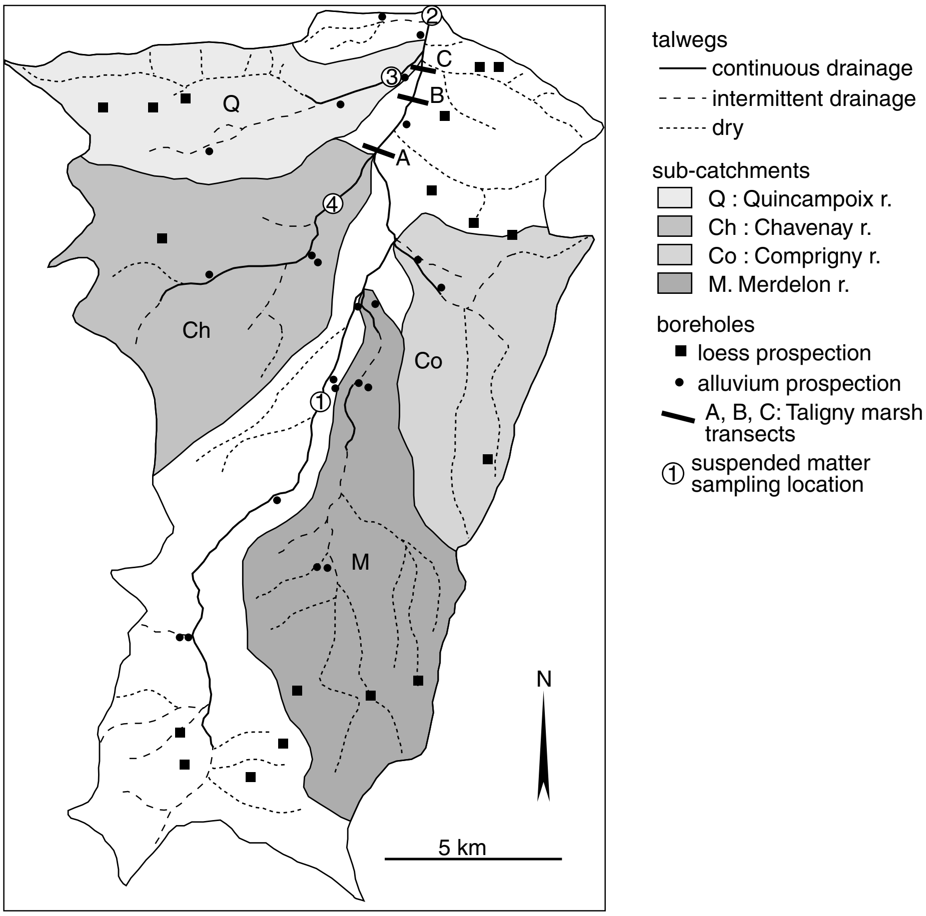

Figure 2. Hydrology and location of boreholes and samples studied in the Négron catchment

and filtered with a 0·45 µm pore size membrane under nitrogen pressure. The filtered material was weighed, and suspended matter concentrations (mg l^{-1}) were calculated. The water discharge at each station was taken from Oubelkasse (1998). As suspended matter concentrations showed little variation at a water discharge greater than 100 l s^{-1} at station 2, the flux of solid matter was calculated by multiplying the mean discharge by the mean suspended matter concentration at each station. The volumetric mass of suspended matter was 2·5 g cm^{-3}. Bedload, composed of fine and medium sand, was very low.

The volume of loess was calculated from the outcrop surfaces and thickness shown on the 1 : 50 000 geological maps of Loudun and Lencloître, the 1 : 50 000 pedological map of Loudun, and confirmed by field surveys (18 boreholes) (Figures 1 and 2). Outcrop surfaces were calculated with the Surfer programme.

Colluvial deposits on slopes, not shown on the 1 : 50 000 geological maps, were studied from geomorphological observations, 182 boreholes or core drillings and nine transects directed parallel to the maximum slope gradient: eight transects were located in the northern outcrops of Turonian chalks (Figure 3) and one transect in the outcrop of Oxfordian limestone (not shown here). Colluvium on chalks was quantified precisely in the northern part of the catchment and the results extended to the southern part in proportion to the chalk outcrop surface in that area. In the northern part we distinguished four areas (Figure 3). In area A, colluvium is mainly associated with 'rideaux' (transects 1, 2 and 3). We measured the length (L) of the front of each rideau, the width (w) of the accumulation of colluvium upstream of the front of the rideau and the maximum thickness (t) of the colluvium (Figure 4A). The volume of colluvium of each rideau was calculated according

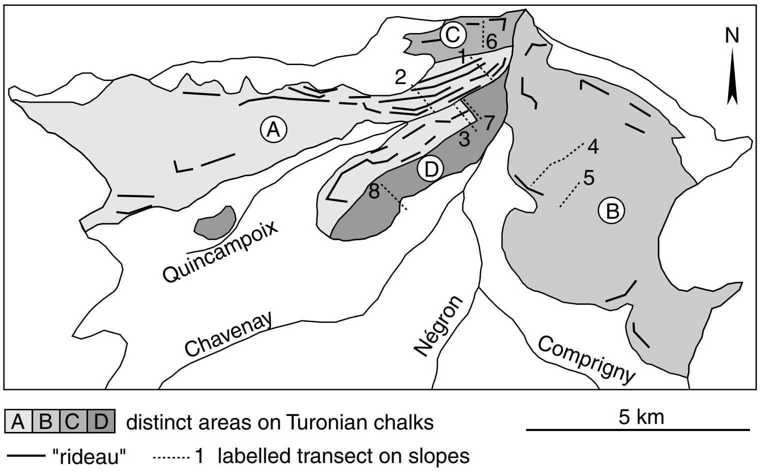

Figure 3. Location of the rideaux, slope transects and areas used to quantify the colluvium stores in the northern part of the Négron catchment

to two extreme hypotheses:

$$\text{maximum volume } (V_{\max}) = Lwt/2, \text{ due to parallel flux of run-off} \quad (1)$$

$$\text{minimum volume } (V_{\min}) = Lwt/6, \text{ due to divergent flux of run-off} \quad (2)$$

The mean volume $[V_m = (V_{\max} + V_{\min})/2]$ of colluvium was calculated.

In areas B (transects 4 and 5), C (transect 6) and D (transects 7 and 8), colluvium generally is not associated with rideaux (Figure 3). Colluvium outcrops form several strips without geomorphogical landmarks, parallel to each other along the elevation lines. Volumes of colluvium were determined for each area from the transects (Figure 4B). For each strip of colluvium we determined by boring the length (l) from the top to the bottom of the transect, the width (w) between the upstream and downstream boundaries of the outcrop of colluvium and the maximum thickness (t) of colluvium. We calculated the maximum, minimum and mean thickness (respectively $T_{\max}$, $T_{\min}$ and T_m) of colluvium, for the whole transect:

$$T_{\max} = (w_1 t_1) + (w_2 t_2) + \cdots + (w_n t_n)/l \quad (3)$$

$$T_{\min} = T_{\max}/2 \quad (4)$$

$$T_m = T_{\max} + T_{\min}/2 \quad (5)$$

The volumes of colluvium on areas B, C and D were calculated by multiplying T_m by the surface (S) of each area and adding the estimated volume of colluvium of the few rideaux. The mass was obtained using a volumetric mass of colluvium of 1 g cm^{-3}.

In order to quantify stores in the valleys, the length of all the catchment thalwegs was measured. The thalweg stretches were classified in 23 classes according to the type of drainage (dry, intermittent or continuous drainage) and the lithology of the bed-rock (Figure 2 and Table II). The length of the thalwegs (L_t), digitized from IGN 1 : 25 000 topographical maps, was calculated with the Surfer program and summed by class. The nature, maximum thickness (t_m) and lateral extension (l_e) of stores in each class were ascertained with 40 boreholes (Figure 2) and morphological data.

The surface of stores (S_s) in a vertical section, retained to calculate the volume, is the mean (S_{sm}) between that of a rectangle (maximum surface: $S_{s\max} = t_m l_e$) and that of a triangle (minimum surface: $S_{s\min} = t_m l_e/2$): $S_{sm} = (S_{s\max} + S_{s\min})/2$. The volume of stores associated with a class of thalweg is the product $S_{sm} L_t$. Where

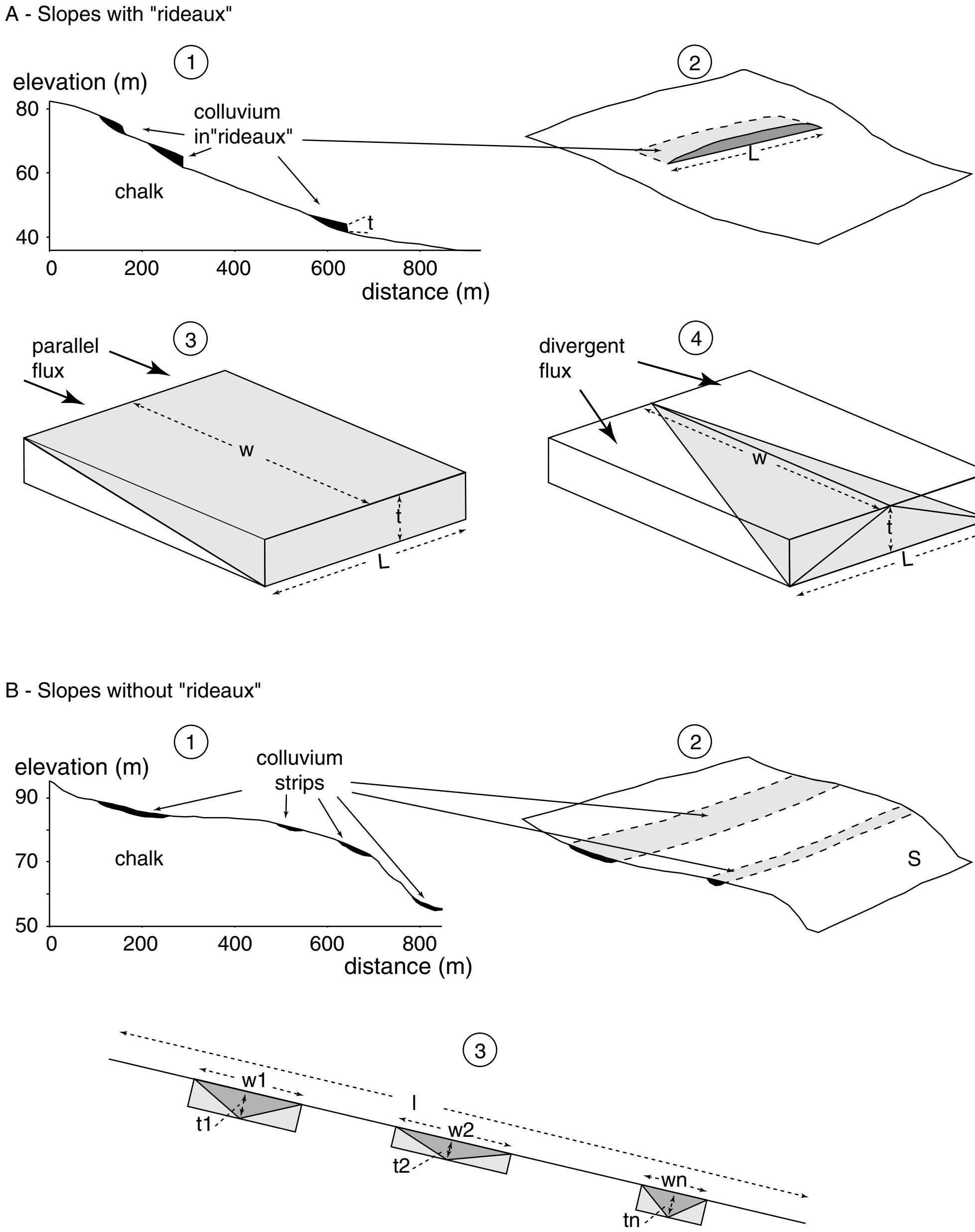

Figure 4. Distribution of colluvium on slopes and parameters used to calculate their volume. (A) Slopes with rideaux: 1, example of transect (transect 1); 2, 3D extent of a rideau; 3, hypothesis for calculating the maximum volume (V_{max} in grey) of colluvium stored in a rideau; 4, hypothesis for calculating the minimum volume (V_{min} in grey) of colluvium stored in a rideau. *L*, *w* and *t*, see explanation in the text. (B) Slopes without rideaux: 1, example of transect (transect 5); 2, 3D extent of the colluvium; 3, data for calculating the maximum thickness (T_{max} in light grey) and the minimum thickness (T_{min} in dark grey) of colluvium for the whole transect. *S*, *l*, *w*, *t*, see explanation in the text

several distinct formations are overlaid, the volume of each formation was calculated according to the proportion of its surface (deduced from its thickness) in a vertical section. Sediments from the Taligny marsh were identified from 17 boreholes, which allowed three transverse cuts in the upstream, mid-stream and downstream parts of the marsh to be made (Figure 5). The outcrop surface of all the colluvium and alluvium stores (slopes and valleys) was determined from L, w, L_t and l_e values.

Table II. Length of the thalwegs in the 23 classes defined according to bedrock lithology and drainage characteristics

Bed-rock		Types of thalwegs						Total
Age	Lithology	Continuous drainage		Intermittent drainage		Dry		
		(km)	(%)	(km)	(%)	(km)	(%)	
Quaternary	Loess			4·9	16	1·1	1	
Eocene	Clay and conglomerate			1	3	0·9	1	
Senonian	Sand and clay with flints					6·4	8	
Turonian	Yellow sandy chalk					3·6	4	
	Micaceous chalk			2·5	8	16·8	20	
	Chalk with *Inoceramus*	6	18	1·8	6	10·5	12	
Cenomanian	Chalk and marl	4·2	13	6·7	22	2	2	
	Sand	11·5	35	6·9	22	8	10	
Oxfordian	Marl	4·5	14	1·9	6	1	1	
	Limestone	6·4	20	5·4	17	34·6	41	
Total	length (km)	32·6		31·1		84·9		148·9
Total	length (%)	21·9		20·9		57·2		100

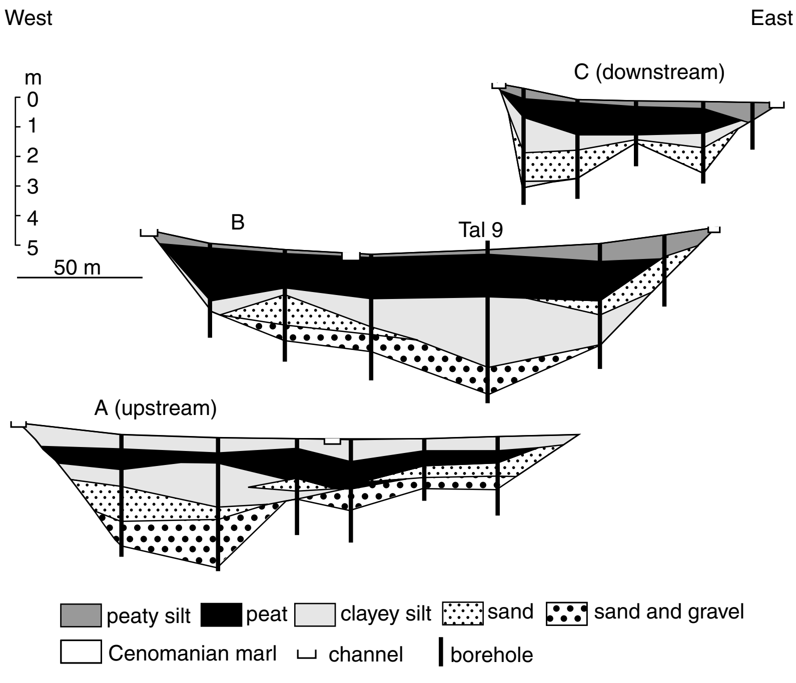

Figure 5. Cross-sections through the Taligny marsh. See Figure 2 for location of sections A, B and C

A total of 123 samples of the bed-rock and superficial stores taken by boring with core samplers were analysed. The proportion of gravel (>2 mm), sand (0·050–2 mm) and silt + clay (<0·050 mm) were quantified by sieving. The quantity of $CaCO_3$ was determined by weighing the insoluble residue after HCl digestion. The organic matter content in peat was calculated by Rock-Eval pyrolysis at the Geology and Organic Matter Laboratory of Orleans University. Palynological analysis of 30 samples and seven ^{14}C datings (Laboratory of Isotope Geochemistry, University of Arizona, Tucson) were carried out on the Tal 9 borehole located in the Taligny marsh (section B, Figure 5). ^{14}C datings were calibrated according to Stuiver *et al.* (1998).

RESULTS

Composition and distribution of the bed-rock in the catchment

The main characteristics of outcropping geological formations in the Négron catchment are shown in Table I. The bed-rock outcrops in an area of 135·4 km^2. Three formations make up approximately 70 per cent of the outcrops: Oxfordian limestone, mainly composed of calcite, Cenomanian sand, mainly composed of quartz and glauconite, and Turonian chalks which show various facies. These chalks are rich in carbonates and contain flints. The <2 mm siliceous fraction of chalk with Inoceramus (lower Turonian) and micaceous chalk (middle Turonian) is composed of CT opal spherolites (Leclaire *et al.*, 1973), while that in yellow sandy chalk (upper Turonian) is composed of quartz.

Other bed-rock formations outcrop less widely ($<7·5$ per cent of the surface each). Cenomanian chalk and marl are richer in carbonates than Oxfordian marl, the siliceous fraction being mainly silty-clay. Senonian and Eocene siliceous and clayey formations ($<2·5$ per cent of the surface each) do not contain carbonates. They are composed of large siliceous elements (flints, Porifera and conglomerates) in variable quantities, embedded in a sandy-clay matrix. Quaternary sedimentary stores cover 26·6 km^2, making up 16·4 per cent of the surface area of the basin.

Slope-sediment stores

These are composed of loess and colluvium. Loess, essentially silty-clayey and not carbonated, has a mean thickness of 1·1 m. It forms a mass of 21×10^6 t (volumetric mass = 2 g cm^{-3}) covering a surface area of 9 km^2 (Table I). It is found in the northern, and especially the southern parts of the catchment, where the altitude is higher.

Colluvium on slopes, whether it is associated with rideaux or not, is greyish-black, sandy-silty-clayey with some gravel, slightly carbonated and without stratification. It is not very compact (volumetric mass = 1 g cm^{-3}), embedding fragments of brick or pottery at different depths and covering in total 10·2 km^2 for a mass of $7·9 \times 10^6$ t.

Forty-four rideaux of accumulated colluvial matter were counted on Turonian bed-rock in the northern part of the catchment (65 per cent of the total surface of these bed-rock; Figure 3). Their length (L) varies from 102 to 1770 m, width (w) from 8 to 210 m, and the maximum thickness of deposits (t), generally between 1 and 2 m, can attain 3·5 m. Rideaux are found particularly in the northwest area (A, Figure 3) where the slope values vary little (0·3 to 3·2°). Colluvial stores are scattered at different levels and are associated with the shape of concave slopes. Taking the whole Turonian surface area (northern and southern zones), colluvial sediments associated with rideaux represent $1·2 \times 10^6$ t spread over an area of 2·4 km^2, and those which are not associated with rideaux represent $4·9 \times 10^6$ t over an area of 5·4 km^2.

Other colluvial stores are found on the Cenomanian and Oxfordian marls on the lower concave part of the slopes. They cover a surface area of 1·8 and 0·6 km^2 for a mass of 1·4 and $0·4 \times 10^6$ t respectively.

Valley-sediment stores

The total length of the thalwegs in the Négron catchment is 148·6 km, of which 57·2 per cent are dry, 20·9 per cent have intermittent drainage and 21·9 per cent have continuous drainage (Figure 2 and Table II). The dry thalwegs are mainly located on Oxfordian limestone (41 per cent), while the drained thalwegs are predominantly on Cenomanian formations (48 per cent), the alluvial plain being up to 215 m wide in the Taligny marsh.

Valley-sediment stores cover a total surface area of 7·4 km^2 for a mass of $28·8 \times 10^6$ t. Boreholes cut through four types of formation: grèze, colluvium, alluvium and peat. Grèze accounts for 5×10^6 t (Table I). Its maximum thickness is 3 m, exclusively located on Oxfordian limestone, and always overlain either by colluvium or by alluvium. They are characterized by an abundance of gravel (27 per cent), essentially calcareous (fragments of Oxfordian limestone) embedded in a highly carbonated, beige, sandy-silty-clayey matrix.

Colluvium, brown in colour, is generally compact (2 g cm^{-3}), containing little gravel, and predominately silty-clayey (Table I); that which is found on Cenomanian marl has a high carbonate content (56 per cent). Colluvium stores have a total mass of $10{\cdot}6 \times 10^6$ t. They crop out over 3·5 km^2 and constitute the total stores in the dry valley sections and in the upper parts of the valleys where they can be up to 7·3 m thick. Downstream they are found at the foot of the slopes; they are rarely covered by alluvium. On the contrary, they often cover the edge of alluvial formations with a layer 30 to 50 cm thick, showing facies similar to that of the colluvium stored on slopes. This valley colluvium, which shows traces of human activity (fragments of brick or pottery), amounts to $1{\cdot}6 \times 10^6$ t, representing 15·1 per cent of the total mass of colluvium stores.

Alluvium is found in sections of intermittently or continuously drained valleys. It has a total mass of $12{\cdot}6 \times 10^6$ t and covers an area of 3·9 km^2. Its average thickness is 1·5 to 2 m, with a maximum of 3·5 m (excluding peat) in the Taligny marsh (Figure 5). In general, coarse material is found in the lower layers ($3{\cdot}0 \times 10^6$ t in total), and fine material in the upper layers ($9{\cdot}6 \times 10^6$ t). The coarse material contains on average 17 per cent predominantly limestone gravel, and 55 per cent predominantly quartzose sand (Table I). The fine material contains on average 75 per cent silty-clay fraction with sand; its carbonate content is close to that of the coarse material. In the higher layers (between 0 and 45–50 cm), this fine alluvium is richer in organic matter (clayey silt or peaty silt), is more carbonated and changes laterally to anthropogenic colluvium. In the Taligny marsh, it covers the peat (Figure 5). This recent fine alluvial layer is estimated at $1{\cdot}4 \times 10^6$ t, i.e. 11 per cent of the total alluvium.

Peat was found in the Quincampoix valley, and especially in the Taligny marsh where it is up to 2·5 m thick: in total it amounts to $0{\cdot}6 \times 10^6$ t. It is brown to blackish, fibrous, rich in vegetal matter (*Phragmites* and fragments of wood) and contains on average 64 per cent of organic matter associated with a silicated silty-clay fraction. Carbonates (7 per cent on average) correspond to whole or fragmented gastropod mollusc shells. This peat changes gradually to superior fine alluvium through stages of blackish organic silty-clay with unpreserved organic debris.

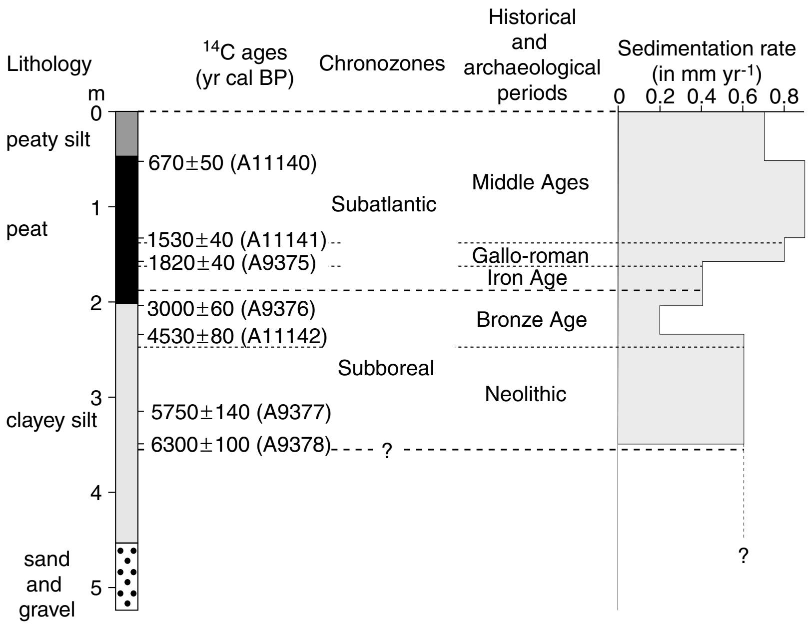

Figure 6. Lithology data, ^{14}C datings, chronology and sedimentation rates from the Tal 9 borehole. See Figure 5 for location and lithology. (A11140), reference of ^{14}C dating. Sedimentation rates were calculated for calendar years from ^{14}C calibrated ages (from Stuiver *et al*., 1998)

The Taligny marsh stores $4{\cdot}7 \times 10^6$ t of alluvium and peat, i.e. one-third of the total alluvial deposit. In the Tal 9 borehole, ^{14}C datings gave ages ranging from 6300 ± 100 years cal. BP (ref. A9378) at a depth of 3·5 m to 670 ± 50 years cal. BP (ref. A11140) at 0·55 m (Figure 6). From pollen grains, found only between 0 and 3·4 m, two main chronozones could be identified.

1. Subboreal (between 3·4 and 1·85 m), indicated in the marsh by the predominance of *Alnus* which decreased slightly in favour of aquatic species towards the end of this period (Bronze Age). On the slopes, trees (*Corylus* predominantly, *Quercus* and *Tilia*) represent less than 50 per cent of the pollen, with some *Cerealia* and anthropogenic species, decreasing above 2·2 m.
2. Subatlantic (between 1·85 and 0 m) is characterized by the general decrease of trees (*Tilia*, *Corylus* and *Quercus* on the slopes, *Alnus* in the marsh) except between 1·6 and 1·35 m (Gallo-Roman period). In the marsh, *Alnus* is replaced by large *Carex*. *Cerealia* pollen is rare below 1·35 m (beginning of the Middle Ages). A major change appears above 0·55 m (after 670 ± 50 years BP), shown by the increase of *Cerealia, Juglans*, heathland, *Cannabis* and aquatic species.

Present suspended matter discharge

Concentrations of suspended matter ranged from 8·4 to 235·2 mg l^{-1} at station 1, 0·5 to 14·5 mg l^{-1} at station 2, 0·7 to 8·1 mg l^{-1} at station 3 and 3·8 to 74·5 mg l^{-1} at station 4, for median discharge of 251, 370, 50 and 69 l s^{-1} respectively (Figure 7), corresponding to a mean flux of suspended matter of 5·0, 2·9, 0·2 and 0·6 g s^{-1} respectively. Flux from the Merdelon and the Comprigny on the right bank were considered negligible. The mean annual flux of suspended matter at the outlet of the Négron station 2 is 93·3 t, while the sum of solid material entering the Taligny marsh is 186·6 t. On average, this suspended matter consists of 75·4 per cent silt and clay and contains 53 per cent carbonates (Table I). The siliceous fraction is essentially composed of quartz.

DISCUSSION

Significance of surface stores

Out of the $57{\cdot}7 \times 10^6$ t of surface sediments stored, it is important to distinguish between those deposited during the Holocene period (colluvium, alluvium and peat) in bioclimatic and dynamic conditions similar to the present day, and those which were deposited previously (loess and grèze).

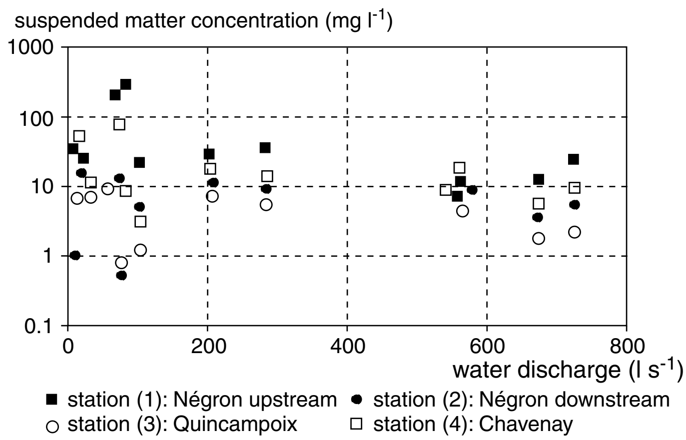

Figure 7. Relation between suspended matter concentration and water discharge at stations 1, 2, 3 and 4. See Figure 2 for location of stations

Pre-Holocene stores

Calcareous grèze (5×10^6 t), varying considerably in grain size and rich in limestone gravel (Table I), is characteristic of formations put down by periglacial solifluction during the last glacial period (Ozouf, 1983; Lautridou, 1985). It is found exclusively on Oxfordian limestone which is hard enough to provide clasts between a millimetre and a centimetre in diameter. It is the oldest surficial formation in the catchment, deposited after a phase of thalweg incision and always found under Holocene alluvium and colluvium. The rare traces of that formation on the slopes show that it was more widespread than now, but was greatly eroded by run-off after its deposition.

Deposition of loess (21×10^6 t) dates back to the great aeolian action period of western Europe of the Pleniglacial Stadial (Lautridou, 1985). It was brought by prevailing southwest to west winds from nearby outcrops of Cenomanian sand (Macaire, 1981, 1986). In the valley bottoms, the calcareous grèze is overlaid by colluvial deposits reworking the loess.

Grèze and loess, inherited from the late Pleistocene period and making up 36 per cent of present stores, are the remains of those formations which were partially eroded and which made up a possible source for the Holocene solid flux.

Holocene stores

Alluvium and the silicated fraction in the peat (29 per cent = $0{\cdot}2 \times 10^6$ t), forms a fluvial store of $12{\cdot}8 \times 10^6$ t of which about one-third ($4{\cdot}1 \times 10^6$ t) is found in the Taligny marsh. In borehole Tal 9, fine sedimentation began 6300 ± 100 years cal. BP. Assuming that the sedimentation rate during the first part of the Subboreal period ($0{\cdot}6$ mm a^{-1} in calendar years) was similar to the previous period, fine sedimentation could have started prior to 8100 year cal. BP and sandy-gravelly sedimentation could have appeared during the first part of the Holocene period (Figure 6). The distribution of the alluvium stores along the Négron, in particular the ratio R = silty-clayey alluvium/sandy-gravelly alluvium (Figure 8), shows that the stratigraphy of detrital sediments in the Taligny marsh (section N6) is representative of the overall stocks situated upstream: the ratio R is between 3 and 3·7 everywhere along the Négron River, except in sections N5 and N7 where stores are sparse. For that reason and because the Négron is a short river, it is likely that the alluvium in the upstream and downstream parts of the catchment are about the same age.

In the south of the Parisian Basin, fine sediments at the valley bottom date from the middle to late Holocene period, and coarser underlying sediments from Late Glacial to early Holocene periods (Garcin *et al.*, 1999; Visset *et al.*, 1999; Straffin *et al.*, 1999). For the calculation of later results it has been assumed that the total alluvial stores was laid down during the whole Holocene period, i.e. over a period of 11 500 calendar years (Stuiver *et al.*, 1998).

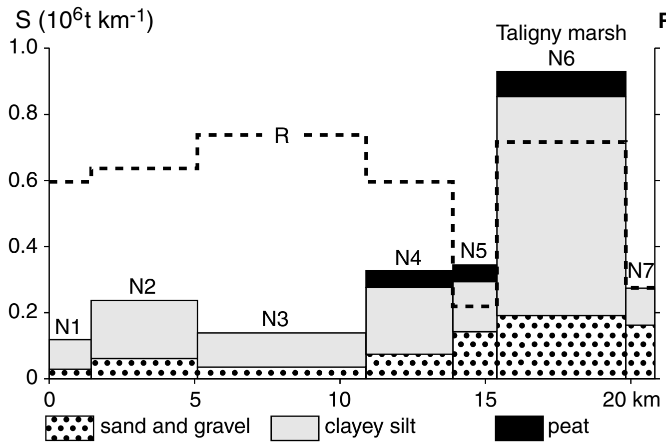

Figure 8. Longitudinal distribution of alluvium and peat stores (S in t per km of length of the valley) and clayey silt/sand and gravel ratio (R), in the Négron valley. N1 to N7, stretches of the valley, from upstream to downstream, for which stores were evaluated

The 18·5 × 10^6 t of colluvium is divided into two stores with distinct facies. The brown and compact silty-clayey colluvium on the valley floors is the result of solifluction or may sometimes be debris flow (because it can contain poorly oriented flints) over various bed-rocks. From the almost total absence of colluvium under alluvium and the stratigraphic relationship between these formations, the main part of colluvial store can be attributed to the Holocene period. By analogy, the colluvial stores in the non-drained parts of the valleys upstream, in places over-lying the grèze, have also been attributed to the Holocene period. If silty-clayey colluvium was deposited during the Late Pleistocene, it was greatly reworked during the Holocene period, probably due to its very fine grain size.

The colluvial stores forming the upper greyish sandy-silty-clayey layer in the valleys and the colluvium on slopes are very recent. Their facies, low volumetric mass (1 g cm^{-3}) and fragments of brick and pottery contained in them, show that they arise from erosion due to run-off from cultivated land of A horizons.

Values of sediment yield during the Holocene period

Sediment yield from present discharge of suspended matter. The present flux of suspended matter (SM) in the Négron at the outlet of the catchment (station 2) in proportion to the total surface of the catchment area (162 km^2) corresponds to a specific sediment yield of 0·6 t km^{-2} a^{-1} (Figure 9). This flux varies little from the total solid flux because the bed-load, made up of fine to medium sand, which is relatively easily suspended at high water, is very sparse. The sandy part represents on average 24 per cent of the SM, and can reach 66 per cent at the outlet.

This sediment yield is very low compared to chemical erosion evaluated at 44 t km^{-2} a^{-1} (Oubelkasse, 1998). This reflects the impact of the predominant carbonated lithology (60 per cent of the basin) which provides mainly soluble material (Meybeck, 1987) and which does not favour mechanical erosion because of its high permeability and the low incline of the slope. Large variations in the suspended load in the water of the Négron and its tributaries which have low discharge rates ($<$100 l s^{-1}; Figure 7), are the result of alternation between supply from ground-water (low suspended load) and from surface water (high in SM) running off cultivated land after heavy rain showers. During more extended periods of rain, the SM from the soil is diluted by large quantities of water from underground and surface reservoirs, which explains the low variation in solid load where the discharge rate is $>$100 l s^{-1} (Probst, 1992).

Comparison of the mean flux of SM at the inlet (Négron, Chavenay and Quincampoix = 5·8 g s^{-1}) and at the outlet (Négron = 2·9 g s^{-1}) of the Taligny marsh shows that the marsh currently stores 50 per cent of SM due to the widening of the valley in this sector (a hollow in Cenomanian sand and marl). Other sections of widened valleys in Turonian chalks and Oxfordian marl also provide good sediment traps. A large part of the sediment yield from the slopes is thus currently stored in the catchment.

Sediment yield from Holocene alluvial stores. Alluvial stores show that the average sediment yield during the Holocene period from surfaces not covered with alluvium (158·1 km^2) is 7·0 t km^{-2} a^{-1} (Figure 9). Assuming that the average Holocene flux of SM was equal to the present flux, 92 per cent of particles in transit in the river water have been retained in the catchment area. But the channels of the Négron and its tributaries were enlarged for many centuries to improve drainage of the floodplain, particularly in the Taligny marsh, increasing the solid flux downstream of the Négron catchment. Thus, the mean retention of particles was probably greater than 92 per cent in the catchment during the Holocene period.

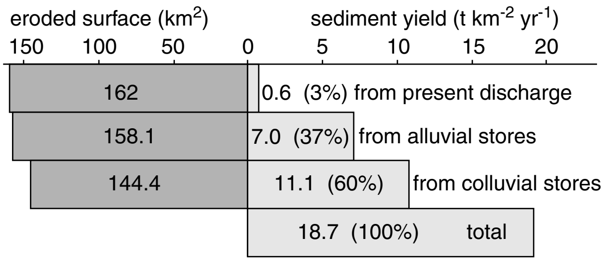

Figure 9. Values of sediment yield and eroded surface in the Négron catchment, calculated according to different approaches

Many factors influence storage: the type and use of the ground surface, the carrying capacity of running water, the drainage density, the degree of bank stability (Robinson, 1978; Trimble, 1983). The rate of sediment storage increases particularly with the increase of the catchment surface area (Milliman and Meade, 1983): according to Robinson (1978), the retention rate in the Négron catchment (162 km^2) would be 88 per cent; the value obtained here (more than 92 per cent) is similar. This high level of retention is comparable to that of a lake in which capacity: inflow ratio is about two months (Brune, 1953), the duration varying according to many different parameters (Heineman, 1984). 'Open' river basins can thus be just as effective as sediment traps as 'closed' lacustrine basins, which are sought for quantifying sediment yield (Bichet *et al.*, 1999; Macaire *et al.*, 1995, 1997).

Sediment yield from Holocene colluvial stores. The total colluvial store ($18{\cdot}5 \times 10^6$ t) in relation to the yield surface (144·4 km^2) during the Holocene period (11 500 years), gives an average sediment yield rate of 11·1 t km^{-2} a^{-1} (Figure 9). This value, which corresponds to a transversal flux relative to the thalwegs, is higher than that calculated from longitudinal fluvial flux (7·0 t km^{-2} a^{-1}). The yield and storage of sediments on the slopes are affected by many natural and anthropogenic factors (Slaymaker, 1988). The value obtained here differs by a factor of 100 from values of colluvial stores of other cultivated sedimentary catchments: it is higher than that estimated in Maryland (Costa, 1975) and lower than that obtained in Wisconsin (Trimble, 1983) and the Aquitaine Basin (Revel and Rouaud, 1985), confirming the wide variation in results due to human intervention. However, in the Négron catchment, the proportion of colluvial stores in relation to total sediment yield (53 per cent) is not very different to that calculated by those authors (36 to 55 per cent).

Whole sediment budget. The gross sediment yield for the Holocene period was 18·7 t km^{-2} a^{-1} (Figure 9) whereas the proportion carried out of the catchment area (net sediment yield) is 0·6 t km^{-2} a^{-1}: sediment yield calculated from stores (18·1 t km^{-2} a^{-1}) is about 30 times greater than the net sediment yield. As Holocene stores cover 14·9 km^2, 89 per cent of the basin was eroded or stable. The solid discharge at the exit of the basin is thus not representative of the real sediment yield which requires store analysis. It is difficult to estimate stores, particularly those dispersed across the slopes. Various models have been suggested to predict the distribution of surface deposits in relation to morphological, lithological and other criteria (Wyns, 1991; King *et al.*, 1999; Mathey, 1997), but their scope remains limited. In the Négron catchment about 75 per cent of Holocene stores are associated with the thalwegs. Analysis of the length of the thalwegs and the width of the valley bottom, easily carried out with DEM, seems to be a promising lead for quantifying the main stores and looking at the real sediment yield.

Spatial variation of sediment yield

Sediments stored in sub-basins of similar surface area (21 to 32 km^2), indicate that sediment yield is much higher in the Quincampoix basin (24·5 t km^{-2} a^{-1}) composed of 66 per cent Turonian chalks, than in the other basins: 5·7 and 3·9 t km^{-2} a^{-1} respectively for the Comprigny and the Chavenay with Cenomanian sand (70 per cent), and 4·4 t km^{-2} a^{-1} for the Merdelon with Oxfordian limestone (78 per cent) (Figure 10). The high yield of the Quincampoix results from the high quantity of silicated elements present in Turonian chalks and the superposed formations (Table I), and fairly steep slopes (on average 1·7 per cent). The sandy or very calcareous lithology of the other sub-basins does not seem to have influenced their sediment yield which remained low, contrary to what is usually observed (Meade *et al.*, 1990), probably due to the very gentle slopes (on average 0·5 per cent).

In coarse alluvium, the sandy proportion (92 per cent on average) mainly consisting of quartz, comes from Cretaceous sand. The limestone gravels (82 per cent of the gravel phase), is exclusively made up of hard Oxfordian limestone; particularly abundant in N5 stretches of the Négron valley (Figure 8); these gravels come from the reworking of grèze whose partial erosion during the Holocene period fed a gravelly wave that moved about 10 km downstream. Judging from the fluvial limestone gravel stored in the Négron catchment, the mass of grèze eroded is $1{\cdot}6 \times 10^6$ t, equal to a quarter of the initial store (present residual store = 5×10^6 t).

The composition of the fine alluvium and valley-floor colluvium on Oxfordian and Turonian bed-rock, little carbonated and silty-clayey (Table I), is similar to that of loess. The high carbonate content (56 per cent) of colluvium on Cenomanian bed-rock originates from the Oxfordian and Turonian carbonated rocks. Loess is particularly sensitive to mechanical erosion (Milliman and Meade, 1983; Chorley *et al.*, 1984). If

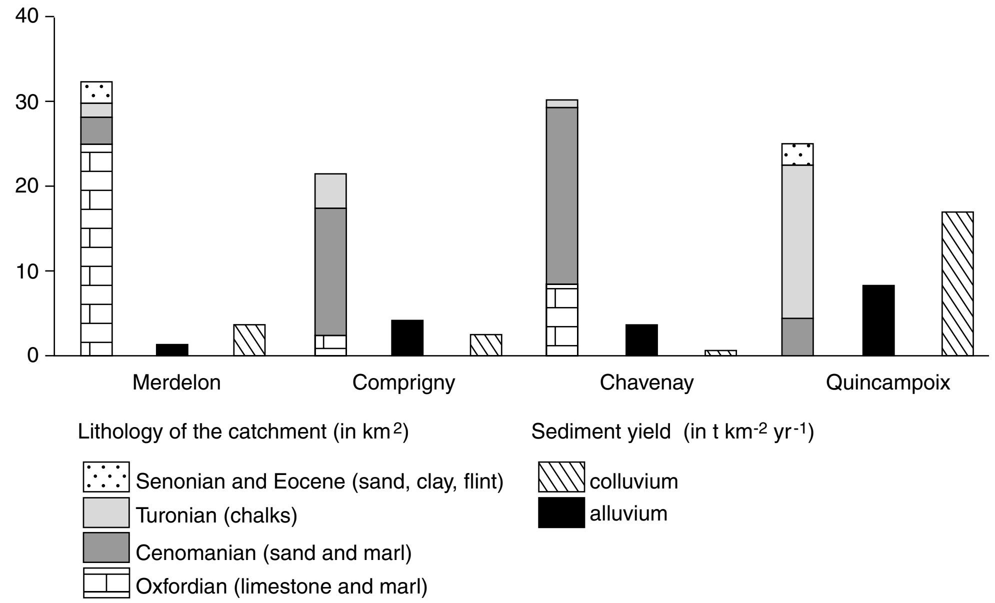

Figure 10. Surface lithology and sediment yield from alluvium and colluvium stores of the Merdelon, Comprigny, Chavenay and Quincampoix catchments

the whole silty-clayey, non-carbonated phase of the alluvium and colluvium comes from loess, it corresponds to a yield of $19{\cdot}9 \times 10^6$ t, almost equivalent to the amount of loess (21×10^6 t) still present. Over a third of the Holocene stores in the Négron catchment ($57{\cdot}7 \times 10^6$ t) could thus come from Pleistocene loess erosion. The peat is autochthonous.

Diachronic variation of sediment yield

Fine sedimentation superseded coarse sedimentation at the beginning of the Late Glacial period in valleys in the north of the Parisian Basin (Antoine, 1997; Pastre *et al.*, 2000), later in the southern part of the basin: after 8100 years cal. BP in the Taligny marsh and in the post-Boreal period in the Authion valley (Visset *et al.*, 1999).

In the Taligny marsh, the channel dynamics corresponding to the lower sandy-gravelly unit gradually lessened during the Holocene period and was replaced by floodplain dynamics (Figures 5 and 8), probably due to the depletion of the gravel source associated with grèze; the short dispersal distance of gravel downstream indicates the moderate energy of water flow of the Négron. From 6300 to 3000 years cal. BP (Subboreal), the fine alluvial material was produced by slopes which were sparsely wooded (<50 per cent tree pollen) but little cultivated, and was deposited in an alder grove. The sedimentation rate changed from 0·6 to 0·2 mm a^{-1} (Figure 6).

The overlying peat was laid down after 3000 years cal. BP. Mainly autochthonous, it indicates a low sediment yield from slopes in spite of increasing wood clearance, probably due to the predominantly pastoral rather than arable land use. The disappearance of *Alnus* in favour of *Carex*, with a slight re-expansion in Gallo-Roman times, resulted either from a lowering of the water level or the use of *Alnus* in the marsh. In the Parisian Basin valleys, peat appears at different times in the Holocene period, from Preboreal to Subatlantic (Antoine, 1997; Garcin *et al.*, 1999; Visset *et al.*, 1999). It is for this reason that the permanent flooding necessary for peat formation seems to be more the result of local hydrologic and topographic conditions (in this case a reduction in river gradient linked to the filling of the valley) than a response to a general climatic effect. The observed accumulation rate of peat, initially low (0·4 mm a^{-1} between 3000 and 1820 years cal. BP), and then higher (0·8 to 0·9 mm a^{-1} after 1820 years cal. BP), could be due to compaction (Figure 6).

Detrital sedimentation returned in the upper 50 cm after 670 years cal. BP up to the late Middle Ages. The lowering of the water level and the end of peat formation (disappearance of *Alnus* and decrease in marsh plants) seems to be linked to drainage of the marsh following the digging of mill races to supply the numerous mills noted since AD 1000 (Guichané, 2002). A fairly deep channel formed (appearance of aquatic plants such as *Nuphar* which need more than 50 cm depth of water) and the plain was submerged only during floods in the Taligny marsh. The increasing sediment yield due to the development of cultivation on the slopes explains the increase of solid material storage (sedimentation rate 0·7 mm a^{-1}).

In the valleys upstream of the Taligny marsh, the increase in carbonate concentrations in fine alluvium close to the surface, with values similar to those of present-day suspended matter at the Négron outlet (53 per cent), shows that erosion affects the deeper soil horizons. This alluvium changes laterally to colluvium showing signs of the recent erosion of cultivated land: alluvium has low volumetric mass (1 g cm^{-3}) and high content in organic matter, is associated with rideaux below substantially eroded ground, and contains fragments of pottery. The rideaux, associated with old division of land into plots, could have existed from Roman times, but their linear layout in the Négron catchment is more characteristic of the Middle Ages (Zadora-Rio, 1991).

The total mass of alluvium showing signs of recent erosion, described above, amounts to $1{\cdot}4 \times 10^6$ t, i.e. 11 per cent of the fluvial stock, and that of colluvium is $9{\cdot}5 \times 10^6$ t, i.e. 51 per cent of colluvial stock. The slopes on Turonian chalks seem to be those most used for agriculture, because they carry the largest part of colluvial stocks and associated rideaux.

If we consider anthropogenic stores to have been deposited within the last thousand years, sediment yield (colluvium + alluvium) rose from 12·7 t km^{-2} a^{-1} to 74·6 t km^{-2} a^{-1} after the year 1000. This increase by a factor of 6 is much lower than those recorded in the USA (factor of 10 to 100), where the human impact is more recent than in Europe (Meade *et al.*, 1990). Moreover, the proportion of sediment produced by crop farming (since about AD 1000) and stored on slopes (88 per cent) is higher than that reported in North America (Costa, 1975; Trimble, 1983) or Brazil (Haggett, 1961) with 50 per cent on average. The formation of rideaux, linked to the historical division of land into plots in the Négron basin, explains this difference. The wave of colluvial sediment will probably reach the valley floors within the next few decades, due to the recent changes in land division and the destruction of the rideaux, modifying the river dynamics: analysis of ^{137}Cs distribution in Turonian chalk area shows this recent increase in mechanical erosion of soils and colluvium stores (Fourmont *et al.*, unpublished work).

CONCLUSION

In the Négron catchment, the values of sediment yield differ widely according to the parameters used for calculation. There is a difference of a factor of 30 between the specific sediment yield calculated from the present solid discharge at the outlet of the basin (net yield) and that deduced from the Holocene sediment stored in the catchment, gross yield being the sum of the two. A complete evaluation of sediment yield requires a quantification not only of alluvial stores but also colluvial stores, which here represents 60 per cent of the total stores. Bearing in mind the difficulty of quantifying colluvium over the whole surface area of a catchment, an approximate assessment of stocks (75 per cent here) can be made by an analysis of the thalwegs, readily made from DEM. In the Négron catchment, gross sediment yield (18·7 t km^{-2} a^{-1}) indicates a mechanical erosion twice as weak as chemical erosion (Oubelkasse, 1998) due to the abundance of carbonated rocks.

Sediment yield varies by a factor of 1 to 5 according to the sub-basin studied. The main factor in this variation is the lithology of the basin, but the bed-rock has less influence than the pre-Holocene surficial formations (grèze and loess) which were considerably reworked during the Holocene period: 25 per cent and 50 per cent respectively. Storage areas also appear small, since the Taligny marsh, which represents 1 per cent of the total surface area of the catchment, holds 30 per cent of the alluvial stocks.

Sediment yield varied significantly during the Holocene period. Over the last thousand years it has increased by a factor of 6 as a result of the growth of agricultural activities. This increase is particularly noticeable in colluvial stores of the rideaux. This wave of colluvium will be noticeable in the fluvial flux and stores which will increase in the coming decades.

ACKNOWLEDGEMENTS

This work was supported by the French GDR CNRS programme 1064 'Agriculture-Environnement'. We wish to thank P. Mérot, leader of this programme, T. Barbier, A. Lenail-Chouteaux and C. Proust for their contribution to the acquisition of field data and DEM data, J-P. Bakyono for sedimentological analysis and E. Yates for translating this text. We thank the two anonymous reviewers for their constructive comments.

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