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Sedimentary Geology 186 (2006) 89–109
Sedimentary Geology
www.elsevier.com/locate/sedgeo

Flow and sediment dynamics in the vegetated secondary channels of an anabranching river: The Loire River (France)

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Received 15 February 2005; received in revised form 16 August 2005; accepted 1 November 2005

Abstract

This study investigates the hydrological and sedimentological mechanisms occurring in the vegetated secondary channels of an anabranching river affected by incision: the Loire River (France). During and after flood events that occurred between 2000 and 2003, observations and measurements were performed on a vegetated secondary channel located in the study site of Bréhémont (790 km downstream the source). Morphological changes and sediment dynamics were analysed using low elevation airborne photographs, topographic and bathymetric surveys, and scour chains. The hydraulic behaviour of the channel was also analysed by measurements performed on flow velocity and direction during different flood stages. In order to quantify the influence of woody vegetation on flow resistance, the roughness of bands of trees was determined from measurements performed on the field. The impact of the disruption of armour layers on bedload pulses, the variation of sedimentary processes during a single flood event and the fixation of bedforms by vegetation are all identified as key processes influencing the behaviour of the study channel. Topographic surveys demonstrate that sediment dynamics is substantial in the upstream part of the channel and that sediment budgets are different according to the temporal scale considered. Moreover, an asymmetrical behaviour of the secondary channel is demonstrated: reduced quantities of sediment deposited and preserved in the vegetated zones contrast with material by-passing observed in the third order channels. Flow velocity and direction measurements indicate that these parameters vary according to the water level and to the morphological units of the channel (pools, riffles, vegetated areas). During low flows, scouring and export of particles from the secondary channel are a consequence of reduced sediment supply from the main channel of the Loire River. For these water levels, sedimentation occurs in pools where velocity and turbulence decrease whereas third order channels are subjected to erosion. During high discharges, large quantities of sediment available in the main channel feed the temporary stores formed by riffles and bars in the secondary channel. The vegetated area located in the downstream part of the secondary channel deflects current trickles at low discharges and decreases flow velocity during high water levels. The sedimentary accretion observed in this area exerts a feedback on flow and sedimentary processes.

Keywords: Secondary channels; Sediment dynamics; Flow velocity; Vegetation; Loire River

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0037-0738/$ - see front matter
doi:10.1016/j.sedgeo.2005.11.011

1. Introduction

Incision of rivers is a natural process that contributes to the formation of features such as valleys, floodplains and terraces. The rapid intensification of this process over the last 200 years (Arnaud-Fasseta, 2003) was noted on American (Hupp and Simon, 1991; Gonzalez, 2001), European (Petts et al., 1989; Tockner et al., 2000) and French rivers (Peiry, 1987; Marston et al., 1995; Bornette et al., 1996; Bravard et al., 1997; Piégay et al., 2000; Steiger et al., 2001; Allain-Jegou, 2002; Guilloy-Froget, 2002). Fluvial incision episodes are now often caused or reinforced by human activities such as dyke raising, sediment dredging, building of dams, and have many consequences such as the collapse of bridges or dykes, and the colonization of marginal areas by pioneer vegetation. This colonization process enhances cross-section obstruction, flood potential and influences sedimentary filling of marginal zones. Although the complexity of interactions between flow, sediment dynamics and vegetation have been highlighted by numerous authors, the influences of vegetation on flow or on sedimentary processes are often studied separately. Investigations performed to analyse the influence of trees and saplings on flow have shown that vegetation increases flow resistance (Fathi-Maghadam and Kouwen, 1997; Darby, 1999). This increase of roughness depends on the physical features of the woody vegetation, on depth of submersion (Fathi-Maghadam and Kouwen, 1997; Wu et al., 1999), on season (presence of foliage) and on tree age (McKenney et al., 1995).

Flow disturbance and retention of sediments by roots influence erosion and deposition processes on the banks (Thorne, 1990; Abernethy and Rutherfurd, 2000), and also cross-sectional geometry and meander migration rates (Hupp and Simon, 1991). In-channel woody vegetation influences sediment dynamics and morphology at different scales. Locally, trees can deform flow and cause the formation of obstacle marks such as frontal scour and sediment tail (Nakayama et al., 2002, p. 199). They also contribute to the formation of mid-channel islands (Wende and Nanson, 1998; Kollmann et al., 1999; Gurnell et al., 2001). On a larger scale, woody vegetation influences channel and bar morphology (Graf, 1978; McKenney et al., 1995; Fielding and Alexander, 1996; Fielding et al., 1997) and contributes to sediment stabilization and morphological evolution of the river bed (Nanson and Beach, 1977; Graf, 1978; Friedman et al., 1996; Rowntree and Dollar, 1999; Hassan and Egozi, 2001).

Coarse woody debris also increases roughness (Dudley et al., 1998) and have a significant geomorphic effect on streams (Zimmerman et al., 1967; Keller and Swanson, 1979; Nakamura and Swanson, 1993; Hassan and Woodsmith, 2004) inducing avulsion or preventing bank erosion (Thorne, 1990).

On fluvial systems with multiple channels, the effect of incision is the evolution of rivers towards a single channel pattern by sedimentary filling of the secondary channels. These areas, that contributed in the past to discharge evacuation during the main part of the year, are now only inundated during floods. To a certain extent, these environments can be compared to ephemeral streams (Laronne et al., 1994; Hassan et al., 1999; Hassan and Egozi, 2001). Little is known about the hydrological and sedimentological behaviour of these zones where colonization by pioneer vegetation contributes to channel narrowing and to the reduction of habitat diversity (Bravard et al., 1997).

The aim of this study is to understand the sedimentological mechanisms that govern the filling of secondary channels and to provide new elements intended for the management of the river bed. From data and observations collected during and after floods, we will try to explain the morphological evolution of a vegetated secondary channel taken as a representative example of the floodplain of the Loire River in its middle reaches. To reach this target, our attention will be focused upon sedimentary evidences, hydraulic processes and vegetation cover. We will focus our attention on various morphological responses to floods of different magnitudes. These elements will lead us to propose a conceptual model based on investigations carried on flow, sediment dynamics and woody vegetation.

2. The Loire River and study site of Bréhémont

2.1. Geomorphology and hydrology of the Loire River

The Loire River, the largest river in France, is 1020 km long and drains a catchment area of 117,000 km^2 characterized by varying climate and lithology. It experiences an irregular flow regime and, in particular, severe droughts. At the Tours gauging station (760 km from the source and 30 km upstream of the study site), the average discharge is 374 $m^3 s^{-1}$, and approximately 1500 $m^3 s^{-1}$ for the 1- in 2-year flood. High discharges are caused by intense rainfall coming from the Atlantic Ocean or occurring in the upper reaches of the river during winter and spring (Dacharry, 1996; Duband, 1996).

Although regarded as “a wild river”, the Loire has been subjected to human activities which have altered its system. Dykes were raised during the Middle Ages to prevent flooding, oblique groynes were built for navigation, two large dams were built in the upstream reaches and intense sediment extraction occurred between 1950 and 1995 (Dambre and Malaval, 1993; Belleudy, 2000). These activities generated several environmental problems such as the incision of the main channel and the lowering of water level during low flows. These phenomena induced the destabilization of civil engineering works such as bridges and dykes, they decreased flow capacity during floods and caused the drying up of drinking water wells. The lowering of mean water level resulted in the drying of secondary channels and, thus, in an evolution from a multiple-channel pattern to a single-channel pattern. As a consequence, a rapid colonization of secondary channels by woody pioneer vegetation and a reduction of habitat diversity occurred. These zones have also been subject to significant sedimentation.

2.2. Study site of Bréhémont and secondary channel A

In its middle reaches, the Loire system is characterized by a multiple-channel pattern similar to that of an anabranching river (Nanson and Knighton, 1996; Gautier et al., 2000). The river bed, confined between embankments, is composed of a braided main channel fringed by vegetated permanent islands and secondary channels only submerged during floods (Fig. 1).

At the study site, Bréhémont (790 km downstream from the source), the river is incised into Cretaceous and Tertiary sedimentary rocks and the width of the valley is 3300 m. The distance between dykes is approximately 700 m and the width of the main channel varies between 175 and 300 m. The slope of the river bed is 0.0003 and the unit stream power of the main channel is 30 W m^{-2} for bankfull discharge (2500 m^3 s^{-1} at the Langeais

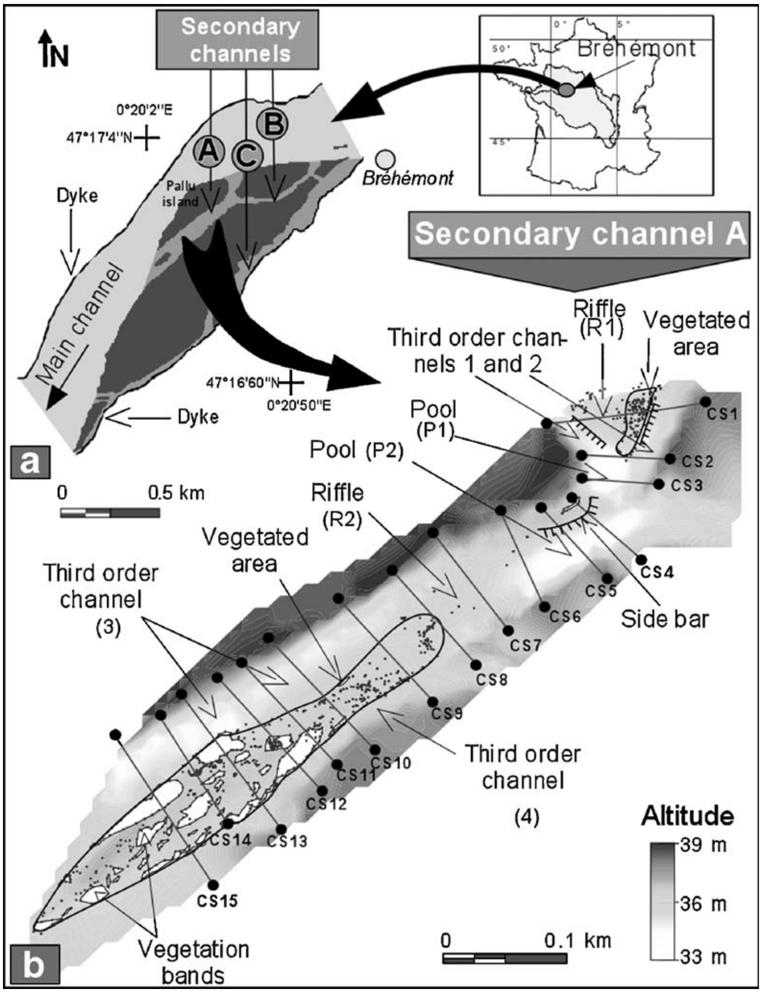


Fig. 1. Location of the study area in the catchment basin of the Loire river (a) and (b) morphological configuration of secondary channel A. Cross-sections are indicated (CS1 to CS15).

gauging station, located 4.5 km upstream of the study site). The bedload is mainly composed of siliceous sand and gravel.

At the study site, the main stream flows close to the right bank whereas islands and secondary channels (A, B and C) are located on the left bank (Fig. 1a). For a discharge at the Langeais gauging station equal to 1280 $m^3\ s^{-1}$, measured flow rates in the secondary channels A and C were respectively 43 $m^3\ s^{-1}$ (3.4% of total discharge) and 24 $m^3\ s^{-1}$ (1.9%). For 1979 $m^3\ s^{-1}$ at Langeais, flows in channels A and B were respectively 136 and 36 $m^3.s^{-1}$.

In the secondary channels, the woody vegetation is mainly composed of black poplars (*Populus nigra* L.) and willows (*Salix* spp.), while islands are colonized by grasslands and hardwood forests (Cornier, 2002).

The secondary channel A was retained because it represents a common configuration in the middle reaches of the Loire River, namely a significant disconnection from the main channel most of the time, the presence of specific morphological units such as riffles and pools, and a substantial colonization by the vegetation (Fig. 1b). Moreover, this site was chosen because it is located close to the Langeais gauging station and is largely documented as far as biological data are concerned.

The secondary channel A is 650 m long and roughly oriented N. E.–S. W. Its width is 120 m at the upstream end but it narrows rapidly downstream. An upstream riffle (R1), bordered by two elongate depressions (third order channels 1 and 2) where the flow is drained during low water levels, gives way to a circular pool (P1). The funnel-shaped morphology of this entrance ends at the confluence with the secondary channel B where pool P2 constitutes the confluence scour. The planform curvature of this part of channel A influences hydraulic and sedimentological processes in P2. On the right bank, the side bar also shows characteristics of a

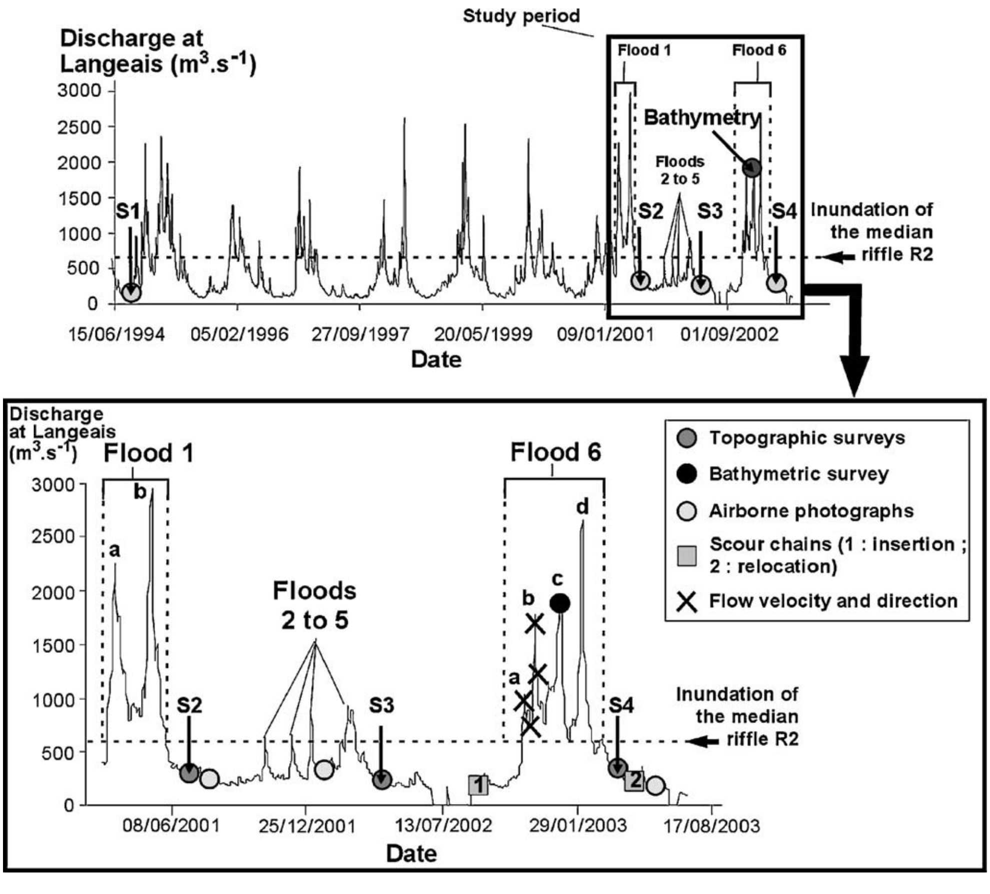


Fig. 2. Hydrograph at the gauging station of Langeais (located 4.5 km upstream of the study site) between 1994 and 2003. Floods 1 and 6 are characterized by several peaks (a and b for flood 1; a, b, c, d for flood 6) while floods 2 to 5 are characterized by a single peak. Topographic surveys, bathymetric survey, airborne photographs, scour chains (insertion and relocation) and measurements of flow velocity and direction are also mentioned.

point bar. Further downstream, the cross section widens and a median riffle (R2) is present. From R2 to its downstream end, the secondary channel A is characterized by an asymmetrical morphology: the third order channel 3 is flanked on the left bank by a higher vegetated zone.

Herbaceous vegetation is well represented in the downstream part of channel A where common couch (*Elytrigia campestris* × *repens*) is densely established. Clumps of other species like strapwort (*Corrigiola littoralis* L.), creeping yellow field cress (*Rorippa sylvestris* L. Besser) and soapwort (*Saponaria officinalis* L.) appear elsewhere in the channel upon sand and gravel substrates. Channel woody vegetation is dominated by *P. nigra* L. although other taxa like ash (*Fraxinus* spp.), elm (*Ulmus* spp.) and box elder (*Acer negundo* L.) are present on higher zones or on the banks.

In 1995, fluvial maintenance operations were performed; the aim of these operations was to increase the flow capacity of secondary channel A during floods. All in-channel vegetation groups implanted before 1995 were destroyed except for three bands located in the downstream vegetated area.

Except for the pools (P1 and P2), where water is present even during low flows, the secondary channel A is only submerged during floods. When discharge at the gauging station of Langeais is less than 650 m^3 s^{-1}, backflooding from the main channel connects this morphological unit with the third order channel 3. As discharge increases, pools and third order channels 1 and 2 are also inundated. The connection between the upstream and downstream areas is established when riffle R2 is flooded, i. e. for a discharge of ca. 650 m^3 s^{-1} (Fig. 2). Inundation of vegetated areas begins when discharge is approximately 1100 m^3 s^{-1} at Langeais.

3. Methods

In this paper, each episode of inundation of the channel A was considered as a flood. Two kinds of floods were distinguished: high magnitude and minor floods. High magnitude floods are characterized by discharges higher than 1100 m^3 s^{-1} (at the Langeais gauging station) and by several peaks while minor floods are characterized by only one peak.

Between 2001 and 2003, six floods occurred on the Loire River (Fig. 2). During the high magnitude floods 1 and 6, maximum discharges recorded were respectively 2980 and 2690 m^3 s^{-1}. These floods were characterized by several peaks (Fig. 2) and were significant in terms of morphological impact. Floods 2 to 5 were minor events characterized by a single peak and their impact on the morphological evolution of the channel was reduced.

Field data were collected during and after floods 1 to 6 (Fig. 2), in order to characterize the sedimentary processes and the morphological responses of the secondary channel A.

3.1. Morphology and sedimentology

After floods 1, 4 and 6 aerial photographs were taken from a helicopter at low altitude. These were compared to those of a previous campaign carried out in 2000. The monitoring made possible the construction of maps of in-channel accretionary macroforms with additional information obtained by field observations using an electronic total station (*Geodimeter 440*) and a data logger. Sections dug into bedforms also allowed establishment of stratigraphical links between sedimentary units.

Changes in channel morphology were determined using the electronic total station after floods of varying intensities. Measuring accuracy was ±2 cm. Fifteen channel cross-sections were surveyed (Fig. 1) and additional points were surveyed at slope breaks. The upstream riffle R1 was surveyed with a higher density of points. Topographical surveys of the channel A allowed the determination of volumes of sediment eroded or deposited during different floods on the fifteen cross-sections (see Rodrigues et al., 2005). The series of points measured at slope breaks were combined with the cross-sections using a triangulation with linear interpolation to construct and compare digital elevation models.

To analyse the morphological evolution of the channel A during flood 6, a bathymetric survey was undertaken using a Marimatech e.sea sound 206C dual-frequency echo-sounder deployed from a light vessel. Boat positioning was fixed using a differential global positioning system (DGPS) RTK Trimble 4700. Measurements were recorded at 1 s intervals along longitudinal transects and cross-sections; banks and vegetated areas were excluded. Scour and fill processes during this event were assessed using thirty-one scour chains (Hassan, 1990; Laronne et al., 1994; Hassan et al., 1999) installed after flood 5. Metal-linked chains were inserted vertically, anchored into the stream bed, and located using the electronic total station. After the flood 6, scour chains were relocated. The depth to which movements of bed material occurred was determined by measuring the length of the chain above the elbow (scour) and the distance between the elbow and the post-flood bed (fill).

3.2. Hydraulic parameters

During flood 6, flow velocities were measured during four different flows (779, 962, 1237, 1710 $m^3.s^{-1}$ at the Langeais gauging station). Velocity profiles were established on six of the fifteen topographical cross-sections. For each profile, flow velocity was measured at six heights above the bed using an Ott electromagnetic current meter (ECM). All the field measurements were performed within 1 min and the accuracy of the measurements was $\pm 0.5\%$ (Robert, 1997). When depth was greater than 2 m, flow velocities were measured with an Ott directional current meter suspended without a streamlined weight. Surface flow directions were also recorded during those campaigns using an instrument of our design constructed from two linked floats and a compass.

In order to interpolate between field data, numerical simulations were performed using the one-dimensional US Army Corps of Engineers River Analysis System computer software HEC-RAS 3.1.2. (USACE, 2004). The computation is based on a finite difference, standard step iterative procedure applied to simulate steady gradually varied flow. The program computes cross-section mean hydraulic parameters by dividing the river into small element reaches of similar geometrical and hydraulic characteristics. Flow energy loss between two adjacent cross-sections is expressed in terms of hydraulic coefficients (roughness, contraction–expansion).

Model geometry was developed using the 15 cross-sections presented in Fig. 1 b. As a downstream boundary condition (in cross-section CS15), a rating curve was constructed from measured values of discharge and water surface elevation. The values of roughness coefficients were calibrated along channel A on measured stages (accuracy ± 5 cm) and discharges ranging from 779 to 1979 $m^3\ s^{-1}$ at the Langeais gauging station. Calibrated values of Manning roughness coefficients are based on the following field observations: dense vegetation and cross-section irregularity for the downstream area (0.05 for the third order channel 3 and 0.08 for the banks and the vegetated area), sparse vegetation and coarse sediments on the median part of the channel (0.036) and irregular bed channel configuration (riffle and pool sequence) for the upstream part (0.04). The model was therefore considered to be able to predict the hydraulic behaviour of the secondary channel for the specified range of discharges.

3.3. Vegetation analysis

In-channel woody vegetation was mapped using the electronic total station. Where colonization was sparse, each tree position was recorded. For dense groves of vegetation, trees limiting the groups were located.

The trees located in the secondary channel A can be divided into two categories. Small trees (height $H<15$ m) are characterized by numerous branches and stems that must strongly increase flow resistance. For tall trees (height $H>15$ m), branches are never submerged and thus the surface opposed to the flow is equivalent to a cylinder. For small trees, stem density was estimated by counting the number of stems within 4 m^2 squares and the diameter of each stem that emerged from the ground was measured at $H/4$. For tall trees, density was estimated using the point centered quarter method (Mueller-Dombois and Ellenberg, 1974; McKenney et al., 1995; Fitzpatrick et al., 1998). For each band, a minimum of ten sampling points were chosen randomly on a transect which is most representative of the tall woody vegetation. At each sampling point, the horizontal plane was divided into four quarters. For each quarter, the distance from the sampling point to the nearest tree and the diameter at 1 m above the bed were recorded. The species of each tree was also identified. Thus, four distance measurements, four diameter measurements, and four species names were recorded at each sampling point along the transect. Stem density was calculated by dividing a unit area by the square of the mean point-to-tree distance (Mueller-Dombois and Ellenberg, 1974; Fitzpatrick et al., 1998).

In order to quantify the effects of woody vegetation bands on flow resistance, Manning's roughness coefficients were determined using the equation of Petryk and Bosmajian (1975) based on a balance of gravitational forces and drag:

$$n_{\mathrm{veg}} = \mathrm{Kn} R_{\mathrm{h}}^{2/3} \sqrt{\frac{C_{\mathrm{d}} \Sigma \mathrm{Ai}}{2gAL}}$$

where n_{veg} is vegetation roughness, Kn is a factor of conversion equal to 1 for SI units, R_{h} is the hydraulic radius, in m, C_{d} is the drag coefficient (assumed to be equal to 1), ΣAi is the total frontal area of vegetation projected onto a plane perpendicular to the direction of flow, in m^2, g is the force of gravity, in m s^{-2}, A is the cross-sectional flow area, in m^2, L is unit length of the channel reach, in m.

Manning's roughness coefficients were calculated for a unit surface of 1 m^2 (McKenney et al., 1995). Therefore, the hydraulic radius (R), the cross-sectional flow area (A), the unit length (L) were equal to 1 and ΣAi was the product of the number of stems per square meter and the average diameter.

Maximum age of vegetation bands was also determined by increment cores taken from the largest trees of the groups. Cores were sanded, and age was determined by counting tree rings.

4. Results

4.1. Bedforms of the secondary channel A (Fig. 3)

Different types of sedimentary facies can be distinguished in the secondary channel: armoured surfaces, isolated dunes, dune trains, erosion marks, vegetation-induced deposits and settling areas (Rodrigues, 2004).

Armoured surfaces are located on top of morphological units such as the side bar and riffles R1 and R2. These surface veneers–formed of gravel (D_{50}=32 mm)–lie on a finer sediment mixture mainly composed of coarse sands and gravels (D_{50}=3 mm) similar to the river bedload (Dietrich et al., 1989; Parker and Sutherland, 1990; Whiting, 1996). The formation of armour layers in general occurs during the falling limb of hydrographs by selective transport of the finest particles (Little and Mayer, 1976; Knighton, 1999; Bridge, 2003) and illustrates a reduced bedload supply from upstream (Dietrich and Whiting, 1989; Whiting, 1996; Hassan and Church, 2000). The disruption of armoured layers allows the erosion of the underlying finer sediment (Jackson and Beschta, 1982; Parker et al., 1982; Duizendstra, 2001) and therefore influences bedload pulses (Reid et al., 1985).

Dunes in the secondary channel are mainly two-dimensional dunes (Ashley, 1990, Miall, 1996). On the west side of the riffle R1 (Fig. 3), these dunes, mainly composed of sands and gravels, are overlapped by armour layers and are characterized by planar cross strata with sets 0.3 m thick. On the left side of the riffle, set thickness and the proportion of coarse sediment decrease (Fig. 3a). Close to the vegetated area, sediments are finer (D_{50}=0.7 mm) than those on the west side of the riffle R1. The dune located at the downstream end of third order channel 2 is reminiscent of a confluence-mouth bar (Best, 1988; Bristow et al., 1993). The location of the slipface of this dune varies

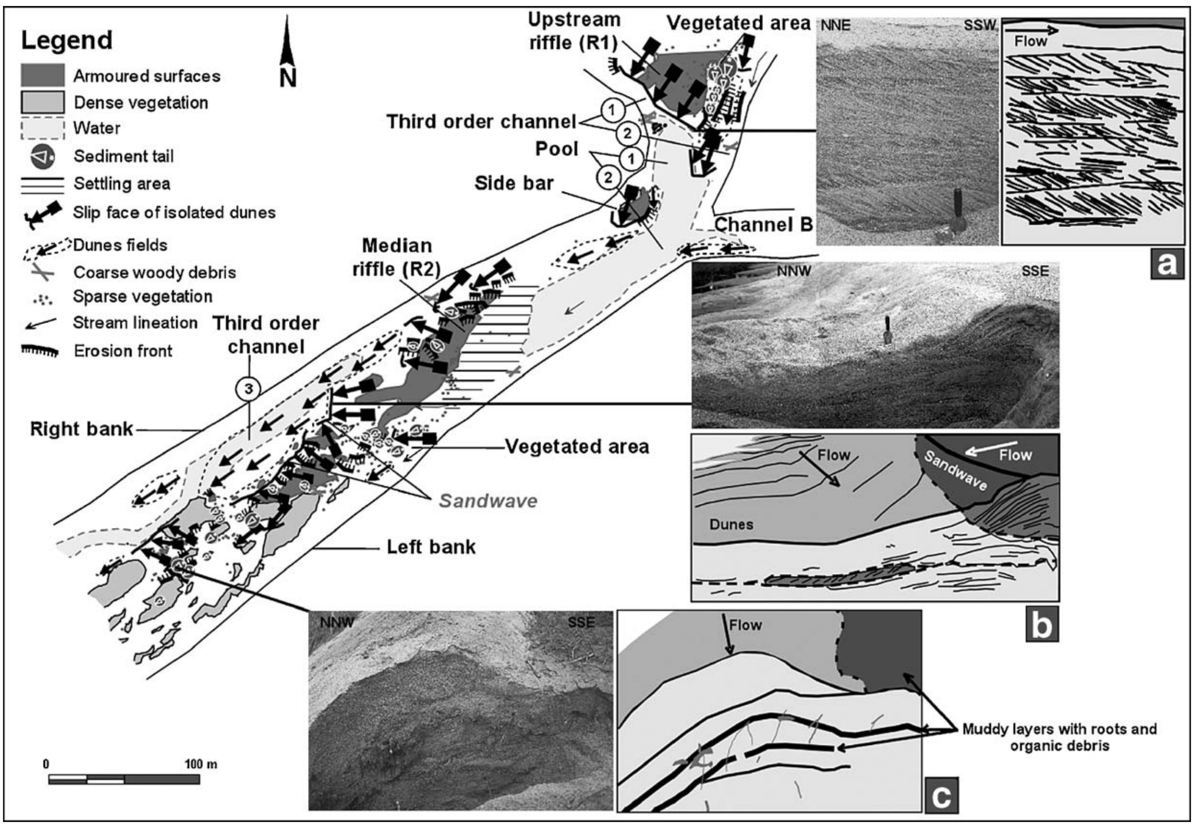


Fig. 3. Morphological configuration and bedforms of secondary channel A (2nd April 2000). Scale in photos is 12 cm wide and 30 cm high.

according to the ratio of discharges between channels A and B (Bristow et al., 1993) and thus, to flood type and magnitude.

Owing to its position, the side bar flanking the pool P2 also shows characteristic features of a point bar and dunes located immediately downstream, characterized by crestlines almost parallel to the channel direction, are reminiscent of those described by Bridge and Jarvis (1982) in the river South Esk (Scotland). According to these authors, vegetation present on the inner bank increases flow resistance which accentuates the gradient in shear stress and turns the near-bed flow inwards. 2D and 3D-dunes present in third order channel 3 are characterized by a length ranging from 1.1 to 3 m and by an average height of 0.07 m. Most of these dunes are characterized by a height: length ratio less than 0.06. This indicates that these dunes are non-equilibrium bedforms (Allen, 1984; Carling et al., 2000) or represent an adjustment of the bed to hydraulic constraints or reduced sediment transport. Ripples are frequently superimposed on these dunes. In the centre of the channel, a large isolated dune is present, characterized by a slipface almost parallel to the direction of the channel. This bedform, locally called a sandwave, is a 2D dune according to Ashley (1990) that shows a planar stoss side and a lee side at sharp angle with the substrate. The height at crestline is 0.5 m and the internal structure is planar cross stratification ($D_{50}=1.5$ mm). This bed wave is different from the sandwaves described by Allen (1984) in tidal environments and characterized by an internal structure showing multidirectional flows (opposite flow linked to tide). In channel A, the orientation of these dunes indicates variation in flow direction during a single flood event. Sections dug in the dunes of the third order channel 3 show relics of sandwave stratification interbedded in dune sediments (Fig. 3b). This interlayering indicates that, according to the water level and to water energy, a succession of sedimentation episodes occurs in the secondary channel during a single flood event.

Trees and saplings present on the channel bed influence local sedimentation processes. Upstream of single trees (or clumps of trees), a horseshoe shaped scour is commonly found. On the lee side of a tree, sediment tails characterized by complex internal structures suggest reduced flow velocities (Allen, 1984; Birkeland, 1996; Nakayama et al., 2002). Nakayama et al. (2002) state that these structures can merge and form linear sediment ridges. The formation of linear bars around flights of trees has been documented by Fielding et al. (1997).

During high magnitude floods, dunes can be deposited in vegetated areas as a result of the decrease in flow velocity induced by vegetation. An initial type of deposit consists of relatively thick dunes (height of 0.6 m) with a slipface perpendicular to the main direction of the channel, formed of relatively well sorted coarse sands and characterized by planar cross-stratification. A second type of deposit is composed of dunes with crestlines almost parallel to the channel direction. These bedforms appear during the falling limb of the hydrograph and indicate a reorientation of the flow towards third order channels at those water levels. The formation of these bedforms can also be attributed to transverse velocity components created by a difference in flow resistance between vegetated and bare zones (Fukoka and Fujita, 1990; McKenney et al., 1995). Sections dug in the sediment tails and in these dunes show interbedded muddy layers with organic debris, typically a centimetre thick, which record intervals between two floods (Fig. 3c).

In the upstream part of the channel, the flow-parallel erosion marks located on the margins of the riffle R1 indicate the reworking of the gravelly dunes and also of the sediments trapped in the vegetated area. On the median riffle (R2), the rills contribute to sediment export from the riffle to the third order channel 3 during falls in water level. Although the formation of these rills depends on slope and grain size (Reineck and Singh, 1980), vegetation can also influence their pattern by directing the current. In the downstream vegetated area, these erosion marks located close to sediment tails can account for the construction of a ridge and swale morphology.

On the exit slope of pool P2, a settling zone, characteristic of falling water level, is highlighted by a thin muddy film cover lying on coarser sediments. Settling also occurs in the downstream end of the vegetated area.

4.2. Evolution of the bedforms according to flood magnitude (Fig. 4)

The bedform pattern of the secondary channel varies according to flood magnitude. So, after high magnitude floods ($Q > 1100$ m^3 s^{-1}), bedforms are similar to those described above (Fig. 4, post-flood 1). During low magnitude floods (Fig. 4, post-flood 4), like events 2 to 5 ($Q < 1100$ m^3 s^{-1}), the riffle R1, the side bar and the vegetated areas were not submerged. However, the lowest parts of the channel were inundated and therefore subject to sediment reworking (Fig. 4, post-flood 4). The lateral extension of erosion marks induced the

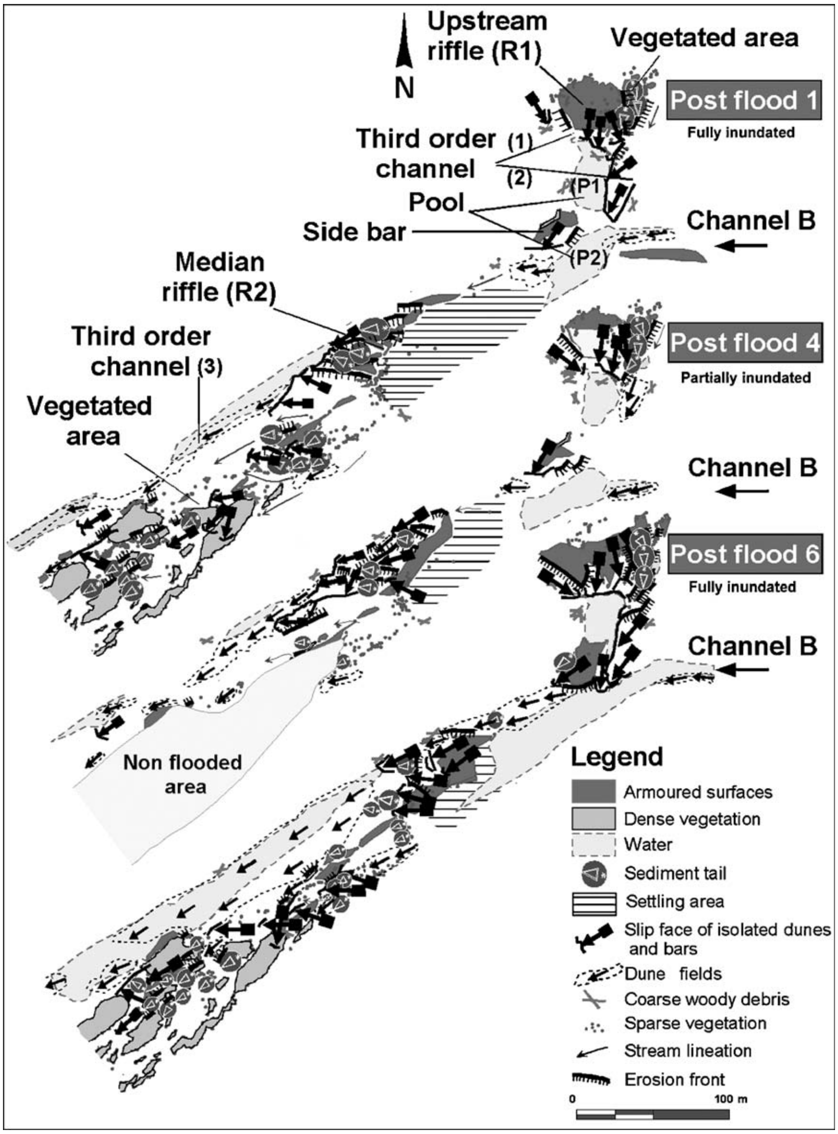


Fig. 4. Bedform evolution between floods 1 to 6 in the secondary channel A.

widening of third order channel 1, dunes replaced the confluence-mouth bar, and the side bar was laterally eroded. During moderate floods, the armoured surface of riffle R2 constitutes the upstream limit of rills. These rills contribute to fine sediment export towards the third order channel 3 where bedforms with crestlines parallel to the channel direction were developed.

4.3. Morphological and topographical evolution during floods

4.3.1. Sediment budgets (Fig. 5)

After high magnitude floods (flood 1 and 6), the riffles, the side bar and the banks were subjected to sediment deposition while the bank of Pallu island and the third order channel 3 were scoured (Fig. 5a). In the downstream vegetated area, sediment deposition was dominant although local scouring occurred between the tree groves during flood 6. Between S1 and S2, 10866 m^3 of sediments were deposited and −6098 m^3 were eroded. Thus, a net sediment deposition of ca. 5770 m^3 occurred in the secondary channel between 1994 and 2001 (Rodrigues et al., 2005; Fig. 5c). Although the fluvial maintenance operation, undertaken in 1995, introduces uncertainty to sediment budgets, it cannot explain the high sedimentation rates in the downstream vegetated area. These works were carried out to increase the flow capacity of the secondary

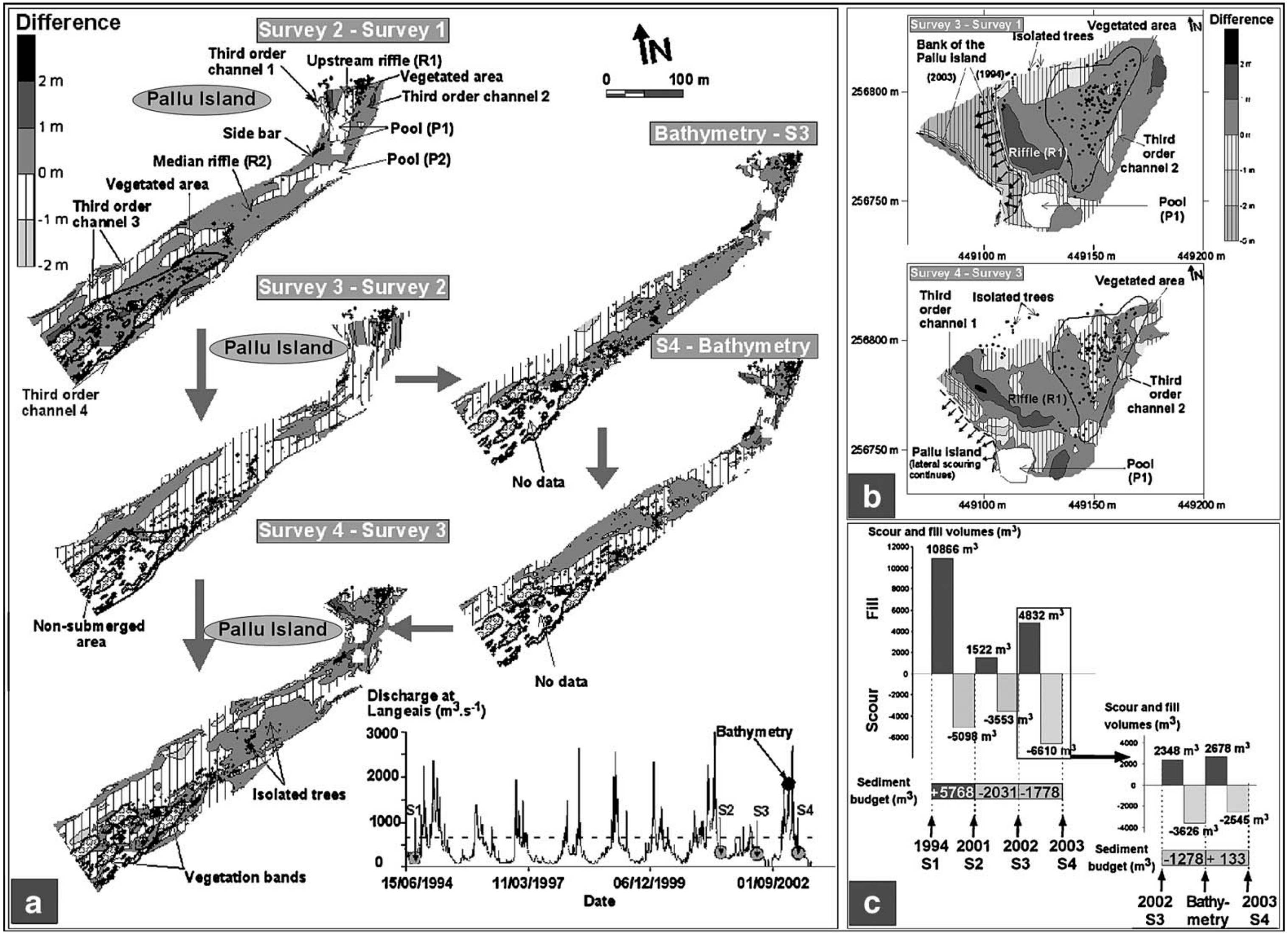


Fig. 5. Difference in DEMs between surveys (a, b) performed on the secondary channel A (hachured areas correspond to scour); scour and fill volume calculated between surveys (c). Topographic surveys were conducted in September 1994, July 2001, April 2002 and April 2003. Bathymetric survey was conducted the 7 January 2003.

channel. During flood six (i. e. between S3 and S4), an erosion of -1778 m^3 of sediments occurred. Between S3 and the bathymetric survey, erosion of -1278 m^3 occurred whereas 133 m^3 of sediments were deposited between the bathymetric survey and S4. The difference between sediment budgets obtained by comparison of topographical measurements (S4–S3) and the bathymetric survey (S4 — bathymetry and bathymetry — S3) can be explained by the exclusion of the banks (no data were collected in these areas during the bathymetric survey).

During moderate floods (floods 2 to 5), the downstream vegetated area was not inundated and scouring was the dominant process (-2031 m^3) in the channel. Erosion and deposition affecting the third order channel 3 illustrate the reworking of sediments deposited in this morphological unit during previous floods.

On a decade scale (i. e. between S1 and S4), sediment deposition was dominant (1959 m^3) in the secondary channel. On a yearly scale (between S2 and S3 or between S3 and S4), sediment budgets were negative. So, the sediment budgets calculated on a decade scale are different to those calculated on a yearly scale.

4.3.2. Sediment budgets in the upstream part of the channel (Fig. 5b)

The upstream part of the secondary channel A is characterized by strong frontal erosion of the bank of Pallu island. The collapse of the bank has induced the migration of the third order channel 1 towards the west and the filling of the old thalweg. Sediment budgets calculated for the upstream zone are strongly influenced by the collapse of the bank. Between 1994 and 2001, scour in this area is estimated at 1850 m^3. If the banks are excluded and if comparison is only performed on the riffle and third order channels, the volume eroded is 450 m^3. Between floods 5 and 6, deposition was dominant: 550 m^3 (including the banks) and 690 m^3 (without the bank retreat). Minor changes were recorded in the vegetated area. These observations suggest that the upstream part of the channel is subject to high rates of erosion or sedimentation according to flood magnitude.

4.3.3. Morphological response of the channel to floods: increasing the cross-sectional asymmetry

Analysis of the sediment volumes deposited and eroded during floods on each cross-section (Fig. 6) demonstrates that channel response to floods varies

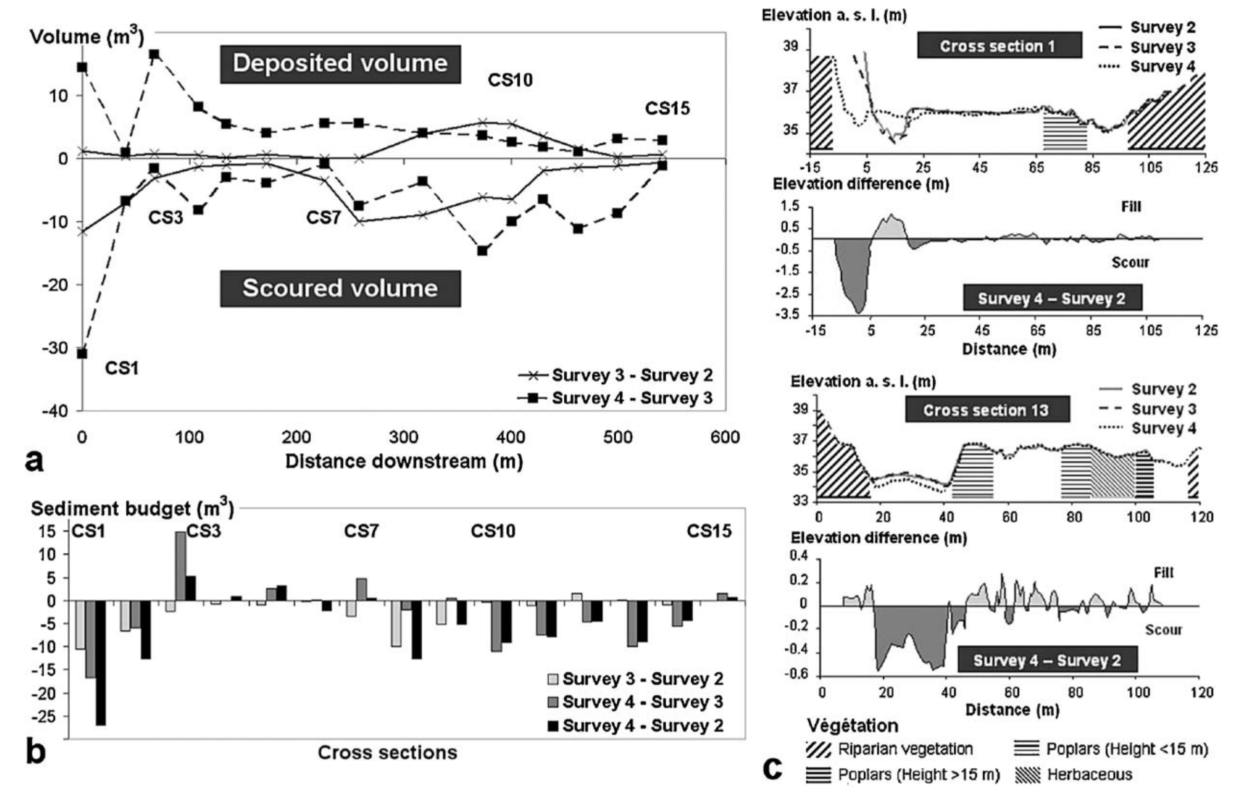


Fig. 6. Scoured and deposited volumes of sediment (a) and sediment budgets (b) calculated on each cross-section between surveys 2 to 4. Cross-sections CS1 and 13 (c).

according to flood magnitude and probably sediment supply. During moderate floods (between surveys 2 and 3) low volumes of sediment deposited in the upstream part of channel A reflect reduced sediment supply from the main channel of the Loire River (Fig. 6a, S3–S2). During high amplitude floods (Fig. 6a, S4–S3), the volumes deposited in the upstream part of the study area are important but progressively decrease downstream. Scoured volumes calculated for moderate and high amplitude floods are significant in the upstream part of the channel A where negative sediment budgets (Fig. 6b) reflect bank collapse of Pallu island (Fig. 6c, cross-section 1). Sediment budgets are near equilibrium between cross-sections 3 and 7 while erosion is dominant in the downstream end of the channel (Fig. 6b). Analysis of cross-sections (Fig. 6c) and DEMs (Fig. 5) demonstrate that the erosion is concentrated in third order channel 3 while the downstream vegetated area is subject to moderate accretion. The results presented here suggest that both high and low magnitude floods have led to the enhancement of the asymmetrical configuration of the channel.

4.4. Evolution during a single flood event

The bathymetric survey conducted during flood 6 shows that, between flood 5 and the first half of flood 6, significant sediment deposition occurred in the zone located between riffles R1 and R2 (Fig. 5a, bathymetry — S3). Conversely, sediment erosion occurred in the third order channel 3. Between the second half of flood 6 and topographical survey S4, sediments deposited in the lower part of the side bar and at the top of the median riffle R2 were reworked. During the last peak of flood 6, sedimentation occurred in the third order channel 1, at the top of the side bar and in the median part of the third order channel 3.

Scour chains show that sediment erosion often precedes deposition during a single flood event (Fig. 7). On the upstream riffle R1, sediment dynamics are important; scour chains C2 and C3 were not found despite excavating to a depth of 2 m. The scour chain C11, located on the side bar, shows that the thicknesses of eroded and subsequently deposited sediments were equal. On the median riffle R2, small quantities of sediments were deposited (the values of scour and deposition are quite similar) while erosion was concentrated in third order channel 3. In the vegetated areas, sediment dynamics were reduced. Values of erosion and deposition were low in comparison with non-vegetated areas and can be explained by the sediment stabilising power of vegetation and lower flow power. Scour chains show that the vegetated areas are accreting slowly. Once deposited, small quantities of sediment accreted in these areas are not easily removed because of the protective effect of vegetation.

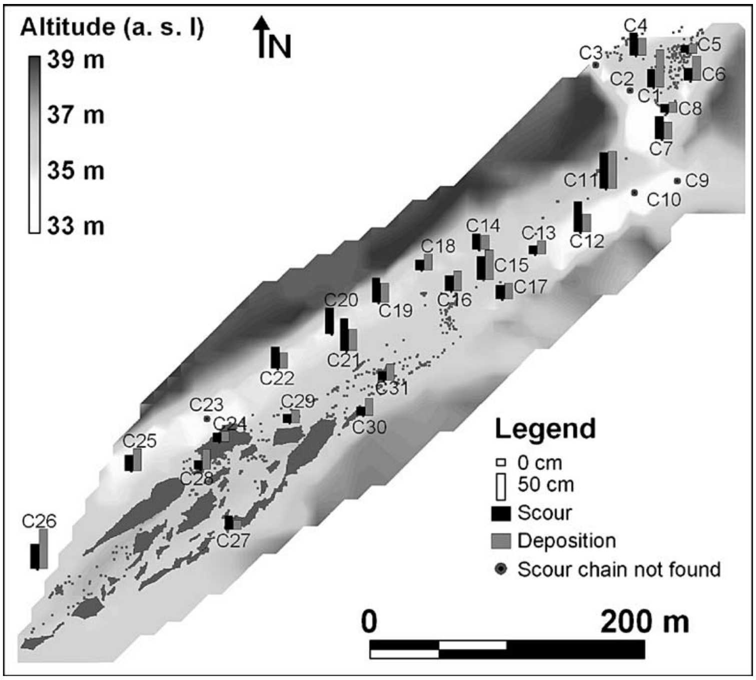


Fig. 7. Sediment heights scoured and filled during flood 6 (estimated with the help of scour chains).

4.5. Hydraulic behaviour of the secondary channel

4.5.1. Flow velocity

Velocity profiles were measured at georeferenced points located on six cross-sections (CS1, 4, 7, 9, 12, 15) for four flow conditions (Fig. 8) during flood 6.

On cross-section 1, measured flow velocity ranged between 0 and 0.8 m s^{-1}. Velocities measured in the third order channels for substantial discharges (1237 and 1710 m^3 s^{-1}) were lower than velocities measured during moderate discharges (779 and 962 m^3 s^{-1}). This may be explained as follows: during low discharges, flow concentrates in the third order channels where the cross-sections are reduced in width and therefore velocities are high. As discharge increases, riffle R1 is flooded and flow parameters (velocity and direction) are less influenced by morphology. For those discharges, turbulent eddies were noted near the bank of Pallu island. Streamflow in the pool P1 was characterized by turbulent eddies and vortices induced by the morphology of the pool and the presence of coarse woody debris (Hassan and Woodsmith, 2004).

During high discharges, flow velocity can reach 1.2 m s^{-1} in the pool P2 and profiles illustrate turbulence that suggests a transverse flow component due to the curvature of the channel (Bridge and Jarvis, 1976; Bridge and Jarvis, 1982). When discharge is high, water delivered by the secondary channel B reinforces those turbulences.

For low discharges (779 m^3 s^{-1}), reduced velocities indicate water stagnation in the pool and weak currents are deflected by the median riffle R2 towards the third order channel 3. Constriction of water flow in this sector increases velocity values. As discharge increases, the median riffle is submerged and velocities increase on the left bank. Further downstream, velocities increase with discharge. During times of low discharge, all the water is drained by third order channel 3 and the downstream vegetated area is not flooded. When inundation of this area occurs (during high flows) the ve-

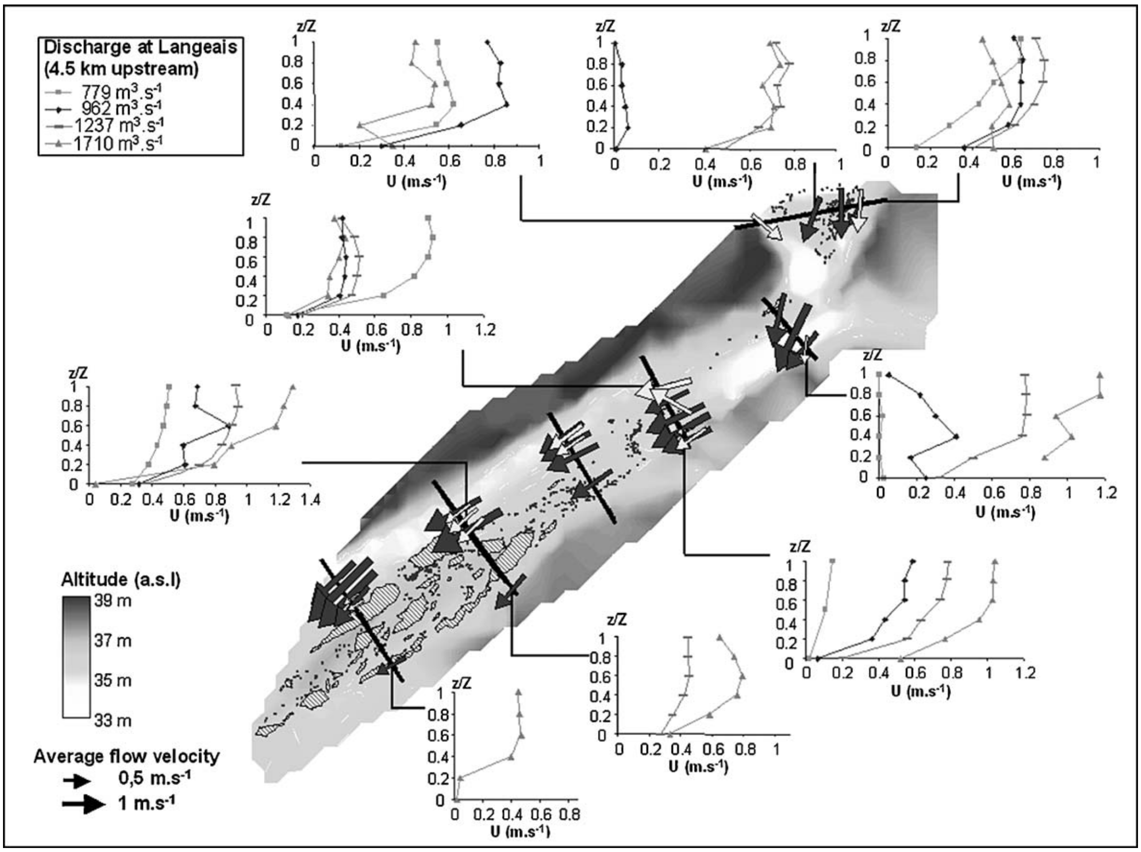


Fig. 8. Normalized velocity profiles measured for four flow conditions (779, 962, 1237 and 1710 m^3 s^{-1} at the Langeais gauging station) in the secondary channel A during flood 6. Flow directions measured for discharges of 779 and 1710 m^3 s^{-1} are represented respectively by grey and black arrows.

locities measured in this zone are low (ranging from 0.1 to 0.7 m s^{-1} for a discharge of 1900 m^3 s^{-1}) in comparison with the third order channel 3, where the velocity can be equal to 1.5 m s^{-1}.

4.5.2. Evolution of flow velocity and bed shear stress along the secondary channel

Average velocities calculated with HEC-RAS in different cross-sections were compared to field data (Fig. 9). Values obtained with the model are similar to the average velocities of the measured distribution. According to numerical computations, average velocities are relatively high on the riffles (R1 and R2) and reduced in the pools during times of low discharges. This was verified by measurements performed on the site (Fig. 9). As water level increases, average velocities tend to homogenize in the secondary channel. The values become higher in pools than on riffles during high discharges. These results are in agreement with the velocity reversal observed in other fluvial systems (Robert, 1997; Milan et al., 2001). For both high and moderate discharges, the average velocity decreases in the downstream part of the channel.

Total bed shear stress was determined from:

$$\tau = \rho g R_h S_e$$

where τ is the bed shear stress, in N m^{-2}, ρ is water density, in kg m^{-3}, g acceleration due to gravity, in m s^{-2}, R_h is the hydraulic radius, in m, Se is the slope of the energy line, in m m^{-1}.

The configuration of bed shear stress along the secondary channel is similar to the evolution of average velocities. The high shear stress noted on the riffles contrast with the low values in the pools during low flows. As discharge increases, shear stress in the pools is higher than on the riffles (Petit, 1987; Bravard and Petit, 1997; Milan et al., 2001).

4.6. Vegetation roughness

In order to compare Manning's roughness coefficients between vegetation bands, this parameter was determined for a unit surface of 1 m^2 (McKenney et al., 1995).

Vegetation bands are divided into three classes. The first group is composed of bands characterized by a Manning's roughness value less than 0.03 (bands 2, 3, 4, 6); these vegetated patches are located in the central part of the channel (between cross-sections 7 and 11) and germinated between 1998 and 2000. The second class has roughness values between 0.03 and 0.05 (bands 1, 5, 9, 13). Except for vegetation band 1, those groups are characterized by tall trees (height > 15 m). For this vegetation class, trunk diameters are large and branches are absent from the lower trunk. The third group is characterized by roughness values between 0.05 and 0.110 (bands 7, 8, 10, 11, 12, 14). The number of trunks per square meter is significant for those trees germinated between 1997 and 1998 (1.5 years after fluvial maintenance operations performed on the channel). These bands provide a dense vegetation filter that may strongly influence flow and sediment dynamics.

Apart from vegetation bands of the first class, Fig. 10 shows that vegetation roughness decreases with increasing tree age. This is explained by the morphological evolution from multiple stem trees towards tall single-stem trees. The roughness of trees also changes with water surface level and presence of foliage (McKenney et al., 1995; Fathi-Maghadam and Kouwen, 1997).

During low water levels, the width offered to the flow by a single small tree (characterized by $H < 15$ m) can be significant because the plant remains erect. As water level increases, two opposing processes are active: (1) the area of the tree that is inundated increases, (2) the stems and branches of young trees bend downstream and so reduce the surface area opposed to the streamflow. So, the hydraulic behaviour of trees varies

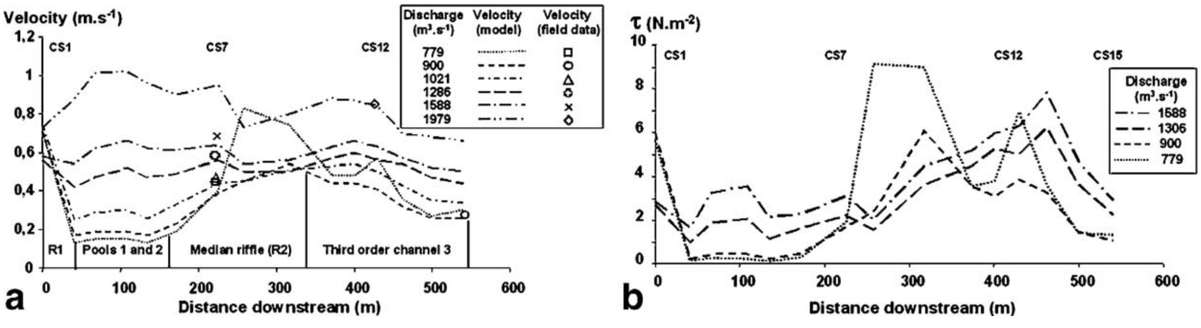
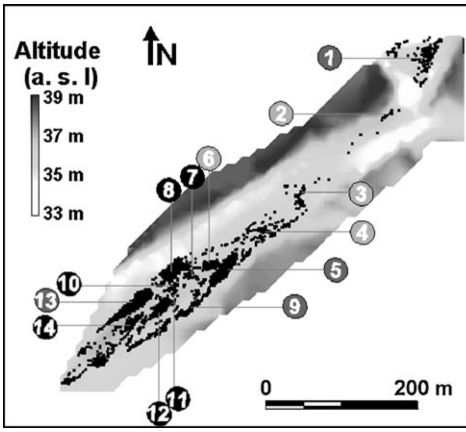


Fig. 9. (a) Mean flow velocities computed by the program and compared to field data; (b) mean shear stress longitudinal evolution computed by the program for discharges ranging from 779 to 1588 m^3 s^{-1}.



Band	Density (trunks/m²)	Maximum height (m)	Average diameter (m)	Germination date	Roughness (n_r)
1	0.82	12.5	0.029	1996	0.035
2	0.75	4	0.017	2000	0.025
3	1.00	4	0.014	2000	0.027
4	0.24	10	0.033	1998	0.020
5	0.20	24	0.117	1989	0.035
6	0.62	16	0.026	No data	0.029
9	0.20	20	0.164	1992	0.041
7	5.50	11	0.042	1997	0.109
8-Populus	3.50	11	0.039	1997	0.083
8-Salix	6.75	10.5	0.030	1997	0.102
10	3.50	7	0.022	1997	0.063
11	3.25	12	0.023	No data	0.062
12	4.25	9	0.029	1998	0.079
13	0.13	26	0.164	1965	0.033
14	2.00	8	0.035	No data	0.060

Fig. 10. Characteristics of in-channel woody vegetation present in the secondary channel.

according to the degree of submergence. For tall single-stem trees (characterized by $H > 15$ m), reduced flexibility prevents them from bending downstream.

The influence exerted by the downstream vegetated area on flow velocity and direction depends on the water level. In this case, for a discharge of 1100 $m^3 s^{-1}$, the combined effect of topography and vegetation contributes to a strong flow deflection towards third order channel 3. As discharge increases, flow directions are less affected by vegetation while flow velocities are significantly reduced. This process can explain the deposition of large bedforms composed of relatively well sorted coarse sands with slipface normal to the channel direction in this area.

5. Discussion

5.1. Hydrological and sedimentological behaviour of the secondary channel during moderate floods ($Q < 1100$ $m^3 s^{-1}$)

From the data and the observations mentioned above, a process–response model that illustrates the working and the evolution of the secondary channel will be proposed below (Fig. 11).

Moderate floods (2 to 5) have led to the erosion of sediments located on the sides of the upstream riffle R1. This lateral scouring, highlighted by the presence of longitudinal scour marks, contributed to the widening of third order channel 1. This process can be explained by high velocities and shear stress values. Moreover, such moderate floods are probably unable to provide a substantial sediment supply from the main channel to the secondary channel A (Fig. 11). In any case, for these discharges, flow energy is not sufficient to transport coarse sediments from the main channel to the third order channels which are located at a higher topographical level (3.7 m above the main channel). For moderate discharges, pools P1 and 2 act as sediment traps: reduced velocities and turbulence may allow sedimentation of coarser particles eroded from riffle R1 (mainly gravels and sands). Low velocities in the pools (less than 0.4 m s^{-1}) prevent massive sediment export from these depressions and fine particles, transported in suspension, can move beyond the depression and settle on the exit slope of the pool P2 where flow expansion is important.

As the sediment supply from the main channel and flow dynamics in the pools reduce, topographical and morphological variations observed in third order channel 3 are a consequence of redistribution of sediments previously deposited on the median riffle R2 and in the third order channel 3. On the riffle R2, relatively low flow velocity and reduced water depth contribute to fine sediment evacuation and to the development of armoured layers. In the third order channel 3, an average current velocity of 0.5 m s^{-1} induces dune and sandwave progradation. Sediments of the bedforms present in the third order channel 3 result in particle export from the median riffle R2 and from the margins of third order channel. When the armoured surfaces are well developed, sediment erosion becomes more difficult and the quantity of reworked particles decreases (Little and Mayer, 1976). If water level falls, dune sediments are reworked, ripples migrate on their stoss side and on the lee side of the sandwaves if grain size is not too coarse.

The processes described here relate to moderate floods and falling limbs of hydrographs, they influence the morphology of the secondary channel for the next flood and make vegetation colonization of the lower topographic elevations difficult (due to the frequency of inundation and to systematic sediment reworking).

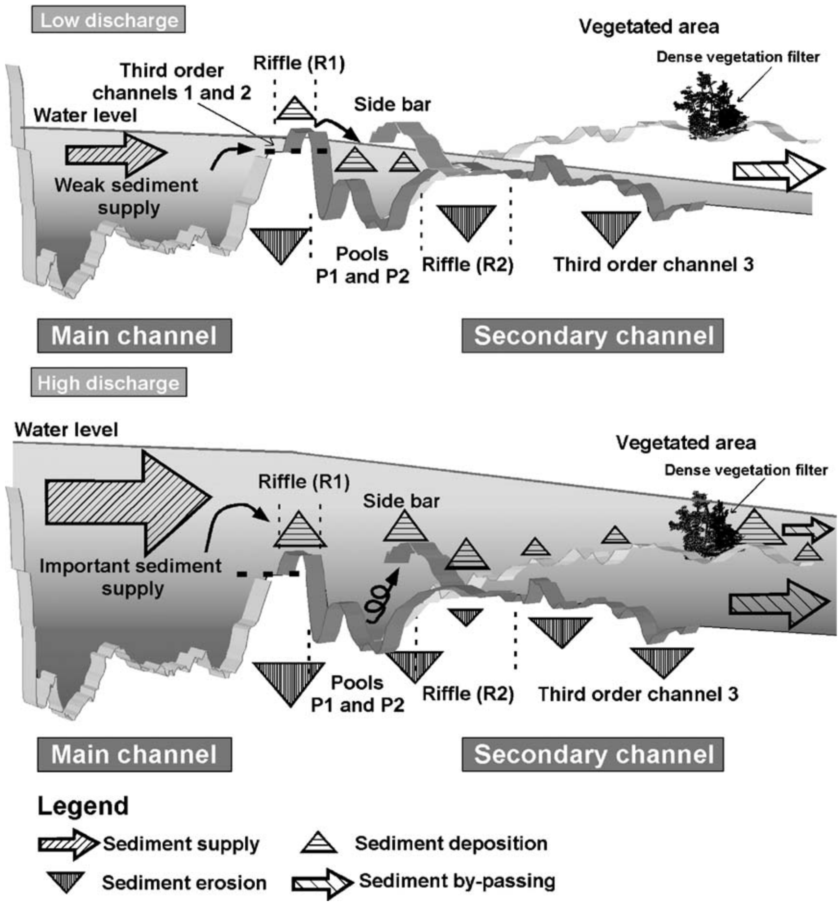


Fig. 11. Cartoon of flow and sedimentary behaviour of the secondary channel A during moderate and significant discharge.

5.2. Hydrological and sedimentological behaviour of the secondary channel during high amplitude floods ($Q > 1100$ m^3 s^{-1})

5.2.1. Upstream part of the channel

After flooding of the upstream riffle R1, flow velocity increases more rapidly in the pools than on the riffles (Bravard and Petit, 1997; Robert, 1997; Milan et al., 2001). For these high discharges, local effects such as constriction of flow in the third order channels (generating high flow velocities) are less perceptible than for low discharges and significant turbulence caused by the frontal attack of Pallu island by flow explains the collapse of the bank.

On the upstream riffle R1, large quantities of sediments deposited by flood 6 are probably due to the migration of gravelly dunes. These bedforms, represent significant sediment supply from the main channel during high water levels (Fig. 11). For these levels, (1) accommodation potential is significant, (2) high energy levels facilitate a massive transport of coarse sediment from the main channel to the riffle R1, and (3) the direction of progradation of the gravelly dunes is similar to the flow directions measured for discharges ranging from 1237 to 1710 m^3 s^{-1}. The deposition of these bedforms depends on the breaching of the armour layers present on the upstream riffle R1. This rupture, highlighted by scour chains C1 and C4 (see Fig. 7), is followed by the erosion of the finer matrix located below (Jackson and Beschta, 1982; Parker et al., 1982; Duizendstra, 2001). As a consequence, the erosion of these sediments increases the available space for sedimentation and also reduces the difference in level between the main channel and the upstream riffle R1 (thus, the energy needed to export sediment in the secondary channel is also reduced).

Minor topographical variations between survey S3 and bathymetry contrast with large volumes of sediment deposited between the bathymetric survey and S4. So, during flood 6, the morphological impact of the first two hydrograph peaks (discharge of ca. 1900 m^3 s^{-1}) in the upstream zone of the secondary channel was reduced although flow depth (between 0.7 and 1.7 m) and velocity (1 m s^{-1}) were relatively high. During the third peak (discharge of 2690 m^3 s^{-1}), significant variations occurred: bank collapse, filling and migration of third order channel 1 towards the west, sedimentation of particles downstream of the vegetated area and deposition of the dune located at the confluence between channels A and B. These phenomena highlight pulses in bedload transport and the fact that armoured layers may not have been disrupted during the first two peaks. The rupture of the armoured surfaces can be associated with the frequency of the flooding period of the upstream riffle (Reid et al., 1985).

On the East side of riffle R1, sediment dynamics is less significant owing to the morphological configuration and to the presence of the vegetated area. Roughness of this vegetation band (n_v=0.035) causes a decrease in flow velocity and the migration of dunes with slipfaces oriented towards the third order channel 2. Although sediments of these bedforms are reworked during low flows by the deflection of gentle currents induced by topography and trees, particles will be preserved thanks to the protective effect of the vegetation. Medium and fine sands can be deposited in the lee side of the trees or on the banks where herbaceous vegetation substantially reduces flow velocity (Madsen and Warncke, 1983; Watts and Watts, 1990; Machata-Wenninger and Janauer, 1991; Sand-Jensen and Pedersen, 1999). The fine sediments not deposited in these areas are mainly evacuated downstream during floods.

During significant discharges (1700 m^3 s^{-1}), flow velocity is 0.7 m s^{-1} on the side bar located close to the pool P2, and 0.9 m s^{-1} in the pools. In this area, confluence with the secondary channel B induces a complex flow pattern similar to that described in other fluvial systems (Best, 1987; De Serres et al., 1999). This complexity is increased by the curvature of the channel in this sector (Bridge and Jarvis, 1982).

Turbulence in the pools is increased by the presence of coarse woody debris (Hassan and Woodsmith, 2004) mainly composed of trees fallen from Pallu island. This turbulence induces the migration of large particles on the upstream part of the side bar. When discharge is equal to 1800 m^3 s^{-1}, the breaching of the armoured layer is followed by sediment scour (see Section 4.4). As with the riffle R1, the side bar constitutes a sediment store which is partially evacuated and renewed during high discharges.

During the falling limb of the hydrograph, reduced water depth, relatively low current velocity and poor sediment supply induce the development of an armoured layer on the top of the bar. As discharge decreases, the side bar emerges and sediments deposited previously are scoured laterally.

5.2.2. Median part of the channel

Scour chains located on the median riffle R2 demonstrate that this riffle is accreting slowly; the sediment store is partially liberated after the disruption of the armour layer. Sediments deposited on this riffle during high water levels are reworked during low flows: fine sediments are evacuated downstream into the third order channel 3 while most of fine particles passing over pool P2 settle between this pool and the riffle R2.

Sandwave slipface orientations indicate that the sediments of these bedforms are deposited during the falling limb of the hydrograph when the flow is drained through the third order channel 3. The presence of these bedforms shows lateral sediment redistribution from the higher vegetated area to the third order channel 3. These sediments are interbedded with those of the dunes of third order channel 3. Owing to their fine grain-size and their topographic position the migration of these dunes should occur even during relatively low flows. The stratigraphic link between dunes and sandwaves is similar to that described by Collinson (1986, Fig. 3.13, p. 29) and indicates that dune migration occurs over prolonged periods.

In the sparsely covered area located upstream from the dense vegetation filter, the flow velocity is approximately equal to 0.5 m s^{-1} for discharges ranging from 1237 to 1710 m^3 s^{-1}. When discharge is high, migration of isolated dunes occurs in this area. The sediments of these bedforms, although reworked during falling stages, contribute to the accretion of this area (see Fig. 7). The incision of the third order channel 3 causes a reduced frequency of the inundation of the vegetated area where the growth of trees enhances sedimentation. Accretion of the colonized area reinforces the incision process in the third order channel 3: increased deflection by the vegetated area reinforces this incision process. The development of the asymmetry of the channel will lead to rarer and shorter periods of inundation of the vegetated area where flow velocity will be reduced, fine sediments will be deposited and other trees than pioneer species will appear. Reduced quantities of sediment deposited in the sparsely covered area will be preserved in the secondary channel whereas morphological changes in the third order channel 3 indicate sediment by-passing. These observations reflect the importance of (1) energy levels achieved during floods and (2) the inundation frequency of the channel on the distribution of accretion and erosion zones. Before water leaves the channel, sandwaves are incised by rills and dunes present in the third order channel 3 acquire their diminished morphology (ratio between height and length less than 0.06) because of the variation in hydraulic constraints and reduced sediment supply (Allen, 1984; Carling et al., 2000).

5.2.3. Downstream part of the channel: the key role of the dense vegetation filter

Measurements taken in the downstream vegetated area highlight a decrease of flow velocity in this part of the secondary channel when discharge is equal to 1400 $m^3\ s^{-1}$. This decrease of flow velocity is caused by high values of Manning's roughness coefficients ($0.029 < n_v < 0.109$). Downstream from the dense vegetation filter, flow velocities are three times less than those measured in the third order channel 3. The impact of trees and saplings on flow depends on water level (ratio between the water level and the height of trees), the presence of foliage (Chow, 1959; Fathi-Maghadam and Kouwen, 1997), and the age of trees (flexibility, tree morphology).

The role of the downstream vegetated area on sediment dynamics varies according to flood stage. Between 1100 and 1400 $m^3\ s^{-1}$ at Langeais, the dense vegetation filter deflects the flow towards the third order channel 3. For discharges ranging from 1400 to 1700 $m^3\ s^{-1}$, the dense vegetation filter does not influence the direction of the flow but causes an important reduction in flow velocity. This phenomenon induces massive sediment deposition in this sector illustrated by the presence of large sediment tails and thick dunes of relatively well sorted coarse sands, oriented according to the main direction of the channel. These deposits, highlighted by the morphological and topographical surveys, increase cross-section obstruction and deflection power of this part of the channel. Moreover, these deposits contribute to the development of a ridge and swale topography. Downstream of the dense vegetation filter, the rarity of coarse sediment fractions shows the retention role played by the vegetation bands that appeared in 1997 and are characterized by high values of roughness coefficients (Rodrigues, 2004). Downstream of the dense vegetation filter, fine sediment deposition dominates and other species than *P. nigra* L. can begin to develop.

Sediments deposited in the downstream vegetated area will not be removed because (1) high discharges able to evacuate these particles are rare because of the incision of third order channel 3 and the accretion of the vegetated zone, (2) roots and herbaceous development enhance retention and stabilisation, (3) vegetation bands located upstream of the deposits play a protective role. When discharge is over 1700 $m^3\ s^{-1}$, the influence of the vegetated barrier is less important because trees begin to bend downstream, reducing the surface opposed to the flow and thus overall flow resistance.

As falling stage begins, the impact of the dense vegetation filter increases, and particularly when discharges range between 1100 and 1400 $m^3\ s^{-1}$. The dense vegetation filter deflects the flow towards third order channel 3 and affects sediment dynamics upstream, promoting the migration of bedforms like sandwaves with their slipface oriented towards Pallu island. This deflection also influences the reworking of sediments deposited earlier in the sparsely colonized zone located upstream from the dense vegetation filter. Downstream from the vegetation filter, reduced sediment reworking and deposition of fine particles are the dominant processes.

6. Conclusions

Flow and sediment dynamics were investigated on a secondary channel of the Loire River located on the site of Bréhémont (France).

Observations and measurements have shown that the hydrodynamics of the secondary channel vary with discharge. For low discharges, current direction and velocity distribution are governed by topography. As discharge increases, those parameters vary according to the morphological units and a velocity reversal may occur in pools and riffles.

Our data show that bedforms of the channel are different according to flood intensity and that sediment budgets were positive in the channel over the period 1994–2001 and negative between 2001 and 2003. Zones of scouring and deposition were clearly identified: sediment deposition occurred in the downstream vegetated area and on the banks while third order channels where subjected to scour. In-channel woody vegetation influences flow and sedimentary processes in a complicated way according to water level, roughness, vegetation physical parameters and season.

Two conceptual models of flow and sediment dynamics were proposed in this paper (Fig. 11) with the aim of explaining the morphological evolution of the channel during this study. During moderate floods, the weakness of sediment supply delivered by the main channel of the Loire River induces morphological changes in the lower parts of the channel expressed by the reworking of sediment previously deposited in these areas. For those moderate discharges, most of the particles eroded from the edges of the upstream riffle R1 are deposited in the pools. Despite low flow velocity and turbulence in the pools, fine sediment can get over those sediment traps and settle on their exit slope. Relatively high velocities measured on the median riffle R2 during low discharges facilitate particles export towards the third order channel 3. During high magnitude floods, the increased sediment supply from the Loire River feeds temporary stocks of sediment (riffles, bars, vegetated areas) and armour layers disruption is an important parameter influencing bedload pulses in the secondary channel. The vegetation bands located in the downstream area of the channel deflect the flow when discharge ranges from 1100 to 1400 m^3 s^{-1} and then reduce flow velocity (when discharge is greater than 1400 m^3 s^{-1}), generating significant sediment deposition in the vegetation filter characterized by substantial roughness coefficients. During the falling limb of the hydrograph, sediment deposition occurring upstream of the vegetation filter can be influenced by the deflecting power of those tree bands. Low deposition rates noted in the vegetated areas located upstream and downstream of the vegetation filter induce sediment accretion in these zones where erosion is prevented by the presence of vegetation.

Leaving aside the consequences of the incision of the main channel on environmental purpose, this phenomenon reinforces the difference in level with the upstream riffle of the secondary channel, hindering water and sediment supply during floods. Thus, the upstream riffle plays a key role in controlling water and sediment fluxes depending on flood types and magnitudes. Thanks to numerous quantitative data, sedimentary budgets have been established. They show the complexity in the sequence of sedimentary events. During moderate floods, the sediment dynamics is practically limited to internal reworking. Conversely, high magnitude floods allow a significant sediment supply. Deposition is then possible even on high zones as a consequence of a favourable accommodation potential. In the vegetated areas, preservation of deposits induces a slow but inescapable vertical accretion that reinforces the asymmetry of the secondary channel leading to the formation of islands.

In view to propose a more accurate model, further studies are necessary to characterize the evolution of the bedform configuration of the main channel. In such a way, the relations with the secondary channel would be clarified for floods of different types and magnitudes. Then, a relevant quantification of the sedimentary input will be possible.

Acknowledgements

We thank the DIREN Centre and the Région Centre for their technical and financial support. ADESVV very kindly lent us the electronic total station. J. P. Bakyono, A. Fourmont, I. Pene-Galland, and C. Rousseau are thanked for their valuable field assistance. B. Gensane provided helpful comments on the manuscript. We are grateful to two anonymous reviewers and to A. D. Miall for their rigorous and constructive reviews of this paper.

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