DISTRIBUTION OF LARGE WOODY DEBRIS ALONG THE OUTER BEND OF MEANDERS IN THE AIN RIVER, FRANCE

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Abstract: The distribution of large woody debris (LWD) was studied along the concave outer bend of three meanders in the Ain River, a 195-km-long tributary of the upper Rhône River. The Ain River is a sixth-order channel dominated by a gravel-cobble bed substrate that meanders through a floodplain covered largely by riparian forest vegetation. The mass of LWD was measured in a 15-m-wide forest band along the three meander bends, with total loads calculated to be 56.1 t ha⁻¹ at the Mollon study site, compared with 22.9 and 21.5 t ha⁻¹ at the study sites of Bublane and Blyres, respectively. The distribution of LWD within any one meander concavity was dependent on three main variables: (1) the position of the concavity in relation to the main flow axis, (2) the height of the bank, and (3) the presence and position of overbank flow channels in the concavity. The type of vegetation community along the channel margin is nondiscriminating, favoring the conclusion that the LWD comes mainly from upstream of the bends rather than locally. The relative influence of each variable is contrasted between the three study sites. The total LWD deposited along concavities was most strongly controlled by meander-bend geometry. The supply areas for LWD, located a few kilometers upstream from the study sites, were also found to influence total LWD along concavities. Findings from this study are applicable to managing instream large woody debris as part of ongoing efforts to restore alluvial forests along French rivers. [Key words: large woody debris, debris line, meandering piedmont river, Ain River, France.]

INTRODUCTION

Previous Research

Research on large woody debris (LWD) deposits in North America has focused on the distribution and biological or morphological role of LWD in the channel, not on the floodplain. Many authors (e.g., Harmon et al., 1986; Bisson et al., 1987; Maser et al., 1988) have studied mountain streams and creeks in the northwestern United States (Oregon, Washington, California, and Alaska) and British Columbia, Canada. Temperate pristine forests, which exist in these locations, are characterized by fluvial systems containing large amounts of LWD. These studies have helped environmental scientists and natural resource managers to understand better the natural links between LWD and fish habitat. Studies on desert streams (Minckley and Rinne, 1985), lowland rivers along the southeastern subtropical coast (Wallace and Benke, 1984), and northeastern mountain streams (Zimmerman et al., 1967; Bulby, 1981) in the United States have highlighted the geomorphic and biologic roles of instream LWD. Studies in New Zealand (Mosley, 1981), England (Gregory and Davis, 1992; Gurnell et al., 1995), and Australia (Gippel et al., 1994) focus on instream LWD, but again, the extent and distribution of LWD on channel margins have been largely ignored.

LWD dynamics are best understood in the mountain streams of old coniferous temperate forests (Heede, 1972; Swanson and Lienkaemper, 1979; Marston, 1982; Robison, 1987). Stream systems larger than fourth-order have rarely been studied and those studies still focused only on instream LWD (Keller and Swanson, 1979; Malanson and Butler, 1990; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996). The LWD dynamics at the contact between the active channel and the riparian zone have not been studied even though analyses of historical records have revealed the role that LWD exerts in vegetation mosaic regeneration and conservation of ecological diversity (Sedell and Luchessa, 1982; Triska, 1984). LWD dynamics are poorly understood in wooded corridors of large rivers with meandering or anastomosing patterns despite research demonstrating a strong influence of LWD on these geomorphological patterns (Hickin, 1984; Harwood and Brown, 1993).

Piégay (1993) and Piégay et al. (1998) recognized the importance of LWD accumulations on the floodplain of the Ain River, a meandering tributary of the Rhône River watershed. These LWD accumulations, along with those on other rivers in France, create management problems. Many of the large rivers experienced tree colonization between 1945 and 1970 owing to changes in agricultural practices (Piégay et al., 1994; Marston et al., 1995). These mature trees supply more and more LWD to rivers, increasing the risks of flooding and erosion. A better understanding of LWD supply, transfer, and deposition is necessary in order to balance the positive ecological factors of LWD against the risks of increased flooding.

Purpose and Objectives

The purpose of the current study is to model the distribution of LWD as a function of channel geometry and floodplain characteristics. This will be accomplished by describing and explaining the variability of LWD along the concave outer banks of individual meanders and between meanders with different characteristics of the Ain River. Two objectives are proposed: (1) to describe the distribution of LWD mass along the concave banks of three meanders with contrasting morphology and channel-margin vegetation, and (2) to explain the distribution of LWD masses along each meander and the differences between the meanders as a function of channel and floodplain characteristics. If these objectives are achieved, managers of ripar-
annual discharge of 130 m³ s⁻¹, adding about 20% to the discharge of the Rhône River (Marston et al., 1995). Discharge exhibits a strong seasonal pattern, ranging from summer low flows less than 10 m³ s⁻¹ to large spring and fall floods (Fig. 2). The 100-year flood is estimated at 2750 m³ s⁻¹ at Chazey (natural reconstituted discharge for the period 1913 to 1977).

In the lower reaches, the Ain River is characterized by slopes ranging from 1.2 to 1.8 m km⁻¹. A gravel-cobble bedload (median size 2.5 cm) is derived from banks of the fluvo-glacial terraces of the Last Glaciation, through which the Holocene channel is incised between 5 and 10 m. The river follows a sinuous pattern through the floodplain, which ranges in width from 0.5 to 2.0 km (Bravard et al., 1990).

The margins of the river were traditionally used for grazing cattle and for harvesting domestic firewood. During the 1950s, these areas were abandoned as humans migrated away from rural areas and agriculture became more specialized. Agricultural specialization triggered a move away from the floodplain to better hillside soils. Construction of Vougans Dam across the Ain in the Jura region in 1951 caused peak flow decreases and bed incision that favored further channel coloniza-

Fig. 2. Mean annual discharge of the Ain River at Chazey-sur-Ain.

River Meanders at Bublane, Mollon, and Blyes

The distribution of LWD was studied along the concave bank of three meanders of the Ain River at Bublane, Mollon, and Blyes. The three meanders are situated within a 15-km-long reach and represent a range in meander geometry and overbank morphology found along the river in its lower course. The meander bend at Bublane, Mollon (5 km downstream from Bublane), and Blyes (10 km downstream from Mollon) are each approximately 600 m in length (Table 1). All three meanders have experienced a downvalley translation of the channel (Hooke, 1977), with bank erosion along the translation axis of meanders (Malavoi, 1985). The downstream location...
migration rate of meanders is high, approaching 9 m per year at Blyes between 1973 and 1991, and more than 15 m per year at Mollon between 1963 and 1991.

The pattern of each meander is unique (Table 1). The sinuosity rate for each meander is calculated between the two inflection points of the curve (l and l') as shown on Figure 1. The curvature of each meander (r/w) is determined by dividing the radius of curvature by active channel width (Hickin and Nanson, 1975). The sinuosity rates and curvatures of the three meanders are different, indicating that each meander is at a different stage of meander evolution. Mollon has the most mature form, with a very high migration rate, which is reflected in the r/w ratio. A chute cut-off is expected shortly. The meanders at Bublane and Blyes (at a more advanced stage than Bublane) are more sinuous, with slower rates of downstream migration rates than at Mollon.

The banks of the three concavities are vegetated but have been modified to some degree by humans. The dominant life-forms are either trees (Populus nigra, Salix alba, Alnus glutinosa, Fraxinus excelsior, Acer pseudoplatanus) or shrubs (e.g., Salix eleagnos, Crataegus monogyna), some of which are pioneer species (Salix viminalis, Salix triandra). Several plantations of poplar and clear-cut plots exist on the Bublane and Blyes sites. The forested floodplain is incised locally by overbank flow channels, most of which are unvegetated and influenced by episodes of overbank cutting and filling.

**METHODOLOGY**

**Measuring LWD Mass**

The mass of each LWD accumulation was measured along each concavity margin from the edge of the river bank extending 15 m inland across the floodplain. For this study, a LWD accumulation consisted of wood masses with at least three pieces greater than 10 cm in diameter and 30 cm in length. The masses of isolated trunks (M1) were calculated with the formula (Keller and Swanson, 1979; Platts et al., 1987):

\[ M_1 = L \left( d_1^2 + d_2^2 \right) / 8D \]  

where \( M_1 \) is the trunk mass (kg), \( L \) is the trunk length (m), \( d_1 \) and \( d_2 \) are trunk diameters measured at the termini of the trunks (m), and \( D \) is the wood density (500 kg m\(^{-3}\)) (following the value cited for softwoods by Harmon et al., 1986, and Platts et al., 1987). Only trunks measuring 10 cm in diameter and 30 cm in length were considered as isolated trunks in the current study.

LWD masses were estimated using a method developed by Piégay (1993) and Thévenet et al. (in press). Each debris accumulation was considered as a parallelepipiped volume (V) with mean depth (d), mean width (w), and mean length (l), and consisting of wood and air. A linear relation between debris jam mass (M2) and parallelepipiped volume (V) was determined. The equation is:

\[ M_2 = 45.3V + 66.27 \quad (R^2 = .6) \quad \text{with} \quad V = dwl \]  

where \( M_2 \) is the debris jam mass (kg), \( V \) is the wood-air parallelepipded volume (m\(^3\)), \( d \) is mean depth (m), \( w \) is mean width (m), and \( l \) is mean length (m).

Compactness of LWD accumulations was very low but comparable from one mass to another. The wood occupied, respectively, 2.6% and 5.4% of the volume of parallelepipeds of 1 \( m^2 \) and 10 \( m^3 \). Total mass of debris accumulations and isolated trunks was calculated for sampling plots of 150 \( m^2 \), each one corresponding to a bank length of 10 m and a width of 15 m from the bank to inside the forest. In total, 180 plots, nearly 60 per site, were sampled.

**Material**

On each plot, LWD mass was differentiated between locations in the floodplain or in the bank. Wood structures were considered in the bank when they had at least one of their extremities embedded in the bank and were less than 1 m from the channel water. Three variables describing LWD were consequently defined: total LWD mass per plot (LWDt), in-bank LWD mass per plot (LWDb), and floodplain LWD mass per plot (LWDf).

Geographical variables also described each plot: (1) bank height (Bh), (2) the position of the plot with respect to the channel axis indicated by an angle value (A), (3) the vegetation unit type (V), (4) the presence/absence of an overbank flow channel (Ch), and (5) the distance of the plot from the nearest overbank flow channel mouth (D).

The bank height (Bh) was defined as the height between the water line and the floodplain floor. Measurements were taken with the low water channel and could be compared from one site to another. Measurements were taken every 4 m. An average bank height was estimated at a point every 10 m along the concavity at the same sites as the LWD sampling points.

The position of the plot was evaluated with respect to the angle (A) (Fig. 1) between the straight line between inflection points 1 and 1' and the straight line between the point 1 and the sampling point. This variable was based on the concept of path direction proposed by Langbein and Leopold (1964). The sampling plots of each meander were distributed from 0° to 40°–60°.

The vegetation unit type (V) was based on five classes, each one being distinguishable in the field: gravel-bed unit (V1), pioneer willows unit (V2), tree unit (V3), clear-cut unit (V4), or plantation of poplars unit (V5). This variable could be inter-
preted partially as a descriptor of the ecological succession from very young stages corresponding to the gravel-bed units and the units of pioneer willows to mature stages (tree unit, clear-cut unit, or plantation of pêlars).

The position of the overbank flow channels along the outer bend of meanders was described by two variables: a discrete variable (Ch) with two classes: presence (1) or absence (2) of an overbank flow channel, a continuous variable (D) giving the distance of a plot from the nearest overbank flow channel. The last variable was created because LWD mass can be deposited not only on the entrance of an overbank flow channel but also on its margins.

Statistical Analyses

As we worked on a large data set (180 plots × 6 site-descriptive variables), a multiple correspondence analysis (MCA) was used to synthesize their structure by discriminating the main patterns occurring in these complex data sets. MCA is used regularly in ecology to analyze the structure of categorical multivariate data (Piault et al., 1984; Tenehaus and Young, 1985). MCA aims to generate quantitative scores, which maximize the mean correlation ratio among qualitative variables. As our data set is composed of both continuous variables and categorical variables, we used the “Hill and Smith analysis option,” which allows mixing of continuous and categorical variables (Hill and Smith, 1976; Chessel and Lascaux, 1997). Data sets were analyzed using the ADE 4.0 statistical software (Chessel and Dolédec, 1996). As Hill and Smith analysis allows us to summarize the previous data table, we focus modeling procedures on the most interesting links between LWD masses and geographical descriptors.

Simple and multiple regressions were used to model LWD masses according to A, Bh, and D. LWD masses were log transformed in order to be predicted from regressions. Nevertheless, as plots without wood are numerous, they were not added to the log-transformed data table because distribution does not follow the normal law. We previously calculated the Geary autocorrelation test (c) on Blyes, Bublanne, and Mollon sites in order to be sure that the values were spatially independent (Geary, 1954; Cliff and Ord, 1973). When there is no spatial structure, the Geary index (c) between the estimated local variance and the estimated variance is 1. Values of LWDf, LWD, and LWDi are not spatially autocorrelated, (c) being always higher than .81 (.50 in the case of Mollon for LWDf and LWDi).

Analyses of Variance also were used to test the dependency between LWD masses and discrete variables (e.g., Overbank flow channel presence/absence or Vegetation types). The probability p of the Scheffe-test was calculated in order to assess this statistical dependency class by class.

RESULTS

Distribution of LWD Mass

The mass of LWD varied greatly from one concavity to another (Table 2). The average mass per plot was 56.1 t ha⁻¹ at Mollon but only 21.5 and 22.9 t ha⁻¹ at Blyes and Bublanne, respectively. Strong differences were observed in the frequency distribution analyses between the three meanders. Some plots had a very low mass of LWD. The tenth-percentile value was only 3.1 t ha⁻¹. The concavity at Mollon had the highest masses of LWD. Mean, maximum, and minimum values were higher at Mollon than at the two other sites.

A high variability of LWD masses also was observed along each concavity (Fig. 3). Preferential sites of LWD accumulation also existed at each concavity. In all three meanders, maximum LWD accumulations were found at the median or upstream portions of the concavities. The upstream bank at Mollon was the most important sector of LWD accumulation, with a maximum of nearly 336.7 t ha⁻¹. Downstream from this sector the masses decreased quickly except in plots located in flood channels with angles between 16° and 18°. Three preferential sites of LWD masses were observed at Bublanne, decreasing in importance from upstream to downstream. Some plots between impact angles of 25° to 30° had no LWD. This was surprising with respect to the high masses stocked farther upstream. The distribution of LWD mass on the outer concave bend at Blyes was different from that observed at the two other meander sites. Two preferential sites were located in the median part of the concavity.

The distribution of LWD masses in bank versus floodplain varied from one concavity to the others and within each concavity. In the Mollon meander, the wood was localized preferentially in the bank, notably in the plots characterized by the higher mass. Most of the plots, however, registered LWD in the floodplain. In the Bublanne concavity, the wood was deposited preferentially in the floodplain on the plots with higher masses. At the Blyes site, distributions of LWD were identified at three sectors. From plot 15 to plot 215, the LWD masses were distributed in a pattern similar to that which occurred at Mollon and Bublanne. From plot 225 to

Table 2. Variability of LWD Masses Along the Three Concavities

<table>
<thead>
<tr>
<th></th>
<th>Blyes</th>
<th>Bublanne</th>
<th>Mollon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of plots</td>
<td>57</td>
<td>58</td>
<td>61</td>
</tr>
<tr>
<td>Number of single trunks</td>
<td>46</td>
<td>13</td>
<td>56</td>
</tr>
<tr>
<td>Number of wood accumulations</td>
<td>88</td>
<td>80</td>
<td>136</td>
</tr>
<tr>
<td>Total mass of trunks per concavity (tonnes)</td>
<td>9.2</td>
<td>2.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Total mass of jams per concavity (tonnes)</td>
<td>9.5</td>
<td>17.9</td>
<td>45.6</td>
</tr>
<tr>
<td>Total mass of LWD per concavity (tonnes)</td>
<td>18.7</td>
<td>20.3</td>
<td>53.0</td>
</tr>
<tr>
<td>Mean mass of LWD per plot (t ha⁻¹)</td>
<td>21.5</td>
<td>22.9</td>
<td>56.1</td>
</tr>
<tr>
<td>Maximal mass of LWD per plot (t ha⁻¹)</td>
<td>98.0</td>
<td>123.3</td>
<td>336.7</td>
</tr>
<tr>
<td>Minimal mass of LWD per plot (t ha⁻¹)</td>
<td>1.0</td>
<td>0.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>20.7</td>
<td>25.1</td>
<td>62.7</td>
</tr>
<tr>
<td>Mean mass of LWD per plot in the floodplain (t ha⁻¹)</td>
<td>10.1</td>
<td>14.2</td>
<td>35.2</td>
</tr>
<tr>
<td>Mean mass of LWD per plot in the bank (t ha⁻¹)</td>
<td>11.4</td>
<td>8.7</td>
<td>20.9</td>
</tr>
</tbody>
</table>

°ANOVA: Mollon ≠ Bublanne and Blyes (p of Scheffe-test < .05).
°ANOVA: Mollon ≠ Blyes (p of Scheffe-test < .05).
plot 365, LWD masses were localized in the floodplain. In the last sector, LWD masses were present in the bank.

Geographical Pattern of Independent Variables

The mean bank height was estimated at 1.58 m at Mollon, 2.31 m at Bublane, and 2.32 m at Blyes (Table 3). Channel geometry varied greatly from one concavity to another because each had been unequally subjected to the incision that the river registered during the 20th century. Overbank flows were observed at a discharge of only 300 m³ s⁻¹ at Mollon when the often-cited bankfull discharge (820 m³ s⁻¹) was not overflowing at the other two sites. The mean bank height was highly variable in each meander (Fig. 4). In the Blyes concavity, the bank was high but dissected by several overbank flow channels. The bank morphology of the Bublane reach contained even greater diversity. The banks were mostly higher than those observed at Blyes, locally a little lower in the central part near an overbank flow channel. In the Mollon reach, the floodplain surface was low compared to the other sites and the overbank flow channel was lower than that observed at Blyes.

The studied meanders have various forms. Mollon was characterized by the most developed meander form, with plots distributed between 0° and 56°. Plots at Bublane and Blyes were concentrated between 0° and 40°-60°.

On the three sites, the concavity outer bank is strongly vegetated. Spontaneous tree or shrubby stages occupied from 55% to 60% of the concavity bank linear (Table 3). The vegetation mosaic had been disturbed by humans at the Bublane and Blyes sites where 30% of the bank linear corresponded to clear-cut areas. One well-developed plantation of black poplar was located in the Bublane site.

These vegetated units were interrupted by overbank flow channels characterized by cobble and gravel deposits containing only discontinuous herbaceous cover. Six unvegetated areas with lower banks were observed on both the Blyes and Mollon meanders. Of the linear of the Mollon concavity bank, 23% was unvegetated, renewed by cobble and gravel bars migrating inside the floodplain forest. The upstream part of an overbank flow channel, located 600 m upstream from the point bar at Mollon, was also greatly modified by recent floods, which explained the number of plots identified as gravel bars (Fig. 4).
Table 4. Results of the $R^2$ Coefficient Calculation and Variance Analysis Between LWD Masses and Geographical Variables

<table>
<thead>
<tr>
<th>Bank height</th>
<th>Angle</th>
<th>Distance to the overbank flow channel</th>
<th>P/A of an overbank flow channel</th>
<th>Vegetation units</th>
<th>Sites p of Schefte-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p &lt; .05)</td>
<td>(p &lt; .05)</td>
<td>(r^2 (p &lt; .05))</td>
<td>p of</td>
<td>Schefte-test</td>
<td>p of</td>
</tr>
<tr>
<td>All stations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log (LWDt)</td>
<td>.07</td>
<td>.05</td>
<td>-</td>
<td>-</td>
<td>1 # 4</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>.09</td>
<td>-</td>
<td>-</td>
<td>0 # 1</td>
<td>4 # 1, 2, 3</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mollon (n = 61)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log (LWDt)</td>
<td>.18</td>
<td>.16</td>
<td>.15</td>
<td>0 # 1</td>
<td>-</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>.19</td>
<td>.14</td>
<td>.12</td>
<td>0 # 1</td>
<td>-</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Byles (n = 50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log (LWDt)</td>
<td>-</td>
<td>.11</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>.10</td>
<td>.27</td>
<td>0 # 1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bublane (n = 42)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log (LWDt)</td>
<td>-</td>
<td>.31</td>
<td>.26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>.15</td>
<td>.32</td>
<td>.35</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Log (LWDb)</td>
<td>-</td>
<td>-</td>
<td>0 # 1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Note that the plots without LWD are not considered. = Not significant for p < .05. Mo = Mollon; Bu = Bublane; Bl = Byles.

LWD projection on the factorial map at the scale of the entire population. The projection of LWD masses on the first factorial map shows that LWD distribution is complex (Figs. 5C, 5D, and 5E). Total LWD per plot seem to be deposited mainly on plots that are located on sites closed to overbank flow channels with gravel deposits and having a high angle between the channel axis and the straight that bends I and I' ($R^2 = .05$) but a low bank height ($R^2 = .07$). A weak relationship was noted between LWD masses and A, Bh, or D (Table 4). The following equation, based on two quantitative independent variables H and A, is developed using data in Table 4:

\[
\log (\text{LWD}) = 2.73 + 0.007 A - 0.20 Bh
\]

($R^2 = .10; p = .0003$)

All sites.

Both LWDf and LWDb are controlled by the previous parameters, but high LWDf and LWDf masses are also observed in sites with high banks or vegetation units (Figs. 5D and 5E). LWDf are also abundant in clear-cut or plantation units.
Fig. 6. Distribution of LWD masses (LWDt, LWDb, and LWDf) according to the presence or absence of overbank flow channels (A) or per vegetation units (B).

LWDt also occur in sites with high banks farther from overbank flow channels. Consequently, univariate relationships between LWD and geographical variables are poorly highlighted (Table 4). We usually registered LWD in overbank flow channels than in other parts of the bends (Fig. 6A). Moreover, Figure 6B shows that gravel units registered higher LWD masses than did other vegetation units. Clear-cut and plantation units had lower masses, notably for LWDt and LWDf. LWD masses stored in pioneer units and tree units cannot be statistically distinguished.

We added vegetation units in regression analysis considering subpopulations. We measured the regression from LWD masses to bank height or plot position, distinguishing gravel units from pioneer and tree units. Clear-cut and plantation units were not studied as they were not observed on all sites and there were insufficient individuals for such analysis when we distinguished subpopulations. We computed 12 simple regressions: LWDt or LWDf = f(Bh; A) for gravel, pioneer, and tree units. Only three were statistically validated: LWDt = f(A) for tree ($R^2 = .23; p = .0003$) and pioneer ($R^2 = .14; p = .04$) units and LWDf = f(Bh) for gravel units ($R^2 = .26; p = .03$). It is consequently impossible to highlight the influence of the vegetation cover on LWD deposits when comparing plots with the same bank height or same angle. The models "LWDt = f(A)" for tree and pioneer units cannot be used to distinguish different preferential sites of LWD deposits according to vegetation cover, as the two lines are almost superimposed and the distribution of the plots within the scatterplot is fairly complex. Vegetation units are partially linked with Bh, as we register an ecological succession from gravel (juvenile unit with low overbank flow sedimentation) to pioneer and tree units (older units with higher overbank flow sedimentation). Consequently, no pioneer and tree plots have a bank height lower than 1.4 m. Nevertheless, gravel

![Figure 6](https://example.com/figure6.png)

Fig. 7. Results of the Hill and Smith Analysis: F1-F2 factorial map of the sampling plots showing projection for the total LWD masses on each meander bend: Bylges (A), Bublane (B), and Mollon (C). See Figures 5A and 5B for significance of F1 and F2.

units are observed for a range of bank heights, reflecting several generations of overbank flow channels that are still functioning. We observe more LWDt masses in low overbank flow channels than in higher ones. The simple regression model is not validated statistically for LWDf owing to a lack of data, but low-bank plots with gravel cover usually have more LWD than high-bank plots with gravel cover.

LWD projection on the factorial map at the scale of each concavity. The link between LWD masses and the geographical variables is site specific, as shown on Figures 7 and 8, on which the first factorial map is presented for each site. LWD masses mainly occur in the Mollon site. The LWD masses in this site are statistically different from those in the two other sites for LWDt and LWDf (Table 4). The value of LWD mass per plot (kg per 150 m$^2$) was related to D, Bh, and A on the Mollon site. LWD masses on the Mollon site are controlled mainly by the presence of an overbank flow channel with gravel deposits, a low bank height, and a high angle, whatever their location in the plots. This site was better connected to the active channel than were the other two sites and had a larger and more diversified population. On the Bublane site, A and D were useful factors explaining LWD distribution along the concavity. The preferential plots of LWD deposits are composed of pioneer or tree units with high angle and are far from the overbank flow channels. Most of the wood is deposited in bank. On Bylges, the main LWD masses occurred in the plots with high angles and plantation or clear-cut cover, mostly in the floodplain. A part of high LWD masses (mostly located in the floodplain) is not explained by selected geographical variables, unlike the Bublane and Mollon sites. In Bylges, the main peak of wood at 300 m of the point bar cannot be explained by the chosen geographical variables.

In-bank LWD increase with bank height decreases in Mollon and partially in Bylges, but with bank height increases at Bublane (Fig. 8). In-bank LWD increase with angle increases in Mollon and Bublane, but with angle decreases at Bylges.
Except for the Mollon meander, explaining in-bank LWD mass distributions according to geometrical descriptors along concavities was difficult. In the case of Bublane, plots that registered high LWD masses contained high banks but were located in front of the upstream channel axis (high angle) when plots with low bank height were occupied by clear-cut units and poplar plantations, which were vegetal units with low trapping efficiency, and had no LWD in the 15-m study width, with a debris line existing beyond. LWD were localized mainly in the floodplain in the lower part of the sections (sections 275 to 355) but were deposited mainly in bank when the bank was high (sections 455 to 475).

In the case of Blyes, the LWD were deposited preferentially at the entrance of two overbank flow channels (respectively, 100 and 200 m from the point bar) that were not localized in front of the main flow axis and whose upstream part was not characterized by low elevation (Fig. 4). In this concavity, this factor seemed to be more important than bank height or plot position.

In-bank LWD or total LWD masses were linked more closely with the independent variables than in-floodplain LWD masses whatever the site (Fig. 8, Table 4). Observations indicated that LWD originated from upstream, not from the eroded bank of the meander, and consequently depended mainly on the meander geometry (A, D, and Bh).

The following site-specific equations, based on quantitative independent variables Bh, A, and D, are developed using data in Table 4:

**Summary of Results**

Three main factors were identified that explained LWD mass distribution along meander concavities, namely, (1) bank height, (2) plot position in relation to main flow axis (with a high A), and (3) position of active overbank flow channels that were not always characterized by low elevation.

When at least two of these factors were present in a given concavity, LWD masses could be deposited massively, mostly in-bank. The Mollon concavity was a typical example. The upstream part had low banks related to the entrance of overbank flow channels and almost in front of the main flow axis (high A). In the Mollon reach, the LWD masses either in-bank or on the floodplain were strongly related to bank height and plot position.

The ability of vegetation to trap LWD or locally supply sites in LWD was also examined. The hypothesis was that vegetation density may control LWD position in the plots and LWD volumes in case of loading owing to bank erosion. If the supply was local, we may think that tree units supply more LWD than clear-cut or shrubby units. Inversely, shrubby units may have a trapping efficiency higher than tree units or plantation units characterized by a lesser density of individuals. In most cases, our hypothesis was not validated. Plot dimensions may not be adapted to such studies. For example, in Bublane, we demonstrated that LWD masses in sectors with low banks and a clear-cut cover were relatively low within the 15-m width of the sampling plots but contained high loads farther inland because the near-bank vegetation did not trap LWD.

Each meander was characterized by a specific distribution of LWD mass among its concavity. A weak relationship existed between LWD mass per plot and each independent variable at the scale of the total population, as several combinations of geographical variables can explain high LWD mass distribution. The difference was explained mainly by the specific meander geometry of each but also by the specific LWD inputs.

**Meander Geometry and LWD Storage Capacity**

LWD mass at Mollon was greater than that observed at either Blyes or Bublane. Two reasons for this difference can be proposed. The first concerns the meander geometry at the different sites. With a sinuosity rate of 1.53, a r/w ratio of 3.11, and
a floodplain that averaged 70 cm lower than each of the other sites, Mollon had optimum retention of LWD inputs (Fig. 9). Differences in meander geometry explained all the large LWD mass distributions where LWD inputs were high. LWD were carried from upstream by flows and deposited mainly in the plots with high angle located in the axis of frontal flows in the meander bend. Lower plots were also preferential sites of deposition because they were often flooded and registered high-velocity overbank flows. These lower plots often corresponded to the mouth of overbank flow channels characterized by higher gradient and flow velocity than the floodplain. The occurrence of preferential sites was higher in Mollon than in other sites. Overbank flow channels, which directed overbank flows, influenced LWD distributions even if they had high elevation, as shown in Bublame.

The second factor concerns the potential supply of LWD upstream from the concavity. When the sources of LWD were located close to the concavities, the preferential sites of LWD deposition, the migration distance from supply sites to deposition sites was short, corresponding to the distance separating the two concavities. In the case of Mollon, LWD originated from eroded banks located just upstream of each concavity. Potential supply sites had been identified using a map entitled "Nature and Morphology of Ain Banks," prepared by Bravard et al. (1990).

A representative distance from the beginning of the first upstream concavity had been determined for each site. This distance varied from 2.3 to 2.6 km, corresponding with the sites that represented a potential eroded bank linear of 4.6 to 5.2 km (Table 5). Results showed that LWD mass deposits depended on LWD supply in addition to the meander capacity to arrest LWD transport. Since this factor was important, it was considered that: (1) LWD transfer took place over a short distance, and the residence time, and thus the transfer time, in the reach was long; (2) the transport was characterized by a longitudinal discontinuity, LWD migration being longer in some reaches than others; and (3) LWD masses at preferential sites of deposition increased from one flood to another.

The LWD upstream supply should be discussed because LWD masses deposited in the Mollon concavity between 1993 and 1996 remained constant from one flood to another (Piégay et al., 1998). The LWD transfer was the same upstream and downstream from the concavity when the downstream concavity had fewer jams than Mollon. Consequently, meander geometry was considered as the main factor explaining LWD mass abundance from one site to another. Moreover, we did not take into account local input when we know that LWD local input is higher in the Mollon reach, where the bank eroded 15 m per year, than in the two others, where bank erosion is less important and vegetation cover less dense (clear-cut and plantation units).

Among the geometrical factors, bank height seems to be the most important one in controlling LWD mass distribution. As shown on Bublame, whose banks were higher than those of Mollon, LWD deposits were lower. In those cases, angle and overbank flow positions appeared as secondary factors controlling LWD distribution in the meander bends. The lowest plots of Bublame (200 m from the point bar) were high compared to those of Mollon. At Bublame, geometric factors also explain LWD mass distribution. As bank height is also high compared to Mollon plots, it could be that the position of the overbank flow channel controls distribution of LWD mass deposits in the meander.

Questions for Future Research

As shown on Figures 5, 7, and 8, several high LWD masses are not explained by selected geographical variables. Moreover, they did not allow us to explain LWD distribution within the plots from in-bank to in-floodplain positions.

If we can identify general biogeomorphological characters explaining distribution of LWD masses within meander bends, several questions may be answered, specifically:

1. Is angle A the best indicator of plot position relative to the main upstream flow axis? The relative position of plots to the upstream flows is difficult to measure, as it may vary according to the discharge. Consequently, we have chosen to measure an angle based on the path direction proposed by Langbein and Leopold (1964), which could be less dependent on discharge and give an average description of the main flow axis. Nevertheless, Piégay et al. (1998) showed on a 4000 m² sampling plot located in the bend of Mollon where LWD were most abundant that the orientation and position of LWD jams changed from one year to another as meander pattern changed. Moreover, other site deposits located downstream from that plot began to register more LWD as jam orientations drastically changed in the

Table 5. Assessment of Linear of Eroded Banks Upstream of Each Concavity

<table>
<thead>
<tr>
<th>Site</th>
<th>Linear of banks observed upstream of each studied reach (m)</th>
<th>Linear of eroded banks observed in the section defined above (m)</th>
<th>Ratio between the eroded linear and the total lineal studied upstream of each concavity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byles</td>
<td>5,200</td>
<td>800</td>
<td>15.40</td>
</tr>
<tr>
<td>Bublame</td>
<td>4,800</td>
<td>1,500</td>
<td>31.25</td>
</tr>
<tr>
<td>Mollon</td>
<td>4,600</td>
<td>2,000</td>
<td>43.48</td>
</tr>
</tbody>
</table>

*Measures were acquired from the map titled "Nature and Morphology of the banks of the Ain river" published in the report of Bravard et al. (1990).
sampling plot with meander pattern modifications. A is a good indicator of preferential LWD deposits but is time specific (event specific) when the meander displacement is rapid.

(2) What is the origin of the LWD deposits? On the Mollon site, the bank is more eroded than those of the other sites and can supply the bend with local wood. The large amount of LWD stored in the Mollon reach could be linked partly to that. LWD that were mobilized could correspond to local debris. One variable also would have been added to the database: the floodplain area per plot eroded between two dates from air photo combinations or using erosion pins in relation with vegetation cover. We observed that bank erosion varied from one plot to another within the Mollon bend, explaining the flood-event specificity of the A angle.

(3) Can this LWD origin be different from one bend to another owing to their specific geometry? This question also may be related to the fact that Blyves was different from the other sites when the type of debris and the local preferential site of deposit were considered. While the jam was the major form of woody deposit in Mollon and Bublane, isolated trunks represented 50% of the deposit at Blyes. Average mass per plot was 11.4 t ha⁻¹ in-bank and 10.1 t ha⁻¹ in-floodplain at Blyes, compared to 35 t ha⁻¹ and 21 t ha⁻¹ at Mollon and 14.2 t ha⁻¹ and 8.7 t ha⁻¹ at Bublane. Compared to less than 38% on the other two sites, 50% of LWD were deposited in the floodplain at Blyes. If these collective facts demonstrate that woody debris originates from different units of the concavity, the work of Harmon et al. (1986) and Bisson et al. (1987) would lead one to believe that LWD would become more important as vegetation units age. Thus, if the LWD were derived from local sources, they should be more important in the tree units than in the shrubbery units. This was not the case on the Aire River.

(4) How can we explain high LWD mass locations? The A angle variability may be the main factor, but in that case, we should register a shift of the preferential sites, as on Mollon, as a spatial trend and not as various wood peaks, as on Bublane or Blyes. The other question is the role of local factors: a tree that falls against the bank during a given flood may trap flowing trees during the next flood. Ephemeral structures such as LWD often explain the local complexity of fluvial forms and processes. This can take place everywhere along bends if trees are present in banks, and also every year.

(5) Why was LWD position within the plots not explained? One question not really analyzed was that of vegetation density. As we did not have enough cases with the same bank height and same angle to highlight the hypothesis of LWD mass differences owing to vegetation density, this analysis was not performed. Moreover, vegetation density varies from one tree unit to another and the vegetation classes chosen in this study might be characterized in a different manner to better identify links between these elements. If we postulate that tree units were more likely than shrub units to stop trunks because they were less flexible, they were also less likely to stop smaller debris. The greater density of individuals in shrub units (3000 to 4000 individuals per hectare) allowed the retention of much smaller debris than tree units (300 to 500 individuals per hectare). This interpretation was validated by the analysis of average mass per deposit, with 140 kg in the Blyes concavity compared to 276 kg at Mollon and 210 kg at Bublane. The Blyes site could effectively filter LWD mass because inputs were of a smaller size than those observed at Mollon or Bublane. This filter effect also varied with respect to both tree density and size of LWD input, the latter controlling vegetation cover along the meander bend.

CONCLUSIONS

In conclusion, this study of large woody debris in the floodplain along three meanders of the Aire River has shown that a high degree of variability exists in the distribution of LWD between different meanders, along the margin of any one meander, and between the bank and floodplain at any one site along the meander. Meander geometry, position along the meander, bank height, and vegetation trapping efficiency provide some explanatory power. LWD accumulations were deposited preferentially along the concave banks of the main channel forming a more or less continuous debris line occasionally breached by overbank flow channels.

Managers in charge of river maintenance contend that preferential sites of LWD deposits are rare on the Aire River, which still is meandering freely and considered to be one of the richest sources of LWD in France. Using air photos and maps, along with an understanding of LWD distribution along the reach, managers should identify preferential sites of LWD deposits according to channel geometry and thereby organize their maintenance actions at selected priority sites.

Riparian forest filters LWD along the concave margins of meandering rivers. At a short distance inland from the bank, the masses are negligible. Conservation or restoration of the forest corridor can thus be an original way to: (1) protect floodplain agriculture against real erosion caused by tree-trunk mobility (Piégay and Bravard, 1997), (2) limit pollutants from bordering agricultural lands from entering the river (Peterson et al., 1992), and (3) maintain a diversified ecosystem (Naiman et al., 1993). LWD abundance along the river margins also can be considered as a floodplain-channel connectivity indicator. The more LWD that is deposited in banks, the lower the banks become and the more they are cut by overbank flow channels.

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