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Influence of large woody debris on the morphology of six central European streams

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Abstract

The impact of large fallen trees on channel form is described for six short stream sections in central Europe influenced by large woody debris (LWD sections), five of which are compared to nearby reference sections free of LWD (reference sections). Three-dimensional models of streambed topography were generated by surveying cross-sections with a spacing of 1 per 1/15 channel width. Parameters derived from digital terrain models and cross-sections compared between LWD sections and reference sections include the extent of pools, bars, and cutbanks, streambed and bank complexity, cross-sectional area, width, depth, and cross-section complexity as described by Andrle's [Math. Geol. 26 (1994) 83] 'angle-measurement-technique' (AMT analysis), a measure of the deviation of a cross-section line from a straight line. Structural diversity is greater in LWD sections at almost all spatial scales, particularly in terms of pool volume (Mann–Whitney *U*-test, $p < 0.01$) and cross-section complexity described by median angle of AMT analysis (Mann–Whitney *U*-test, $p < 0.05$). Large pools are clearly associated with large fallen trees and attain volumes up to 36 m^3. With the exception of the ratio of one LWD section where the fallen tree is oriented parallel to flow, the ratio of pool volume to bed planimetric area ranges from 424 to 693 m^3/ha, which is in the upper range reported for small, high-gradient streams in Oregon, NW America (229–755 m^3/ha) [Can. J. Fish. Aquat. Sci. 47 (1990) 1103]. Pool volume of LWD sections is strongly correlated to the blockage ratio (Spearman rank order correlation, $r_s = 0.93$, $p < 0.01$). Differences in channel morphology between the LWD sections and reference sections indicate a strong morphologic control of large woody debris in these central European stream sections.

Keywords: Large woody debris; Channel morphology; Digital terrain models; Angle-measurement-technique; Central Europe

1. Introduction

The influence of large woody debris (LWD) on stream channel morphology has been studied extensively in small North American streams, but there are few studies from other regions to allow intra-regional comparisons. Keller and Swanson (1979) described general morphological changes generated by LWD for streams in the Pacific Northwest. Subsequent workers from this region observed significant increases in bed load transport after LWD removal (Beschta, 1979; Bilby, 1981; Klein et al., 1987; MacDonald and Keller, 1987; Smith et al., 1993) or the breakage of single log jams (Mosley, 1981). Cross-section width as well as depth and their variability are higher in channel sections with high LWD loading (Keller and Tally, 1979; Hogan, 1987; Fausch and Northcote,

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1992; Nakamura and Swanson, 1993; Trimble, 1997; Buffington and Montgomery, 1999). Murphy et al. (1986), Carlson et al. (1990), and Fausch and Northcote (1992) reported a strong correlation of pool volume and LWD quantity, whereas Evans et al. (1993) found the effect of wood on pool volume to be masked by other geomorphic factors such as a shallow base of bedrock that constrained pool depths.

Comparable investigations are rare for Europe, where the impact of LWD is far less obvious. However, because of very different stream characteristics, forest communities, and management practices, significant differences may be expected from results reported for the North American streams. Gregory et al. (1985) described significant influences of LWD dams on channel morphology in small to medium sized streams in S. England. Piégay et al. (1998) described changes in channel topography and sedimentation in a sixth-order river (Ain River, France) characterised by complex LWD accumulations. LWD accumulations in the French alpine river Drôme were found to be rare and ephemeral, and therefore to have little effect on channel morphology (Piégay et al., 1999). Except for one recent study that quantified LWD-induced changes in channel depth and width in two small central European streams (Gerhard and Reich, 2000), little is known about the impact of LWD on channel morphology in central European streams and rivers.

This study describes small-scale channel morphology of six central European stream sections influenced by single, large fallen trees, and compares five of these sections to reference sections free of large wood. The streams studied can be classified as large streams or small rivers and represent low-gradient meandering lowland streams and lower mountain streams, two of the most common stream types in the northwestern part of Germany. Various parameters derived from digital terrain models (extent of pools, bars, and cutbanks; bed and bank complexity) and cross-sections (area, width, depth, 'angle-measurement-technique' according to Andrle, 1994—a method to measure the deviation of the cross-section line from a straight line) are considered. These parameters are tested to examine potential differences in channel morphology between stream sections with and without large woody debris.

This study focuses on small-scale channel morphology instead of a reach-scale for three reasons. First, morphological features associated with single LWD pieces are easy to interpret. Second, the influence of single, large fallen trees on channel morphology is of special interest because single trees are increasingly used in central European river rehabilitation projects to enhance structural diversity. Third, appropriate study stream sections with high LWD loadings on a reach-scale are rarely found in central European streams.

2. Study streams

Because of the long-lasting human impact and the management of riparian forests, large fallen trees are rarely found in central European streams. Stream managers usually remove LWD from streams for flood control reasons. However, some single logs impacting streams can still be found in remote areas.

Six stream sections, most of which are located in Northrhine-Westphalia (Germany) (Fig. 1), were selected for this study. Three of the study stream sections (Lippe, Berkel1, Berkel2) are located in the lowlands of Northrhine-Westphalia, in low-gradient river plains dominated by Holocene sediments and Quaternary sands. Three streams (Ahr, Möhne, Berg. Land) are located in lower mountainous areas, primarily consisting of argillaceous shale.

For five of the study streams, a section influenced by one to three fallen trees (LWD section) and a nearby reference section without LWD were selected (for details concerning the selection of reference sections, see Section 3.1). No comparable reference section could be found within the short restored reach of the Lippe River in which the LWD section is located. Stream morphology up and downstream of this reach is heavily modified by human and thus not comparable to the restored reach. Investigations were, therefore, restricted to the LWD section. The large fallen tree, the impact of which was investigated in the Berg. Land stream section, is located in the upper part of a mid-channel bar. Because no similarly wandering reference section could be found in the vicinity, the channel on the right side of the bar was used as a reference section. This was possible because the obvious effects of the fallen tree are restricted to the channel on the left of the bar. The study streams (LWD sections and reference sections) are character-

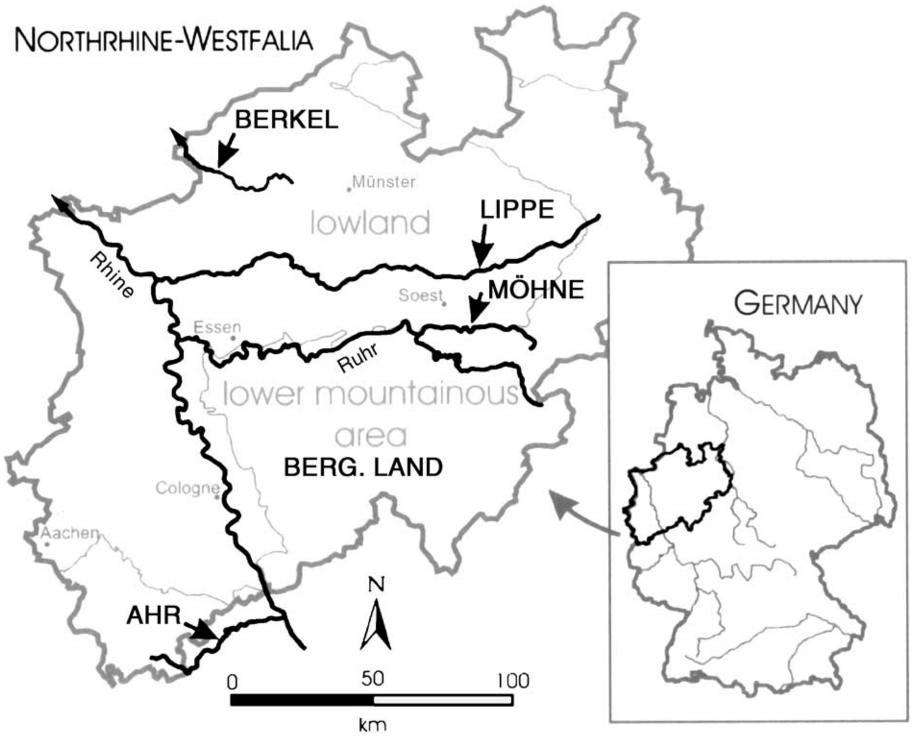

Fig. 1. Location of the study streams in Northrhine-Westphalia and Rhineland-Palatinate (location of the Ahr study stream), Germany. The author is under a legal obligation not to exactly locate the Berg. Land stream section.

ised in Table 1. In order to further illustrate the characteristics of LWD sections, a photo of the Berkel1 LWD section is given in Fig. 2.

3. Methods

3.1. Experimental design

The impact of large fallen trees on small-scale channel form is described by comparing channel morphology of stream sections influenced by large woody debris (LWD sections) with nearby reference sections free of LWD (reference sections).

The LWD sections were demarcated based on the extent of the large fallen tree(s) and the morphological features (pools, bars, cutbanks, channel widening) in the area of the fallen tree(s) that were visible or detectable by wading. Because demarcation of morphological features in the field was difficult, areas up and downstream of these sections were mapped to ensure complete portrayal of these morphological features. Investigating longer stream sections would enclose areas not influenced by the fallen tree(s) and, thus, distort the results because parameters describing channel morphology are related to bed planimetric area.

LWD sections are some tens of meters in length and are located in specific areas of the channel reach (e.g., a single riffle; half a meander wavelength; deeply entrenched, straightened section). Therefore, comparable stream sections free of large wood were chosen as reference sections rather than randomly chosen sections, which would enclose geomorphological features different from the LWD sections. Because of the high variability of channel conditions (e.g., riparian vegetation, slope, discharge, bedrock confinement, riprap), choosing a reference section as similar as possible to the LWD section seemed more appropriate than investigating a greater number of 'reference sections' (e.g., several riffles) to quantify the variability of the specific channel area.

Table 1
Data on the investigated stream sections and the investigated large woody debris (LWD), RS = reference section, LWD = LWD section

Study streams	Berkel1		Berkel2		Ahr		Möhne		Berg. Land[a]		Lippe
	RS	LWD	RS	LWD	RS	LWD	RS	LWD	RS	LWD	LWD
Stream characteristics											
Catchment area (km^2)	247.5		247.5		538		275		180.5		1906
Mean section width (m)	12.0	17.8	15.4	16.8	22.7	31.3	18.1	20.3	18.1	16.0	40.5
Slope of water level (%)	0.05	0.07	0.05	0.05	0.3	0.1	0.2	0.2	0.1	0.6	0.04
Length (section mapped, m)	28.0	50.5	33.5	28.5	41.8	67.0	38.0	54.0	30.0	30.0	44.0
Stream type	lowland		lowland		lower mountain		lower mountain		lower mountain		lowland
Bed material	sand		sand		gravel/ cobble/ boulder		gravel/ cobble		gravel/ cobble		sand/silt/ marl
Bank material	sand		sand		gravel/ cobble/ boulder		clay		gravel/ cobble/ clay		sand/silt
Riparian vegetation	sparse poplar		sparse poplar		sparse poplar, willow		sparse alder, willow, ash		dense beech, oak, alder		sparse willow
Section sinuosity	straight		straight		straight		meander		straight		bend
Peculiarity of section	deeply entrenched		deeply entrenched		riffle		meander		near-natural		bend
Bank line riprap (bank line length %)	50	10	0	0	0	20	30	30	0	0	0
LWD characteristics[b]											
Date of input[c]	1998		1995		01/1999		03/1998		not known		1997
Diameter at breast height (cm)	75/65/65		50/75		115		40/60		125		75
Horizontal orientation (°)[d]	100/115/115		85/0		75		90/65		95		0
Vertical orientation[e]	ramp/ramp/on bed		ramp/bank		on bed		ramp/ramp		above bed		on bed
Individual tree volume (m^3)[f]	7.19/4.14/3.55		2.13/2.44		5.4		1.1/5.14		12.34		9.68
Length/channel width	>1		>1		~ 0.7		>1		>1		~ 0.3
Blockage ratio[g]	0.48		0.13		0.21		0.36		0.34		0.05
Root-wad anchored in bank	no/yes/yes		yes/no		no		yes/yes		no		cabled
LWD input	natural		natural		natural		natural		natural		restoration project
Discharge (m^3/s)											
Mean annual discharge											
Mean low flow	0.368		0.368		0.458		0.847		0.472		7.09
Mean discharge	2.83		2.83		4.78		4.22		3.39		23.98
Mean high flow	31.4		31.4		74.2		42.1		46.0		110.4
Peak flow	59		59		149		96		112		178
Discharge since LWD input[h]											
Mean low flow	0.471		0.347		mean discharge data not available		0.782		date of LWD input not known		6.84

Table 1 (*continued*)

Study streams	Berkel1		Berkel2		Ahr		Möhne		Berg. Land[a]		Lippe
	RS	LWD	RS	LWD	RS	LWD	RS	LWD	RS	LWD	LWD
Discharge since LWD input[h]											
Mean discharge	3.80		3.10				4.31				24.08
Mean high flow	43.2		32.7				39.6				113.2
Peak flow	48		48				51				178
Peak flow recurrence interval (year)	10		10		2		5				10

[a] The author is under a legal obligation not to exactly name the stream investigated.
[b] LWD characteristics are given for individual trees (several values) or for entire LWD (single value).
[c] Date of LWD input is assessed by means of a consultation of local stream managers, stream ecologists and residents.
[d] Horizontal orientation according to Robison and Beschta (1990a) with 0° the root-wad pointing upstream, 90° perpendicular to flow and 180° the root-wad pointing downstream.
[e] Vertical orientation was classified: ramp position, root-wad inside the channel and the other end supported on the opposite bank- on bed, resting on the stream bed- bank, LWD lies between top of bank and mean water level parallel to flow-above bed, inside the bank-full channel but completely above low-flow water level.
[f] Tree volume inside bank-full channel.
[g] Blockage ratio is the cross-sectional area blocked by LWD according to Gippel et al. (1996).
[h] Discharge data since LWD input are not available for the year 2000 at the Berkel and Möhne study streams.

3.2. Field investigations

Topographic data were acquired in July/August 2000 using a Leica TCRA1103 electronic total station. Some pools were not wadable and were mapped using a small boat.

A preliminary investigation was carried out with the aim to determine topographical survey point densities necessary for an accurate description of mesoscale stream morphology. The original data set of the Ahr LWD stream section with a point density of 3.1 points/m^2 (which is assumed to represent mesoscale mor-

Fig. 2. Downstream view at the Berkel1 LWD section at mean flow. Two large fallen trees in the foreground are mainly submerged at mean flow; tree with root-wad in the background is located above mean flow water level.

phology) was progressively thinned to a density of 0.5 points/m^2. Terrain models were computed for each data set and compared to the original surface (Fig. 3). No clear limit was noticeable, but errors increase rapidly when point densities are < 1 points/m^2. Therefore, survey points were measured at a distance of ~ 1/50 channel width (~ 0.3 m) in cross-sections with a spacing of about 1/15 channel width (maximum spacing < 1 m) to ensure point densities >1 points/m^2. Topographic breaks in slope of particular geomorphological importance (e.g., bank top, cutbanks, extent of pools) were measured separately.

In some zones, measurement was not possible (e.g., areas covered by dense vegetation, debris accumulations or wood accumulations). Therefore, point density varies slightly between LWD and reference sections of most study streams. Differences in point densities between LWD sections and corresponding reference sections are less than 10%, except the Möhne stream (29%). In the Möhne LWD section, dense overhanging limbs of riparian trees that could not be cut partly covered the stream and hindered measurement of a larger number of survey points, resulting in a comparatively low point density. Point densities range from 1.4 to 3.1 points/m^2 depending on the cross-section spacing.

The circumference of the large fallen trees was measured at several points of the stem and the main limbs using a measuring tape. Approximate date of input and input mechanism (natural, restoration project) were determined by means of a consultation of local stream managers, stream ecologist, and residents.

Water surface slope was determined by hydrostatic levelling. Due to the afflux caused by the large fallen trees, slope at some LWD sections is high compared to the corresponding reference sections. Therefore, channel sections both upstream and downstream of the sections investigated were included in water level measurements, in order to describe mean channel slope rather than the drop in water level associated with the large fallen trees.

3.3. Terrain models

Three-dimensional terrain models were computed from the field data using the GIS ‘‘ArcView 3D-Analyst’’ to describe the stream morphology of LWD sections and reference sections (Fig. 4). Surfaces were created as triangulated irregular networks (TINs) following Lane et al. (1994) and Milne and Sear (1997) using the topographic breaks measured separately in the field.

The extent of pools and bars was determined according to Beebe (1997). Parts of the stream bed at least one standard deviation below the mean depth are defined as pools. Conversely, parts of the stream bed at least one standard deviation above the mean depth of the streambed are defined as bars. Pool and bar volume was computed for single morphological features using the ArcView 3D-Analyst tool ‘‘Area

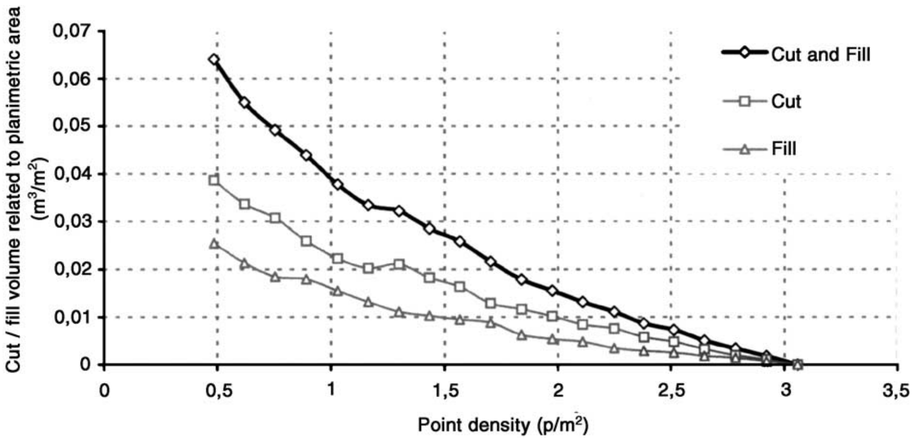

Fig. 3. Terrain model surface error (per unit stream area) against survey point density.

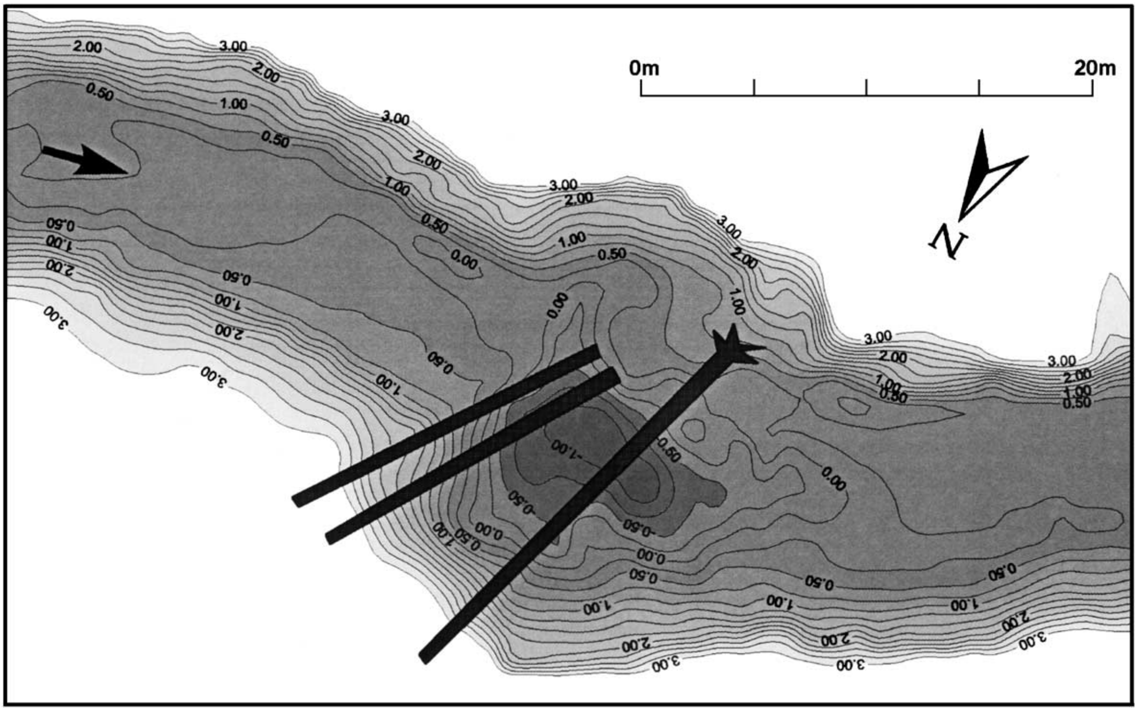

Fig. 4. Contour map of Berkel1 LWD section three-dimensional model. Height above/below mean streambed height is given in meters. Streambed area one standard deviation above/below mean depth of streambed (0.5 m) is defined as bar and pool, respectively. Pool is located downstream of the first large fallen tree, which is located on the streambed. Sketch of the large fallen trees is not to scale; flow is from left to right.

and Volume Statistics". Pools and bars were classified according to Church (1992).

Nonvegetated areas of the bank steeper than 65° and above the mean water level were defined as cutbanks. The outlines of these cutbanks usually correspond to topographic breaks measured in the field.

Because the length of the bank is highly dependent on the scale considered (Andrle, 1994), these linear features were standardized to the accuracy of the field data, which is the same at all stream sections (point density about 0.3 m at bank-top break lines).

3.4. Cross-sections

The terrain models indicated cross-sections measured in the field were not exactly perpendicular to the channel, especially in zones of high structural diversity caused by LWD where the channel direction could not be accurately determined in the field. Because some channel-related parameters (e.g., cross-section width) depend on the exact perpendicular orientation of the cross-sections, they were not based on measuring points but derived from the terrain models with a spacing of 1 m (corresponding to accuracy of field data, 16–53 cross-sections per stream section). For this purpose, the ArcView extension "Profile Extractor" was used. In addition, the following parameters were calculated: area (cross-sectional area), horizontal

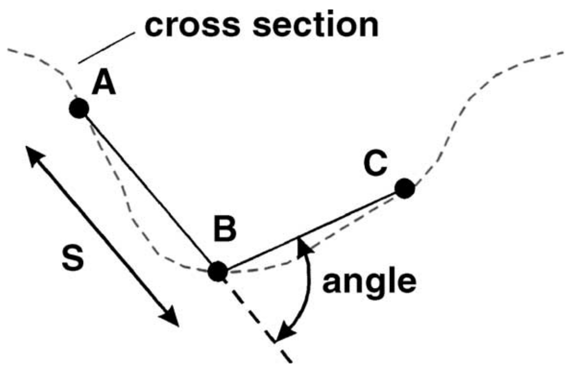

Fig. 5. Measurement of cross-section angle for AMT-Analysis.

Table 2
Qualitative and quantitative description of morphological features present at LWD sections (LWD) and reference sections (RS); absolute size of morphological features and volume of pools/bars related to bed planimetric area and area of cutbanks related to section length are given; based on the close proximity to the large fallen trees, their shape and visually observed flow patterns, some morphological features are classified as 'clearly associated with LWD'

Stream section	Morphological feature	Volume (m^3)	Planimetric area (m^2)	Maximum depth/height (cm)	Surface area (m^2)	Pool/bar volume (m^3/ha)	Cutbank area (m^2/100 m)	Clearly associated with LWD
Berkel1 LWD	pool	16.8	51.4	75		593.5		+
	side bar	~ 2	~ 21	~ 22		53.0		
	cutbanks				20.7		86.6	+
					13.4		56.1	+
					3.3		13.8	+
Berkel1 RS	pools	0.4	5.3	20		20.1		
		0.3	6.4	17		15.1		
		0.3	12.1	11		15.1		
		0.06	3.5	3		3.0		
		0.03	1.3	9		1.5		
		0.006	0.8	1		0.3		
	side bar	~ 0.5	~ 12	~ 31		20.1		
Berkel2 LWD	pools	7.2	26.6	60		247.6		+
		5.6	19.5	89		192.6		+
	mid-channel bar	3.1	16.9	41		106.6		+
	cutbank				30.7		107.7	+
Berkel2 RS	pools	1.1	23.3	7		41.1		
		0.4	10.4	11		14.9		
		0.2	7.2	2		7.5		
	mid-channel bar	0.1	4.8	8		3.7		
Ahr LWD	pool	35.9	163.9	54		423.8		+
	mid-channel bars	2.9	28.3	23		34.2		+
		2.6	19.5	66		30.7		+
		1.4	19.1	29		16.5		+
		0.2	6.1	10		2.4		+
		0.04	1.8	6		0.5		
Ahr RS	pool	15.9	116.7	56		226.1		
	side bar	~ 4	~ 24	~ 38		55.5		
Möhne LWD	pools	59.6	143.1	98		692.7		
		0.5	11.4	16		5.8		
	point bar	~ 49	~ 154	~ 87		568.3		
	cutbank				94.8		171.4	
Möhne RS	pools	20.2	97.3	53		382.8		
		4.5	21.3	59		85.3		
	point bar	~ 12	~ 43	~ 76		223.6		
	cutbank				67.6		177.4	
Berg. Land LWD	pool	11.8	37.3	70		516.2		+
	mid-channel bar	0.2	3.6	12		8.7		
	side bar	~ 3	~ 8	~ 104		109.4		+
	island	7.7	31.7	44		336.9		
Berg. Land RS	pool	8.0	37.3	65		321.1		
	mid-channel bar	0.08	5.6	4		3.2		
	island	9.6	25.7	60		385.3		
Lippe LWD	pools	9.3	96.5	38		58.0		
		3.5	44.2	25		21.8		
		1.7	21.1	21		10.6		+
		0.5	16.5	10		3.1		
		0.3	11.2	7		1.9		

Table 2 (*continued*)

Stream section	Morphological feature	Volume (m^3)	Planimetric area (m^2)	Maximum depth/height (cm)	Surface area (m^2)	Pool/bar volume (m^3/ha)	Cutbank area (m^2/100 m)	Clearly associated with LWD
Lippe LWD	pools	0.1	4	5		0.6		
		0.08	6.1	5		0.5		
		0.04	3.4	3		0.2		
		0.02	2.1	3		0.1		
	point bar	~ 28	~ 215	~ 27		172.7		
	mid-channel bar	5.6	61.2	28		34.9		+
	cutbank				26.1		59.0	

length (width), and maximum depth. Cross-section depth values, calculated with a spacing of 0.1 m by the extension "Profile Extractor", were used to calculate mean depth. Channel dimensions were determined for the cross-sections at bank-full stage, which can be defined as the point where a break in the slope of the banks occurs and water begins to flow onto the floodplain (Wolman and Leopold, 1957).

3.5. AMT analysis

To describe the complexity of cross-sections at different spatial scales, the angle-measurement-technique (AMT) was used following Andrle (1994) and Nestler and Sutton (2000). An Avenue script was written to perform AMT analysis in ArcView using the cross-sectional data computed by the extension "Profile Extractor". A starting point A along the cross-section is randomly chosen. The point of intersection B between a line of length S beginning at point A and the cross-section is calculated. This process is repeated beginning at point B. The angle between the two lines is calculated (Fig. 5). For each scale S, a sample of 500 angles is stored, which was found to be sufficient to produce minimal error while still keeping computational time to a reasonable level (Andrle, 1994). The mean angle describes the extent to which the cross-section deviates from a straight line at the given scale S. More complex cross-sections, therefore, have greater mean angles.

Because mean angle increases markedly with the entrenchment of the channel, AMT analysis was restricted to the streambed. Otherwise, differences in entrenchment of the streams would mask differences in streambed morphology. The influence of the large fallen trees on channel entrenchment was not investigated. Only values of S greater than the accuracy of the field data (survey point spacing in cross-sections of about 0.3 m) were used for analysis.

4. Results

4.1. Terrain models

Large pools are associated with the large fallen trees in all LWD sections except the Lippe (Table 2). Median pool volume (m^3/ha) is higher in the LWD sections than in reference sections (Mann–Whitney U-test, $p<0.01$, $n=29$). Differences are greatest in the LWD sections of the lowland streams Berkel2 and Berkel1, which have pool volume of 7 to 11 times that of the reference sections. Several small pools are present in the reference sections, and one to two large pools in the LWD sections. In spite of the later date of LWD input, pool volume is markedly higher in the Berkel1 LWD section, which is possibly due to the higher blockage ratio (Table 1).

Differences are less apparent in the mountain stream sections (1.5 to 2 times the pool volume of reference sections), where bend scour pools (Möhne), trench pools (Berg. Land), and a deep thalweg (Ahr) are present in the reference sections.

Volume of sidebars and point bars is largely dependent on the delineation of riverbed and banks. Small differences in the extent of riverbed and banks result in large differences in bar volume. Therefore, only clearly identified bars (mid-channel bars) are considered. Mid-channel bars that are discernible in the terrain models are restricted to LWD sections of the Berkel2, Ahr, and Lippe. The mid-channel bar volume is 29 times higher in the Berkel2 LWD section compared to the corresponding reference section. In the Ahr, several bars formed downstream of the large fallen tree. The same is true for the zone between the LWD and the outer bank at the Lippe. No mid-channel bars (Berkel1, Möhne) or bars of marginal extent (Berg. Land) are present in the other stream sections.

The occurrence of cutbanks is restricted to LWD sections of the lowland sand bed streams (Berkel1, Berkel2, Lippe) and the outer bank of the stream sections at the meandering lower mountain stream (Möhne). Cutbank area is nearly the same in the Möhne study sections indicating that the large fallen trees at the LWD section did not increase cutbank area.

Increase in streambed surface area compared to planimetric area indicates topographic complexity of the streambed. High values indicate a rough streambed surface and, therefore, high form drag (Buffington and Montgomery, 1999). All streams except the Möhne show an increased stream bed surface area compared to planimetric area in the LWD sections (Fig. 6). In the Möhne, meander morphology leads to a high value at the reference section. The differences are most obvious in the lowland streams (Berkel1 four times, Berkel2 seven times higher than reference sections) and the lower mountain stream Ahr (four-fold higher).

Increase in bank line length compared to section length is a measure of bank line complexity. Bank line length is higher at all LWD sections compared to the corresponding reference sections (Fig. 7) except for the Möhne stream section where a large curve in the downstream part of the reference section lengthens the bank considerably. By far the highest values are found at the Berg. Land stream, which is probably due to the near-natural condition of this reach. Differences between LWD sections and reference sections are due to the channel widening induced by LWD (lowland stream Berkel1 and Berkel2, respectively, 2- and 1.6-fold higher in LWD section) and a curve in the shoreline caused by the uprooting of the tree and further bank erosion at high flow (lower mountain stream Berg. Land, 1.7-fold higher than reference section). The cause of the increase in bank length at the Ahr LWD section (1.6-fold higher) is not apparent.

4.2. Cross-section parameters

Considering the quartiles of all values, a distinct increase in variability of cross-sectional area was

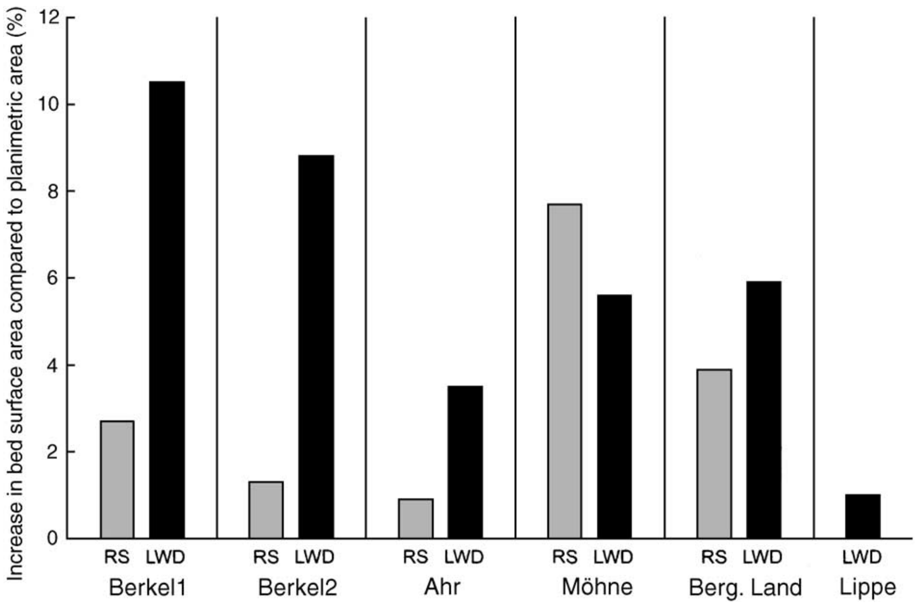

Fig. 6. Increase in bed surface area compared to planimetric area (%). RS = reference section, LWD = LWD section.

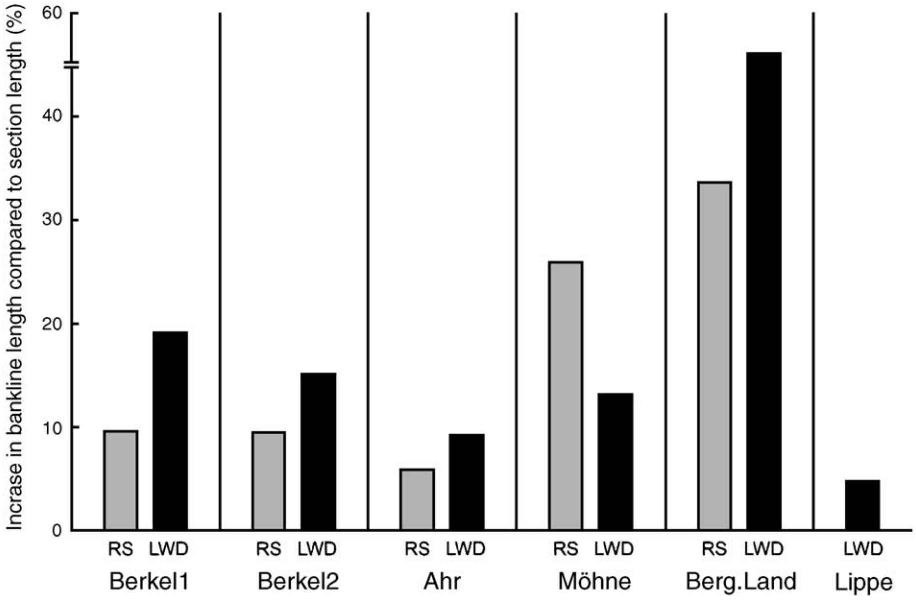

Fig. 7. Increase in bank line length compared to section length (%). RS = reference section, LWD = LWD section.

noted at the Berkel1 LWD section (Fig. 8A). Here, widening of the channel caused by bank erosion and a deep scour pool increased the area of single cross-sections dramatically. Differences are less pronounced at the Berkel2, Ahr, and Berg. Land streams and are marginal at the Möhne. Median cross-sectional area is greater at the lowland sand bed LWD stream sections Berkel1, Berkel2, and at the lower mountain stream Berg. Land (Mann–Whitney U-test, $p < 0.01$).

Differences in variability of cross-sectional area between LWD sections and corresponding reference sections at the lower mountain streams Ahr and Berg. Land are due to the wide range of channel depth values. In addition to channel depth, higher variability of stream width at the LWD sections causes differences in cross-sectional area variability at the lowland sand bed LWD stream sections Berkel1 and Berkel2 compared to corresponding reference reaches (Fig. 8B–D). At the Möhne stream, only the variability of stream width is considerably higher at the Möhne LWD section compared to the reference section (Fig. 8B). Median cross-section width is higher at all LWD sections compared to the corresponding reference sections, except the Berg. Land stream (Mann–Whitney U-test, $p < 0.01$). Here, at the right side of the mid-channel bar where the reference section is located, widening of the channel in the lower part increases stream width.

Variability of maximum depth can be considered to be a measure of thalweg complexity. Differences between LWD sections and reference sections are most striking at the lower mountain streams (Ahr and Berg. Land), considerable at the Berkel stream, and small at the Möhne stream (Fig. 8C). This is also true for the variability of mean depth, which indicates that pools in some LWD sections cover a large part of the cross-sections and are not restricted to a narrow thalweg (Fig. 8D). Median cross-section depth is greater at the lowland sand bed streams Berkel1, Berkel2, and at the lower mountain stream Berg. Land (Mann–Whitney U-test, $p < 0.05$).

The differences in variability of cross-section parameters between LWD sections (sample A) and reference sections (sample B) was tested using the interquartile coefficient as a measure of dispersion. Variability of cross-section area and cross-section maximum depth is higher at the LWD sections (Mann–Whitney U-test, $p < 0.05$, $n = 10$), whereas variability of cross-section width, mean depth, and width/depth ratio show no significant difference.

Variability and median of width/depth ratio do not differ between LWD sections and corresponding refer-

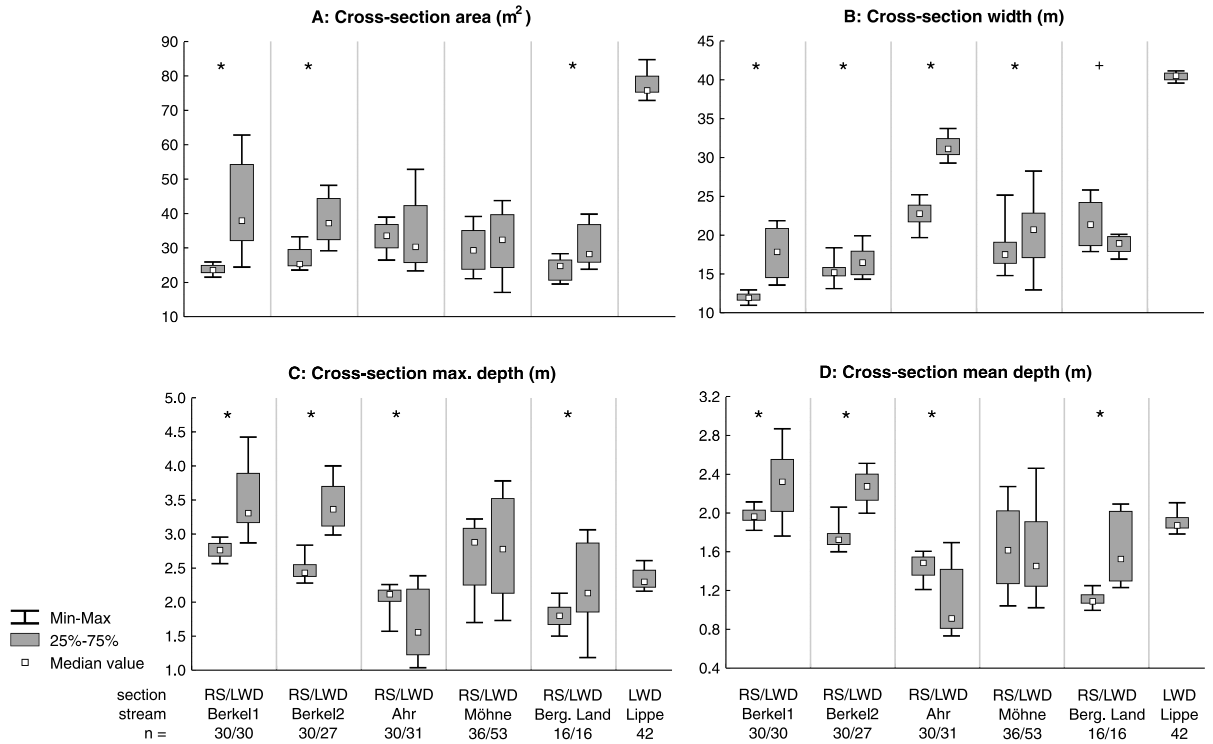

Fig. 8. Variability and median of cross-section parameters (A: area; B: width; C: maximum depth; D: mean depth) at reference sections (RS) and LWD sections (LWD). Min–Max, 25–75%, and median are shown; n = number of cross-sections investigated, * = significant differences between LWD section and corresponding references section (Mann–Whitney U-test, $p < 0.01$), + = significant differences between LWD section and corresponding reference section (Mann–Whitney U-test, $p < 0.05$).

ence sections, except the Ahr stream, in spite of an evident change in channel morphology. Low variability of width/depth ratio at the LWD sections is probably due to the simultaneous increase in width and depth because of bank and bed erosion. Hence, width/depth ratio is considered to be an inappropriate measure to describe the effects of LWD on channel morphology at the stream sections investigated in this study.

4.3. AMT analysis

Median angle of each spatial scale S was calculated based on cross-sectional mean angle data for each stream section (Fig. 9). The median angle of LWD sections is significantly greater compared to the reference sections at all scales, with the exception of the 30-, 40-, 70-, and 80-cm scales (Mann–Whitney U-test, $p < 0.05$).

Stream sections may be roughly grouped into three categories (Fig. 9). Group A consists of Ahr, Berkel1, and Berkel2 reference sections and the Lippe LWD section, which all have a relatively flat stream bed. Median angle is low (2–4°) and decreases slightly at larger scales. Group B consists of the Berg. Land reference section and shows an increase in median angle up to almost 6° at the scale of 80 cm and a slight decrease at larger scales. Group C consists of the Möhne LWD section and reference section as well as the Berg. Land, Ahr, Berkel2, and Berkel1 LWD sections.

Median angle increases with scale at the Möhne stream sections, whereas values seem to approximate to angles ranging from about 7–9° at the other study sections at larger scales. Increase of median angle at lower scales is highest at Berkel1 and Berkel2 LWD sections. Differences between these two curves at

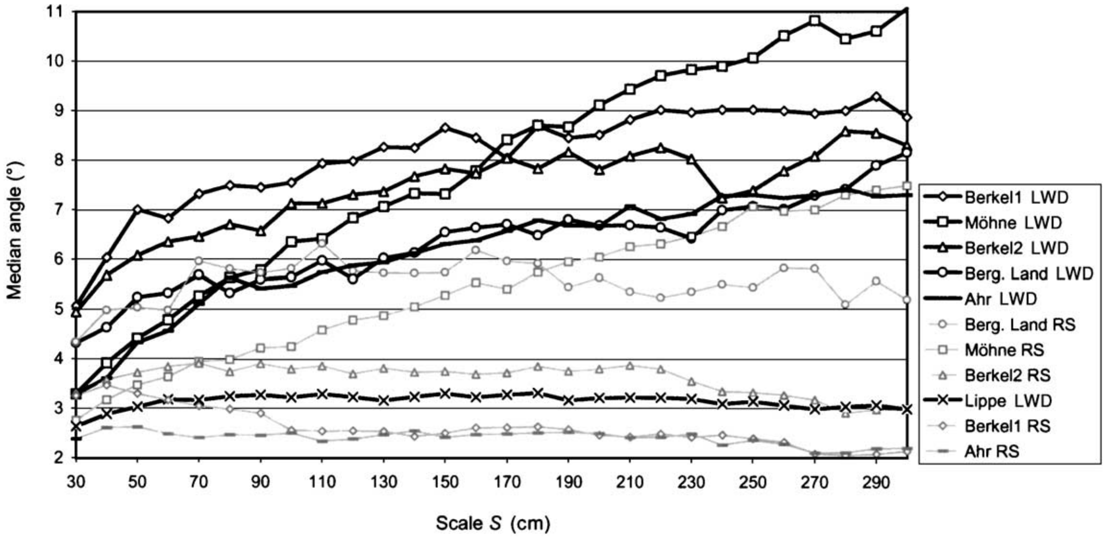

Fig. 9. Median of mean angle of cross sections at scales *S* ranging from 30 to 300 cm. Study sections in legend are listed according to the mean angle over all scales *S*. RS = reference section, LWD = LWD section.

larger scales are probably due to the larger and deeper pool at the Berkel1 LWD section.

In comparing LWD sections with the corresponding reference sections, greater median angles at the LWD sections are statistically significant for the Berkel1, Berkel2, Ahr, and Möhne stream sections at all scales. Differences in the near-natural Berg. Land stream sections are statistically significant only for the largest scales investigated (280, 290, and 300 cm), where median angle is low at the reference section (Mann–Whitney *U*-test, $p < 0.05$).

This is probably due to the overall form of the pools, with a circular pool at the LWD section and a narrow trench pool at the reference section (short axis of the trench pool parallel to cross-sections). Therefore, lines AB/BC of AMT analysis can span the entire pool at larger scales, resulting in lower mean angles at the reference section.

4.4. Relationship between stream morphology, LWD, and stream characteristics

The relationship between stream morphology (pool volume, pool area, mid-channel bar volume, mid-channel bar area, cutbank area, related to bed planimetric area; maximum pool depth, bed and bank line complexity, median angle of AMT analysis over all scales *S*), LWD characteristics (blockage ratio, channel volume blocked by LWD volume, horizontal orientation, vertical angle, mean height above bed, diameter at breast height, time since LWD input), and stream characteristics (slope, catchment area, width, power per unit width) was assessed by Spearman correlation analysis because of the nonnormal distribution and low number of cases ($n = 6$).

Pool volume of LWD sections is strongly correlated to the blockage ratio ($r_s = 0.93$, $p < 0.01$), which indicates that blockage ratio is one important parameter determining the hydraulic and, therefore, morphological influence of large fallen trees, as stated by Gippel et al. (1996). Not surprisingly, channel width is strongly correlated to catchment area ($r_s = 0.98$, $p < 0.01$). No other correlations were found to be significant for the variables examined in this study.

5. Discussion

5.1. Power of parameters to describe change in channel morphology

Differences between LWD sections and reference sections were described using a wide range of parameters, derived from both terrain models and cross-sections (extent of morphological features; bed and bank complexity; cross-sectional area, width, maximum depth, mean depth; AMT analysis; see Section 4). However, only differences in distinct morphological features such as pools, bars, and cutbanks could be detected. This is due to the experimental design of comparing LWD sections with reference sections. Long-term studies (e.g., survey of several years) are necessary to examine less evident morphological features, such as large, flat, depositional areas.

5.2. LWD characteristics

It can be assumed that nearly all trees investigated are located where they entered the channel and changed little in position because either (1) they are still anchored in the bank with their root-wad, (2) the cutbank caused by the uprooting of the tree remains in close vicinity to the tree, or (3) the position of the tree is known because it was placed in the stream within the scope of a restoration project or was observed by local stream managers, ecologists, or residents. Moreover, most trees that entered the channel naturally are oriented nearly perpendicular to flow (deviation from perpendicular $\pm 25°$), which indicates that trees did not rotate at high flows (e.g., Q_2 to Q_{10} floods which have been recorded since the wood entrance). In addition, remapping of the tagged points on trees in 2001 revealed no change in position. Only one tree can be considered to be driftwood (Berkel1, tree oriented parallel to flow). Therefore, it can be inferred that the impact of LWD on channel morphology changed little over time and LWD characteristics listed in Table 1 represent LWD conditions that influenced channel morphology since LWD input. However, wood and debris accumulations trapped by the trees could have formed and disappeared or changed during floods, and have transiently increased or changed blockage ratio and the impact on channel morphology.

Besides anchoring of root-wads in stream banks, stability of trees investigated that naturally entered the channel is enhanced by length of trees compared to channel width which is greater than or equal to two-thirds of the channel width. Flume studies of Braudrick and Grant (2000, 2001) showed that presence of root-wads, length, and diameter of trees increase the stability of logs. Bryant (1983) and Lienkaemper and Swanson (1987) observed that trees considerably longer than channel width result in relatively stable wood pieces. Gurnell and Gregory (1995) also observed that deciduous trees, which fall into the channel, are often anchored in the bank by their root-wad.

LWD mass in European streams is low compared to wood loading in North America, but we can expect that it could be comparable in reaches where the human impact is reducing (Elosegi et al., 1999; Piégay et al., 1999; Hering et al., 2000; Diez et al., 2001). In central European streams similar to those investigated in this study, large fallen trees of comparable size are extremely rare (Hering et al., 2000). The main reasons for the low LWD loading in the streams investigated are sparsely vegetated banks (Fig. 2) and the removal of LWD by stream managers. Even in nature reserves stream managers are under a legal obligation to remove LWD if it is considered to be a flood risk to works downstream. Due to changes in EG agricultural policy and nature conservation laws, extensive farming on floodplain areas becomes more common. Therefore, in some exceptional cases, large fallen trees are left in the channel. Considering the impact of the large fallen trees investigated on channel morphology, it can be assumed that channel morphology of these streams is far from that which characterizes the potential natural state.

5.3. Comparing observed scour patterns with those described in literature

The pool at the Ahr LWD section is located directly upstream and to the side of the large fallen tree that lies perpendicular to flow in the middle of the channel. Mid-channel bars consisting of fine gravel accumulated downstream of the tree. This scour pattern is very similar to those described by Abbe and Montgomery (1996) for LWD jams at the apex of bars in a large alluvial river. This is possibly a typical scour pattern at LWD obstructions located on the streambed in the middle of the channel, either nearly perpendicular or parallel to flow, if peak flows do not overtop the obstruction.

Cherry and Beschta (1989) and Hilderbrand et al. (1998) observed that different scour patterns depend on angle to flow and vertical angle of logs. Scour at the Berkel1 LWD section occurs downstream of one of the large fallen trees, which is oriented perpendicular to flow (Fig. 4). This scour pattern can be classified as a plunge pool according to terminology of Robison and Beschta (1990b) and corresponds to the scour pattern described by Hilderbrand et al. (1998) as perpendicular dam. Moreover, the pool in the Berg. Land LWD section can be described as an underflow pool (Robison and Beschta, 1990b). No other scour pattern associated with the single, large fallen trees investigated in this study corresponds to those described by the authors mentioned above.

5.4. Assessing the morphological influence of single, large fallen trees investigated

Pool volume of the LWD sections investigated is well within the upper range of pool volume found in some small, high-gradient streams in Oregon, NW America, where pool volume ranged from 229 to 755 m^3/ha (Carlson et al., 1990). Single, large fallen trees can, therefore, be considered to be capable of increasing pool volume locally to an extent comparable to North American conditions even in low-gradient central European streams.

Differences between LWD sections and reference sections are most striking in the lowland sand bed Berkel stream. This is true not only for bed morphology (e.g., pool volume, bed complexity) but also for stream bank morphology (cutbank area, bank complexity, variability of cross-section width) and cross-section complexity (AMT analysis). Some rare habitat types (e.g., deep pools, which are used as rearing habitat for certain fish species; Fausch and Northcote, 1992; Spalding et al., 1995; Young, 1996) are restricted to the immediate vicinity of large fallen trees.

In the lower mountain streams, morphological channel changes caused by large fallen trees are pronounced, but less evident on the stream banks. This is probably due to resistance of bank material and low entrenchment (e.g., cutbank area increases with channel entrenchment). Meander morphology and local geomorphic controls such as local geology are likely to mask the influence of LWD on channel form, as suggested by Evans et al. (1993) and Hilderbrand et al. (1997).

The effect of the single, large fallen tree on channel morphology at the Lippe (by far the largest study stream) is low compared to those on the other study streams. This is probably due to low blockage ratio (0.5%), which depends on stream size and the orientation of the log parallel to the banks. Nevertheless, two distinct morphological features (small pool, small mid-channel bar) are clearly associated with the large tree in the Lippe channel (Table 2).

Considering the extent of morphological features at LWD sections compared to reference sections, the effect of the large fallen trees on channel morphology is evident in most study streams (Table 2, Figs. 6–9). Although sample size of paired sections is small ($n = 5$) and reference sections vary in structural diversity, the differences between LWD sections and reference sections are statistically significant for some parameters (pool volume, median angle of AMT analysis).

However, morphological changes were not observed directly. Therefore, differences in structural diversity between LWD sections and reference sections could partly be caused by morphological differences that existed prior to LWD input. Comparability of LWD sections to reference sections is limited by differences in bank line riprap (Berkel1, Ahr) and slope (Ahr, Berg. Land). Bank line riprap at the Berkel1 and Ahr reference sections consists of loose boulders and building rubble, which possibly hinders lateral erosion. However, lateral erosion does not occur at the Berkel2 reference section, which is free of bank line riprap and comparable to the Berkel1 stream sections.

Five of the study streams were remapped in 2001. Provisional results show that considerable changes in channel morphology occurred in all LWD sections, except for the Berg. Land stream, indicating that channels are still adjusting to the presence of the large fallen trees. Some of the channel features that were present at the first mapping period in 2000 developed (e.g., pools got deeper, sidebars expanded), but others diminished (e.g., pools filled, mid-channel bars eroded). Although channel morphology before the first mapping in 2000 and prior to LWD input is not known, and morphological changes observed over a 1-year period may not be representative in the longer term, it is hypothesized that there is no clear trend towards an equilibrium state of channel morphology. Dynamic feedback between flow produced by the large fallen trees and channel morphology may result in changing trends of morphological development.

Because changes in channel morphology are highly dynamic (as remapping in 2001 suggests), and morphological differences described are strongly dependant on channel conditions (channel morphology, discharge, sediment supply) and LWD characteristics, transferability of the results is limited. However, given similar channel conditions and LWD characteristics, differences between LWD sections and stream sections free of large wood of the same order of magnitude are to be expected in central European rivers.

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