Geomorphic Effects of Large Wood in Streams and Rivers and Its Use in Stream Restoration: A Central European Perspective

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1 Introduction

1.1 The need for stream and river restoration

Streams and rivers are fundamental parts of the landscape in temperate ecoregions. Because of their elongated, linear form, they link many other aquatic ecosystems like lakes or the marine environment and are additionally connected to terrestrial ecosystems through long stream and river banks. They are the main routes of transport for water, suspended sediment, and solid matter on the earth's surface. The direction of flow and transport is essentially uni-directional and horizontal in nature (from headwater streams to the see) compared to other ecosystems like forests and lakes. But streams and rivers are also connected to other ecosystems bi-directional and in the vertical dimension through the interchange of matter with the floodplain during floods and through groundwater, respectively. Hence, a certain stream or river section not only strongly depends on the whole catchment upstream, but also strongly influences the catchment downstream.

Streams and rivers are also highly important for man. We rely on them for different uses like water supply, fishery, hydropower, navigation, waste disposal, recreation, and mining of raw materials. In addition, streams and rivers represent a potential threat to silvicultural or agricultural land uses, settlements, and traffic infrastructure on the adjacent floodplain through floods and erosion. Therefore, streams and rivers in Central Europe have been altered by man throughout ancient and modern times to ensure these uses and to prevent hazards. Deforestation and land-use change had a noticeable influence on erosion and alluvial deposition since the Mesolithic Age (Liedtke and Marcinek (2002), p. 150), probably strongly decreased the input of large wood, and changed stream hydrology. River clearing and engineering for the improvement of navigation date back to the Roman era (Herget 2000). But the most severe alterations of stream and river morphology occurred in the 19th and 20th century. Virtually all rivers were cleared, straightened, and deepened to improve navigation; dams were built for fish hatcheries, water mills, large hydroelectric power plants, and drinking water reservoirs; large areas were sealed, which led to an increase in surface runoff; and bank- / bed-revetments and embankments were built even in many small streams (Kern 1994).

These human alterations led to a severe degradation of stream ecosystems. Despite the loss of many aquatic habitats and species, several processes and functions like the retention of flood waves, the self purification ability, and the recreation value were impaired, which in turn restricted uses like water supply, fishery, and recreation. In addition to these hydromorphological changes, dumping of pollutants and toxic substances decreased water quality. As a consequence, the restoration of streams and rivers has become a widely accepted social objective in developed nations, which increasingly becomes established in law like in the "European Water Framework Directive", recently enacted by the European Union (European Commission 2000). Because this directive requires a good ecological status of all European rivers to be achieved by 2015, there is presently a strong demand for cost-effective stream restoration. In Central Europe, the main problem is the poor hydromorphological status of most streams, while severe pollution, obvious effects from toxic substances, and acidification have almost vanished in the past decades (Brookes 1987; Lorenz et al. 2004; Verdonschot and Nijboer 2004).

Stream restoration in Central Europe started in the 1980's. Most of these restoration projects were restricted to short stream sections and focused on the design of new channels and channel features using heavy machinery. In many cases bank revetments had to be used to prevent lateral channel migration, even after stream restoration, because natural channel dynamics could not be admitted due to the adjacent land use (Smukalla and Friedrich 1994). Such technical approaches are known to be rather expensive, causing costs of 100-500 € per meter channel length, and therefore, these methods can only be applied in short channel segments (Gunkel (1996), p. 335). It has been widely stated and it can be considered to be "state of the art" that streams and rivers should alternatively be restored by initiating natural channel dynamics, which causes the formation of a natural channel pattern and channel features, whenever possible (Kern 1994; Gunkel 1996; Patt et al. 1998). Such approaches, which focus on the restoration of natural processes, are thought to cause less costs and hence, are of special interest, because long stream reaches and even whole catchments have to be restored to fulfil the demands of the Water Framework Directive.

One out of several measures to initiate natural channel dynamics by altering local channel hydraulics is the placement of cylindrical tree boles, rootwads or whole trees with rootwads and branches. A great variety of terms has been used for such "wood in streams" in the past (see reviews in Gregory (2003), Kail and Gerhard (2003)), but in general, they are recently simply referred to as "wood" or "large wood", if they exceed 0.1 m in diameter and 1 m in length (Gregory et al. 2003a). Large wood is a natural component of all aquatic ecosystems in temperate forested ecoregions. By contrast, large boulders and groins, which can alternatively be used to initiate natural channel dynamics, either do not naturally occur in all stream and river types or must be considered to be completely artificial. Therefore, the placement of large wood is considered to be the most natural way to initiate natural channel dynamics.

1.2 The role of large wood in temperate stream and river ecosystems

Many studies indicate that large wood is one of the key factors of ecosystems in temperate forested ecoregions, which influences not only stream hydraulics and morphology, but also hydrology, sediment budget, and biota across a wide range of spatial and temporal scales (see reviews in Harmon et al. (1986), Maser and Sedell (1994), Gurnell et al. (1995), Gregory et al. (2003a)).

Large wood increases hydraulic resistance (Shields and Gippel 1995; Buffington and Montgomery 1999; Manga and Kirchner 2000) and flow energy is dissipated at log steps (Keller and Swanson 1979; Keller and Tally 1979; Heede 1981; Marston 1982; Abbe and Montgomery 2003; Curran and Wohl 2003), yielding an increased water retention (travel time) during floods (Gregory et al. 1985; Ehrman and Lamberti 1992). Flow diversity is enhanced spatially by acceleration and deceleration of the current (Beebe 1997), resulting in increased niche and habitat variety, e.g. for fish species and age groups (McMahon and Hartman 1989; Rabeni and Jacobson 1993). Decreased transport capacity in reaches with high loads of wood results in sediment storage. Such storage effects are apparent in the increase of bed load transport after the removal of wood (Beschta 1979; Bilby 1981; Klein et al. 1987; MacDonald and Keller 1987; Smith et al. 1993; Webb and Erskine 2003) or the breakage of single log jams (Mosley 1981). Organic matter settles in lentic zones that develop behind large wood and is trapped by complex woody structures (Bilby 1981; Speaker et al. 1984; Ehrman and Lamberti 1992). Wood therefore increases the availability of food for macroinvertebrates, and hence, potentially increases biomass and alters the composition of functional feeding groups (Smock et al. 1989).

Changes of channel morphology and sediment budget caused by large wood range from the increase in sediment patchiness and the number of different surface textures (Rice and Church 1996; Buffington and Montgomery 1999) to the increase in pool volume (Murphy et al. 1986; Carlson et al. 1990; Fausch and Northcote 1992), initiation of bank erosion (Nakamura and Swanson 1993), the formation of bars (Fetherston et al. 1995; Abbe and Montgomery 2003) and log steps (Keller and Swanson 1979; Keller and Tally 1979; Heede 1981; Marston 1982; Abbe and Montgomery 2003; Curran and Wohl 2003), the creation of avulsions, chutes, meander cut-offs (Keller and Swanson 1979; Collins and Montgomery 2002; Webb and Erskine 2003), and large-scale modifications of channel form, channel type, and floodplain structure (Abbe and Montgomery 1996; Piégay and Gurnell 1997; Abbe and Montgomery 2003; Brooks et al. 2003; O'Connor et al. 2003). Different parameters have been used to describe these effects of large wood on channel cross-sections and single channel features. Cross-section width as well as depth and their variability are higher in channel sections with high large wood loadings (Keller and Tally 1979; Hogan 1987; Fausch and Northcote 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 large wood 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.

In addition to the impact of large wood on stream biota through the modification of abiotic factors, wood itself serves as a habitat and food resource for macroinvertebrates, fish, and other aquatic and terrestrial vertebrates.

Macroinvertebrates use wood as refuge, as an oviposition and pupation site, as an attachment site for filter feeding, wood is used for case construction by several Trichoptera, and finally, invertebrates feed on the epixylic biofilms on the wood surface and on wood itself (Dudley and Anderson 1982; Anderson et al. 1984; Harmon et al. 1986; Benke and Wallace 2003). Invertebrate biodiversity, density, and biomass is especially high on wood compared to other substrates. Dudley and Anderson (1982) listed 185 species that are closely associated with wood in streams of the Pacific Northwest (USA). In the literature reviewed by Benke and Wallace (2003), invertebrate density and biomass on wood generally approaches or exceeds 10,000 m^{-2} and 1 g m^{-2}, respectively. Furthermore, wood alters the composition of functional feeding groups and is of special importance in streams and rivers where other stable substrates are missing, like in sand-bed streams with shifting sand (Benke and Wallace 2003).

Riverine fish use large wood as a cover to decrease predation risk, as spawning and nesting cover, for egg attachment, as a velocity refuge during high flows, as a foraging site (insectivorous fish species), and submerged wood visually isolates individual fish, therefore decreasing inter- and intraspecific interference competition (see review in Crook and Robertson (1999), Dolloff and Warren (2003), Zalewski et al. (2003)). Dolloff and Warren (2003) named 86 fish species that are associated with large wood in the southeastern United States.

Other aquatic and terrestrial vertebrates, like birds, reptiles, amphibians, and mammals use wood as habitat, shelter, and wood increases the food resources of these animals (e.g., leaf litter, insects, fish). For example, birds are known to use wood for perching, basking, hawking, and nest in wood accumulations, turtles were observed using partially submerged logs as basking sites, snakes and lizards use wood as protection from predation and as thermal shelter, amphibians use wood for egg deposition, mice built their nests of dry grass under logs, and river otters, skunks, and mink at least partly rely on food resources potentially enhanced by wood (see review in Steel et al. (2003)). The vast majority of the studies mentioned above have been carried out in North America.

In contrast to North America, the relevance of large wood for stream ecosystems has long been overlooked in Central Europe, presumably because it is rarely found in Central European streams due to the long term human impact on streams and the extensive management of virtually all forests over many centuries. But recently, large wood in streams is becoming a research topic of increasing interest in Central Europe, because (a) there is an ongoing discussion about the potential natural state of Central European streams and rivers, which should be used as reference and target conditions in stream restoration, and literature shows that large wood was a key component in other pristine temperate forested ecoregions before the European settlement like in North American, and (b) there is an urgent need for cost-effective methods for stream restoration as it has been mentioned above.

Verdonschot and Tolkamp (1983), Eckert et al. (1996), Hering and Reich (1997), and Pusch et al. (1999) were the first to describe the role of large wood for channel morphology, biota, and management in Central European streams and rivers. The influence of wood on stream hydraulics caused diverse flow patterns and increased flow resistance in a lowland sand-bed stream in Brandenburg, Germany (Mutz 2000). Mutz and Rhode (2003) observed exceptional high rates of surface-subsurface water exchange in the hyporeic zone of this sand-bed stream with a high wood standing stock, which indicates that large wood increases hyporeic oxygen concentration and thus influences the decomposition of organic matter and the self purification ability. Hoffmann and Hering (2000) summarized detailed studies on macroinvertebrate communities inhabiting wood (Feld and Pusch 2000; Spänhoff et al. 2000; Warmke and Hering 2000), on single species (Hoffmann 2000), and general studies on habitat association of aquatic invertebrates and named 103 taxa that are closely associated with wood in Central European streams. Only recently, two studies investigated the effect of large wood on fish communities. Abundance and biomass of brown trout (*Salmo trutta*) and rainbow trout

(*Oncorhynchus mykiss*) increased in a stream section in Liechtenstein after the placement of large wood (Zika and Peter 2002). A comparable increase in the abundance of rainbow trout after wood placement in another stream of the Alpenrhein system was reported by Becker et al. (2003). Except for two recent studies, little is known about the impact of large wood on channel morphology in Central European streams and rivers. Gerhard and Reich (2000) quantified changes induced by large wood in channel depth and width in two small lower-mountain streams, and Mutz (2000) described stream morphology of a small sand-bed stream with a high wood loading. Transferability of the results of North American studies is limited, because the natural setting (e.g., discharge, geology, vegetation) differs from Central European conditions, although the fundamental principles of how large wood influences stream and river ecosystems are probably the same in all temperate forested ecoregions.

1.3 The use of large wood in stream and river restoration

Considering its beneficial effects on stream hydrology, hydraulics, sediment budget, morphology, and biota, large wood can be used, not only for initiating natural channel dynamics, but also for many other objectives in stream restoration projects. Therefore, wood is often added in stream restoration projects, e.g., for local bank protection (Shields et al. 2001), as grade control (Rosgen 1996), to enhance spawning habitat (riffles) and rearing habitat (pools) for fish (House and Boehne 1986; Crispin et al. 1993; Cederholm et al. 1997; De Jong et al. 1997), to create cover for fish (De Jong et al. 1997) or to enhance habitat for benthic macroinvertebrates (Hilderbrand et al. 1997). The vast majority of these restoration projects have been carried out in the north-western U.S. to restore fish habitats by the placement of artificial instream structures such as log weirs. In many other North American river restoration projects, tree revetments are used to protect banks in formerly stable, meandering channels, which are developing into braiding rivers with unstable banks due to detrimental channel works and land use changes upstream (Kondolf 1996). Therefore, channel stabilization rather than initiating later channel dynamics is one of the primary objectives in North American river restoration projects.

In contrast to North America, only few restoration projects have been carried out in Central Europe in which large wood has been used. Gerhard and Reich (2001) and Kail and Hering (2003) give some basic information about the use of large wood in stream restoration, but detailed information about restoration projects are rarely found in open literature. Hence, monitoring results, which can be used as case studies and from which management guidelines can be derived, are missing. Moreover, transferability of the results from North American restoration projects is limited, because land-use pressure is particular high in Central Europe, and the natural setting (e.g., discharge, geology, vegetation) and restoration objectives differ.

1.4 Stream or river restoration – a definition of terms

The term "stream (or river) restoration" is used for a wide variety of project objectives, ranging from conventional bio-engineering (e.g., using vegetation for bank protection instead of concrete walls) to the restoration of natural processes aiming to generate natural instream structures (e.g., riffles, pools, undercut banks) and a natural channel pattern (Kondolf 1996). Restoration objectives should be clearly stated, not only qualitatively but also quantitatively whenever possible, because they serve as a reference condition (a) to identify the deficits by a comparison of the objectives with the present state (Deutscher Verband für Wasserwirtschaft und Kulturbau 1996; Gunkel 1996; Patt et al. 1998) and (b) to allow for a sound project evaluation (Kondolf 1995; Downs and Kondolf 2002; Shields et al. 2003a).

Stream restoration was defined in the U.S. as "the return of an ecosystem to a close approximation of its condition prior to disturbance" (National Research Council USA 1992). In many stream types irreversible changes have occurred (e.g., extinction of species, Late Holocene alluvium) and hence, the re-creation of a previous pre-historical state is impossible (Kauffman et al. 1997; Brown 2002). This is especially true for a densely populated cultural landscape like Central Europe where streams have been altered by man since the Mesolithic Age. Therefore, the "potential natural state" of a stream, which would develop from the present state under the present conditions without further human influence, is used as a reference and target condition in Central European stream restoration projects since the mid-1990's (Deutscher Verband für Wasserwirtschaft und Kulturbau 1996). Within the scope of this thesis "restoration" is defined as any approach to develop a degraded ecosystem towards its potential natural state.

1.5 Scope of the thesis

The main objective of the thesis is to help develop a Central European perspective on the significance of large wood in streams and rivers and its use in stream restoration. Four studies are compiled in this thesis, which focus on (a) the potential natural state of Central European streams in respect to the amount and distribution of large wood, (b) the influence of large wood (single large fallen trees) on channel morphology, (c) the quantification of the potential use and the simulation of the effects of large wood in restoration projects, and (d) the review of restoration projects in which large wood has been used so far.

As restoration should approach to develop a degraded ecosystem towards its potential natural state, stream restoration projects in which large wood is used should be geared to the potential natural amount and distribution of large wood. The potential natural state, so called "Leitbilder", which can be used as reference and target conditions in stream restoration, have been developed for many different stream and river types in Central Europe (e.g., Landesumweltamt Nordrhein-Westfalen (1999, 2001)). It has been pointed out in the corresponding textbooks that large wood is an important component in all stream and river types, but it was further stated that detailed descriptions of the amount and distribution can not be given due to the present lack of knowledge on large wood in Central European streams. As a first step to develop reference conditions for large wood in Central European streams, the amount and distribution of large wood in some of the most natural stream sections was investigated (see section 2).

The main objective of stream and river restoration projects that try to initiate natural channel dynamics is to create natural channel features like pools, bars, and cut banks, which in turn are important habitats, e.g. for fish (see 1.2). That is, stream and river restoration primarily tries to change channel morphology by modifying channel hydraulics. To markedly alter channel hydraulics and morphology, the wood pieces placed in the streams and rivers must be sufficiently large. In many streams and rivers this holds true only for large fallen trees, which are increasingly used in restoration projects. But few is known about the exact effect of such single large fallen trees on channel morphology; about the type and size of the channel features, which are caused by such large wood pieces, and the time and discharge necessary for such channel features to develop. Therefore, the impact of single large fallen trees on channel morphology was investigated in six short channel sections in Central Europe (see section 3).

Despite the beneficial role for stream ecosystems, large wood must be considered to be a potential threat to land uses and works in the channel and on the adjacent floodplain. Large wood can be transported downstream, damaging bridges and other works and rises the water level, thus increasing flood probability upstream. Fixation of the large wood pieces can prevent downstream transport, but probably markedly increases the costs and is less preferable from an ecological point of view, because many channel features can only be created and maintained, if natural wood transport and dynamics are restored. Therefore, in a densely populated area like Central Europe, adjacent land uses rather tightly constrain the options for stream restoration projects in which large wood is used without additional anchoring. The potential use and effects of large wood in Central European streams was quantified to assess, if large wood recruitment and placement are suitable methods to restore a considerable part of the streams and rivers (see section 4).

Several authors pointed out that the experiences gained in restoration projects may provide valuable information for the improvement of future project designs (Bryant 1995; Kondolf 1995, 1996, 1998; Roper et al. 1997; Bash and Ryan 2002; Downs and Kondolf 2002; Bisson et al. 2003; Reich et al. 2003). However, large wood has been rarely used in Central European stream restoration projects in the past, and only two of these restoration projects have been described in more detail in open literature (Gerhard and Reich 2000; Semrau et al. 2003). Therefore, a mail survey was started to summarize the experiences that have been gained so far and to derive management guidelines (see section 5).

2 Quantity and distribution of large wood in Central European streams – present and potential natural state

2.1 Summary of the section

Nine investigations concerning the volume of large wood in Central European streams are summarized. Altogether, 34 stream sections were examined ranging from Northern German lowland streams to brooks in alpine regions. The study streams are among the most natural streams in Central Europe and are in a "near-natural" condition according to Central European standards (riparian forest currently unmanaged, no removal of large wood for at least 10 years, bordered by deciduous forest).

Considering large wood of a diameter > 0.1 m and wood accumulations, the median volume of large wood related to stream length is 17.2 $m^3\ km^{-1}$ and 37.8 $m^3\ ha^{-1}$ related to stream bottom area. The median number of logs (> 0.1 m diameter) is 200 logs km^{-1} and 300 logs ha^{-1} related to stream length and bottom area, respectively. The spacing of larger logs (diameter > 0.2 m, length > 3 m), which can be classified as "small fallen trees", is 21 small fallen trees per kilometre stream length. Large fallen trees (diameter > 0.5 m, length > 10 m), which can act as key-pieces in the formation of wood accumulations, are missing completely. Regarding the three main ecoregions, the median standing stock of large wood related to stream bottom area in alpine streams (2 $m^3\ ha^{-1}$) is significantly lower compared to the median in lowland streams (41.8 $m^3\ ha^{-1}$) and for streams in lower mountain areas (36.9 $m^3\ ha^{-1}$, Mann-Whitney-U-test, $p < 0.05$). Regarding only stream sections in the lowland and lower mountain area, median volume of large wood is 41.4 $m^3\ ha^{-1}$.

The range of volumes found in the study streams can be regarded as the minimum volume of large wood that should be present in a "near-natural" Central European stream. However, it is hard to estimate how closely these values represent natural conditions. From the distribution of size classes, comparison with the amount of wood in some of the most natural streams flowing through deciduous forest in other temperate forested ecoregions, and the historical description of the river Oder, it is deduced that the current large wood standing stock is considerably less than the potential amount of large wood. For centuries, all of the streams have been anthropogenically influenced. Historic alterations of the stream, its floodplain, and the riparian vegetation may still affect large wood supply and standing stock. It is concluded that virtually all streams in Central Europe are highly altered with respect to the loading of

large wood, and stream restoration projects should aim to increase the input of large wood even in the most natural stream sections.

2.2 Scope of the section

In general, there are three complementary ways to deduce the potential natural state of streams in respect to large wood. First, the present state of the most natural stream sections, which developed under the present natural setting with a low human impact, can serve as a basis for the description of the potential natural state. Second, complementary information about the historical state of the streams can be used to describe the state of streams with a low human impact. However, it is necessary to assess how the remaining human impact influenced the present and historical state of these most natural stream sections. Third, models of wood dynamics in streams and rivers can be used to predict the abundance and distribution of wood in the potential natural state. As a first step to derive the potential natural state of Central European streams, the amount and distribution of large wood in some of the most natural stream sections was investigated.

In North America, extensive studies concerning large wood have focused on the standing crop of wood in streams of various forest types. Thus, detailed analyses on the amount of large wood in pristine streams are available from many parts of North America (e.g., Triska and Cromack (1980), Swanson et al. (1984), Wallace and Benke (1984), Harmon et al. (1986), Naiman et al. (1986), Robison and Beschta (1990a), Bilby and Ward (1991), Marcus et al. (2002), review in Gurnell (2003)).

In contrast to North America, only few studies on large wood standing crop in Europe have been published. In the last years, some investigations estimating quantities of large wood in single floodplains have been carried out in France, Great Britain, and Spain (Piégay 1993; Piégay and Gurnell 1997; Elosegi 1999; Diez et al. 2001; Gurnell 2003). However, a comparative investigation of large wood in Central European streams is still lacking.

Due to the long term human impact on streams and the extensive management of virtually all forests over many centuries, large wood is rarely found in Central European streams. Because undisturbed natural streams no longer remain, it is impossible to investigate the amount of wood in streams under pristine conditions. Moreover, we do not have a reliable data source on the standing crop of large wood in the most natural streams under the current conditions. However, in the last few years some investigations have been carried out concerning the amount of large wood in Central European streams.

The main objective of this section is to summarize these investigations and to describe the quantity and distribution of large wood in stream sections with currently low human impact and thus a comparatively high amount of large wood. Moreover, its variability due to location, riparian forest type, and human impact is investigated. Based on this information, it may be possible to deduce the potential natural state, which can serve as a reference and target condition in stream restoration projects.

2.3 Study streams

The results of nine investigations were compiled, concerning the quantities and distribution of large wood in streams in different parts of Germany, and at two sites in Tyrolia (Austria) and the Alsace (France) (Figure 2.1).

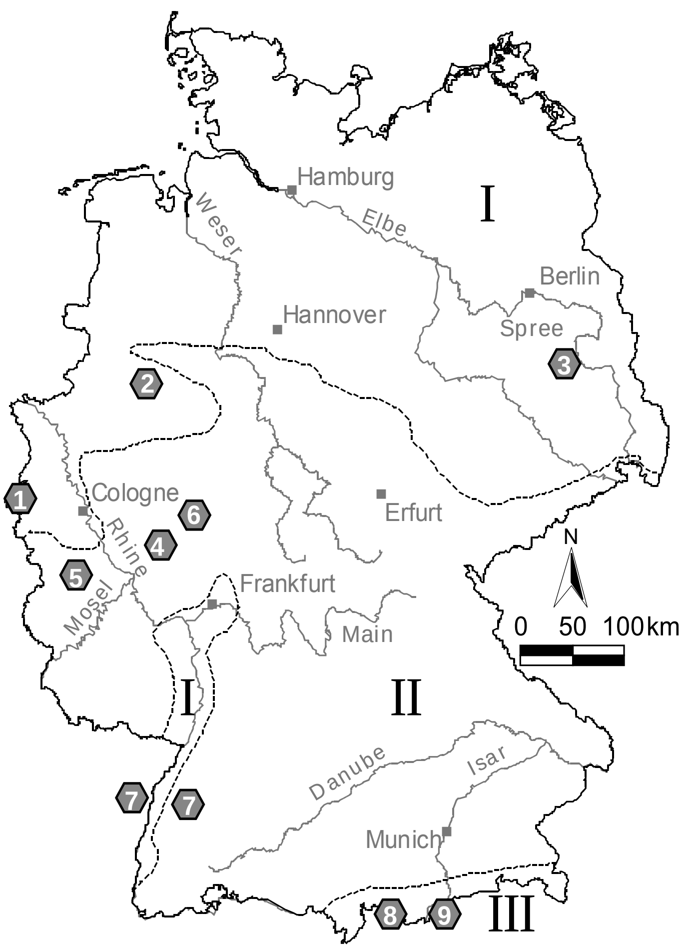

Figure 2.1: Location of the stream groups 1-7/8 in Germany, stream group 7 in Alsace (France), and stream group 9 in Tyrolia (Austria). I = lowland, II = lower mountain area, and III = alpine region correspond to the ecoregions 14, 9 and 4 according to Illies (1978). Borders of the lowland ecoregion is modified according to Briem (2003). Numbering of the stream groups corresponds to the numbers of the streams in Table 2.1 and the numbers of the stream groups in Table 2.2.

Table 2.1
Characteristics of stream sections examined. nd = no data available.
Stream number: the first numeral indicates the stream group (compare Figure 2.1 and Table 2.2).
Bottom area of section examined: group 1-7 streams - bottom area was calculated from mean width of bankfull channel; group 8 streams - areas investigated were located between the border of bankfull channel and the shoreline at mean discharge; group 9 streams - the whole floodplain was regarded.
Removal of large wood: par. = infrequent removal of large accumulations, no = no removal since at least 10 years.
Use of floodplain: - = unmanaged riparian forest or gravel banks; (f) = currently unmanaged riparian forest; m = meadows.
Riparian forest type: f(2) = riparian forest on both sides of the stream; f(1) riparian forest on one side of the stream; g = narrow gallery forest (width less than average height of trees); a = alluvial floodplain with sparse vegetation, forest only on hillslopes.
Riparian vegetation: dominant tree species; A-g = *Alnus glutinosa*; Ac-p = *Acer pseudoplatanus*; B-pe = *Betula pendula*; Ca-b = *Carpinus betulus*; Co-a = *Corylus avellana*; Fa-s = *Fagus sylvatica*; Fr-e = *Fraxinus excelsior*; Fra-a = *Frangula alnus*; P-a = *Picea abies* (native in study area); Pi-sy = *Pinus sylvestris*; Po-hy = *Populus x hybrida*; Pr-p = *Prunus padus*; Py-p = *Pyrus pyraster*; Q-ro = *Quercus robur*; Q-ru = *Quercus rubra*; Sa-f = *Salix fragilis*; Sa-spec = *Salix spec.*; So-a = *Sorbus aucuparia*.

stream number	stream	stream order	altitude (m above sea level)	slope of stream bottom (%)	bottom substrate	mean channel width (m)	length of section examined (m)	bottom area (m2)	removal of LW	use of floodplain	riparian forest type	riparian vegetation	mean discharge (l/s)	date of investigation
1-1	Buschbach	1	40	0.28	sand	1.2	500	600	no	--	f(2)	A-g, B-pe	nd	11/97
1-2	Schaagbach tributary	1	47	0.40	organic	1.4	240	336	no	--	f(2)	A-g	nd	11/97
2-1	Gellenbach	2	55	nd	sand	3.7	1300	4800	no	(f)	f(2)	Fa-s, Q-ro, B-pe, A-g, Fr-e	nd	5/96
3-1	Briese	3	40	0.03	sand	7.1	36	238	par.	--	f(2)	Pr-p, A-g, So-a	nd	4/98
3-2	Demnitzer Mühlenfließ	2	43	0.12	sand	5.0	24	96	no	--	f(2)	A-g, Fa-s, Q-ro, Co-a	90	4/98
3-3	Nonnenfließ	nd	30	0.17	sand	5.5	48	168	no	--	f(2)	Fa-s, Ac-p	nd	4/98
3-4	Nieplitz	nd	69	0.19	sand	5.0	24	72	no	--	f(2)	Fr-e, Py-p, Fra-a, Q-ro, Q-ru, So-a	nd	5/98
3-5	Riembach	nd	86	0.25	sand	2.9	32	92	no	--	f(2)	A-g, So-a	nd	6/98
3-6	Schlaube	3	60	0.29	sand	7.4	84	386	no	--	f(2)	A-g, Fa-s	300	4/98
3-7	Verlorenwasser	nd	75	0.32	sand	4.5	43	192	no	--	f(2)	A-g, So-a, B-pe	220	6/98
3-8	Schwarzer Bach	1	64	2.10	sand gravel	3.3	20	52	no	--	f(2)	A-g, Fa-s	nd	5/98
3-9	Waldbach	1	55	0.58	sand	0.7	28	42	no	--	f(2)	Fa-s	nd	4/98
3-10	Böberschenkfließ	1	70	2.40	sand gravel	3.8	60	114	no	--	f(2)	A-g	nd	4/98

Table 2.1
(continued)

stream number	stream	stream order	altitude (m above sea level)	slope of stream bottom (%)	bottom substrate	mean channel width (m)	length of section examined (m)	bottom area (m2)	removal of LW	use of floodplain	riparian forest type	riparian vegetation	mean discharge (l/s)	date of investigation
4-1	Wenigerbach, section 1	1	125	nd	stones	5.5	100	nd	no	--	f(1)	Ca-b	~73	8/97
4-2	Wenigerbach, section 2	1	105	nd	stones	5.2	100	nd	no	--	g	A-g	~73	8/97
4-3	Wenigerbach, section 3	1	155	nd	stones	2.8	100	nd	no	--	f(2)	A-g, Sa-spec	~73	8/97
5-1	Rote Wehe	3	255	nd	stones	6.0	60	359	no	--	f(2)	A-g, Fa-s	nd	12/97
5-2	Weiße Wehe	3	360	nd	stones	8.1	108	875	no	--	f(2)	A-g, Fa-s	nd	12/97
6-1	Orke Dalwigkstal	5	295	nd	stones	nd	150	nd	no	m/f	g	A-g, Sa-f	nd	11/95
6-2	Orke Niederorke	5	275	nd	stones	nd	100	nd	no	m/f	g	A-g, Sa-f	nd	11/95
7-1	Eberbach (Black Forest)	1	300	2.18	stones	4.0	400	nd	no	--	g	A-g	nd	1995
7-2	Heßbach	1	300	2.19	stones	4.1	300	nd	no	(f)	f(2)	Po-hy	nd	1995
7-3	Halbmühlbach	1	140	0.52	sand	8.8	1100	nd	no	(f)	f(2)	A-g, Fr-e	nd	1995
7-4	Sauer tributary	1	150	0.25	sand	4.4	600	nd	no	--	f(2)	Fa-s	nd	1995
7-5	Sauer	3	140	0.11	sand	10.9	1600	nd	no	--	f(2)	A-g, Fr-e, Fa-s	nd	1995
7-6	Eberbach (Alsace)	2	150	0.06	sand	7.9	500	nd	no	--	f(2)	Q-ro	nd	1995
8-1	Isar Wallgau	5	845	nd	gravel	nd	nd	832	par.	--	a	P-a, Sa-spec., Pi-sy	nd	8/95
8-2	Isar Vorderriss 1	5	775	nd	gravel	nd	nd	200	par.	--	a	P-a, Sa-spec., Pi-sy	nd	8/95
8-3	Isar Vorderriss 2	5	780	nd	gravel	nd	nd	13518	par.	--	a	P-a, Sa-spec., Pi-sy	nd	8/95
8-4	Finzbach	3	890	nd	gravel	nd	nd	2183	no	--	f(2)	P-a	nd	8/95
8-5	Neidernach	3	830	nd	gravel	nd	nd	17300	no	--	f(2)	P-a	nd	8/95
9-1	Isar (Schröfeln)	5	815	nd	gravel	300	400	120000	par.	--	a	P-a, Sa-spec., Pi-sy	nd	9/98
9-2	Isar (Schröfeln - Vorderiss)	5	800	nd	gravel	300	400	120000	par.	--	a	P-a, Sa-spec., Pi-sy	nd	9/98
9-3	Isar (Vorderiss / Fall)	5	770	nd	gravel	300	400	120000	par.	--	a	P-a, Sa-spec., Pi-sy	nd	9/98

The investigations were carried out between 1995 and 1998 by institutes of different universities. The streams or stream sections investigated (n = 34) represent streams of all Central European ecoregions (lowlands n = 17, lower mountain area n = 9, alpine region n = 8; ecoregion 14, 9, and 4 according to Illies (1978), modified according to Briem (2003)).

Only streams where (a) logs have not been removed during the past 10 years or only large accumulations are infrequently removed and (b) where there is no indication of recent management of the riparian vegetation are considered. Although the study streams probably are among the most natural stream sections in Central Europe, all of these streams and riparian forests have been managed in the past. None of the streams is located in an old-growth forest. These streams were selected to highlight the minimum standing stock of large wood present in "near-natural streams" according to Central European standards. As the data originate from nine distinct investigations concerning different stream types and employing slightly different methods, the streams are grouped by investigation. The study streams are further characterised in Table 2.1.

2.4 Methods

In all investigations (a) mean or maximum and minimum diameter and length were measured for each log, (b) the volume of logs was calculated by assuming that they were of cylindrical shape, and (c) single logs and large wood accumulations ("debris jams") were distinguished (except one stream section).

Due to the very different stream types and investigation intensities, the investigations differ in some aspects, which limits comparability of the data. The methods mainly differ in regard to (a) the diameter of the smallest wood pieces recorded, (b) the frame of reference for the large wood volume (stream bottom area or section length), (c) the border of the area investigated, and (d) the method to calculate volume of large wood accumulations. These methodological differences are summarized in Table 2.2 and highlighted in the following description.

- Group 1 streams: For each log and accumulation, the proportion of its volume located in four zones was measured (according to Robison and Beschta (1990b)). Due to the method used it was possible to calculate the wood volume inside the bankfull channel and neglect large wood above the bankfull channel and on the stream banks. The volume of accumulations was calculated from length, width, and height.
- Group 2 stream: Only accumulations (dams) were surveyed, single logs were not measured. Thus, the total volume of large wood present in the channel is probably higher than the

volume recorded. For each accumulation, the volume was calculated from length, width, and height of the dam. This value was multiplied by 0.5 to allow for hollow spaces.

- Group 3 streams: Only the volume present inside the bankfull channel was considered. The volume of accumulations was calculated from the following data: cover density in vertical view (4 classes estimated); share of twigs (diameter ~ 0.01 m), branches (diameter ~ 0.05 m) and logs (diameter ~ 0.1 m); length and width of the accumulation. All accumulations were seen as a single layer. The area covered with wood was calculated from the cover density and the area of the accumulation. This value was multiplied by the percentage and mean diameter of twigs, branches, and logs, respectively.
- Group 4 streams: For each log and accumulation the proportion of the volume located inside and located outside the bankfull channel was measured. Only the main trunk of whole trees was measured, neglecting branches and twigs. The volume of accumulations was calculated by measuring length and mean diameter, and estimating the density.
- Group 5 streams: The same method as described for group 1 was used. All logs forming accumulations were measured individually.
- Group 6 streams: All large wood at least partially located inside the bankfull channel was recorded. The proportion of the logs and accumulations located inside and above or outside the channel was not distinguished. Therefore, it is not possible to separate the volume of wood inside and outside the channel. The volume of accumulations was calculated by measuring mean length, width and height, and estimating their density.
- Group 7: For each piece of wood located at least partially inside the stream, the volume inside and outside the channel was measured. The volume of accumulations was calculated as the product of mean length, width, and height. This value was multiplied by 0.5 to allow for hollow spaces. Only data on the volume of large wood but not on the number of logs are available.
- Group 8: The large wood was surveyed on banks of the alluvial floodplains not flooded at low flow. However, these gravel banks are flooded at times of high discharge and therefore, belong to the bankfull channel. The areas investigated do not usually represent a transect through the channel. The volume of accumulations was calculated by measuring mean length, width, and height, and estimating their density.
- Group 9: Ten floodplain sections were examined. The areas investigated can be seen as a transect through the whole floodplain, including the active channel and the terrestrial parts. All logs forming accumulations were measured individually.

Table 2.2
Main methodological differences between the investigations and list of references. [a]only accumulations were surveyed. LW = large wood.

stream group	number of streams/stream sections investigated	diameter of smallest wood pieces recorded (cm)	LW related to bottom area	LW related to section length	border of area investigated	reference
1	2	5.0	x	x	bankfull channel	Kail (1999)
2	1	a	x	x	shoreline at mean flow	Meyer unpubl. data
3	10	2.5	x	x	shoreline at mean flow	Mutz unpubl. data
4	3	5.0		x	bankfull channel	Weiß unpubl. data
5	2	5.0	x	x	bankfull channel	Hering unpubl. data
6	2	6.4		x	shoreline at mean flow	Hering and Reich (1997)
7	6	7.0		x	bankfull channel	Eckert et al. (1996)
8	5	6.4	x		terrestrial gravel bars	Hering and Reich (1997)
9	3	5.0	x	x	borders of floodplain	Gerhard unpubl. data

To account for these differences and to increase the comparability between the nine investigations, only logs with a diameter > 0.1 m and accumulations inside the bankfull channel were considered. A diameter > 0.1 m is most frequently used in literature to define large wood (Gregory 2003; Kail and Gerhard 2003). These data were used to calculate the following parameters for each stream section: volume of logs (except 1 stream section), volume of accumulations (except 5 stream sections), total volume of large wood (calculated from log and accumulation volume), number of logs (except 7 stream sections), number of accumulations (except 5 stream sections), ratio of log volume to accumulation volume (except 6 stream sections). These values were related to the bottom area of the bankfull channel and to the length of the stream section examined. However, in some alluvial floodplains the values were related only to the area sampled (5 stream sections of investigation number 8), and in some cases they were only related to section length (11 stream sections of investigations number 4, 6 and 7). Bottom area was assessed for 9 out of these 11 stream sections using mean channel width and section length.

2.5 Results

2.5.1 Quantity of large wood (volume / number)

The stream sections investigated show a wide range of large wood standing stock values in relation to both, section length and bottom area of the bankfull channel. The volume of large wood related to stream length varies from 1.5 $m^3 km^{-1}$ to 2061.1 $m^3 km^{-1}$, with a median volume of 17.2 $m^3 km^{-1}$ (29 stream sections regarded). Most of the streams (86%) have a standing stock of less than 50 $m^3 km^{-1}$ (Figure 2.2). In relation to bottom area, quantity of large wood ranges from 0.5 $m^3 ha^{-1}$ to 3747.4 $m^3 ha^{-1}$, with a median volume of 37.8 $m^3 ha^{-1}$ (32 stream sections regarded). Large wood standing stock is less than 100 $m^3 ha^{-1}$ in 81% of the sections (Figure 2.3).

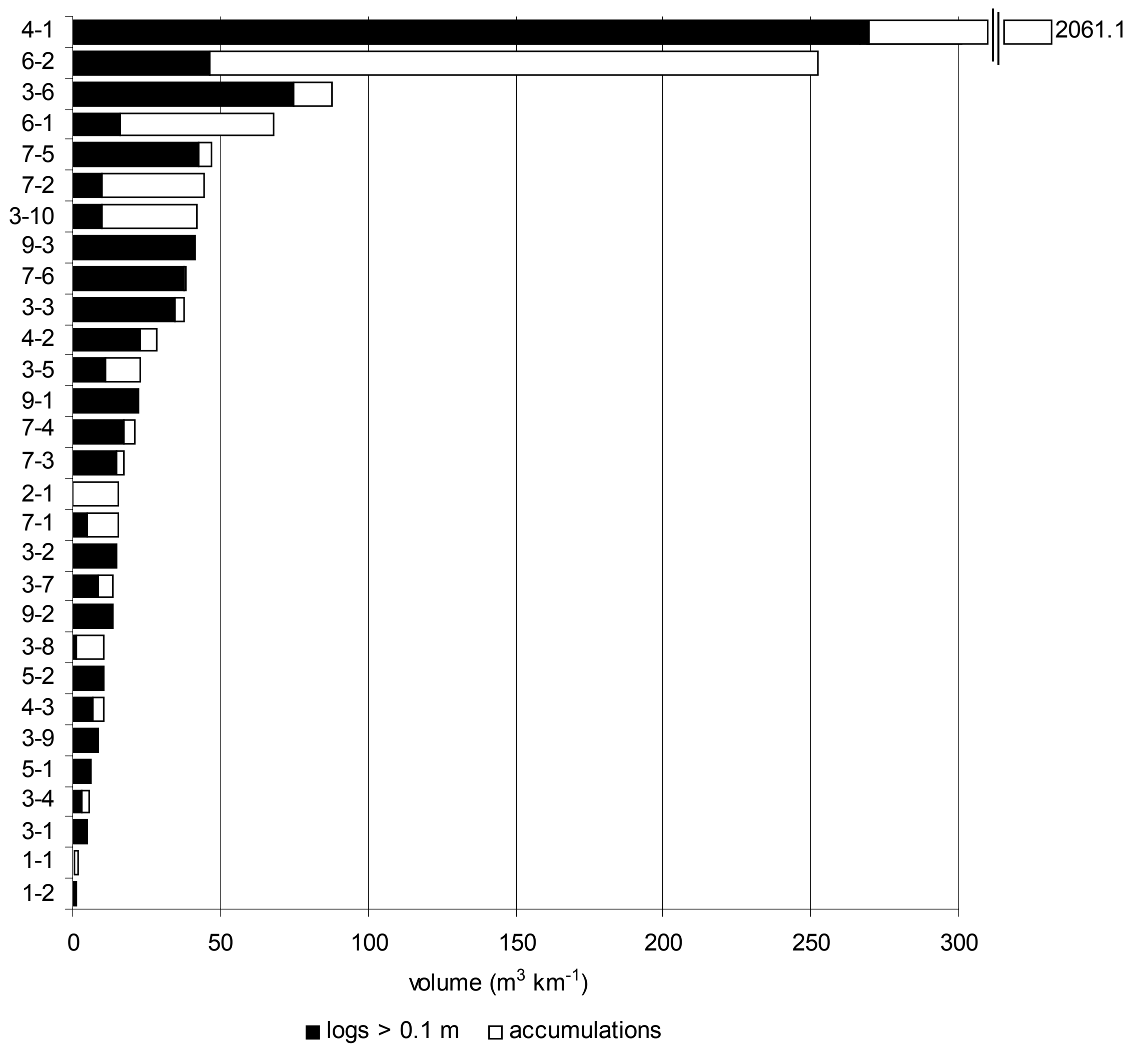

Figure 2.2: Volume of large wood in the stream sections related to 1 km section length. Stream numbers correspond to the numbers in Table 2.1. Only the volume of logs with a diameter > 0.1 m and volume of accumulations is regarded.

By far, the largest standing stock was found in a section of a mountain stream located on a steep slope, where several large beech trees (*Fagus sylvatica*) had fallen into the stream (section 4-1). Here, quantity of large wood is about 100 to 120 times the median of all stream sections (related to bottom area and stream length, respectively).

Compared to the volume of large wood, there is less variability in the number of logs (diameter > 0.1 m). In relation to section length, the number of logs ranges from 28 to 805 logs km^{-1}, with a median number of 200 logs km^{-1} (22 stream sections regarded). In relation to bottom area, the range in the number of logs is 7 to 1905 logs ha^{-1}, with a median number of 303 logs ha^{-1} (22 stream sections regarded). The largest number of logs in relation to section length and the smallest number in relation to bottom area is found in the wide

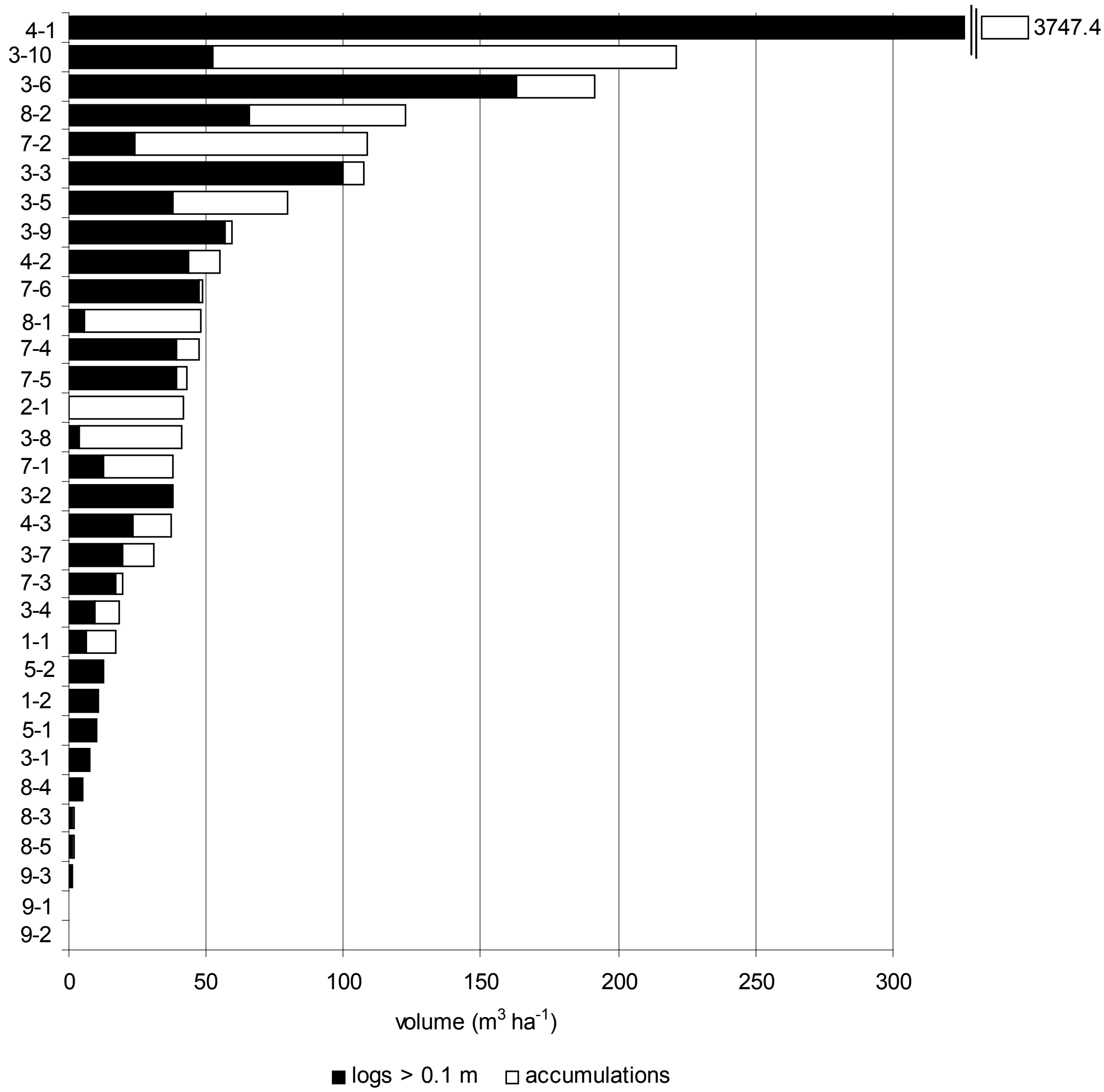

Figure 2.3: Volume of large wood in the stream sections related to 1 ha bottom area. Stream numbers correspond to the numbers in Table 2.1. Only the volume of logs with a diameter > 0.1 m and volume of accumulations is regarded.

alpine streams.

The highest number of accumulations ("debris jams") recorded is 656.3 jams km^{-1}, where even small accumulations were recorded (section 3-5). The median number is 77.4 jams km^{-1} (based on 22 stream sections). With respect to stream bottom area, the median number is 206.3 jams ha^{-1}. The highest density of accumulations was found in the above mentioned Riembach (section 3-5, 2282.6 jams ha^{-1}).

2.5.2 Relationship between quantity of large wood and stream parameters

The relationship between large wood standing stock (both related to section length and to bottom area) and various other recorded parameters (stream order, mean stream width, slope and length of the stream sections examined) was assessed by correlation and regression analysis, but no statistically significant correlation was found (Spearman rank-test, $p < 0.05$).

It was further tested, whether the percentage of large wood standing stock accumulated in debris jams is dependent on stream order, mean stream width, or slope of the stream bed. The percentage of the volume of large wood accumulated in debris jams is significantly correlated to the slope of the stream sections (Spearman rank-test, $p < 0.01$, $r_s = 0.62$, $n = 18$). The scatterplot (Figure 2.4) shows that the correlation mainly results from four sections with high gradients (sections 3-8, 3-10, 7-1, 7-2).

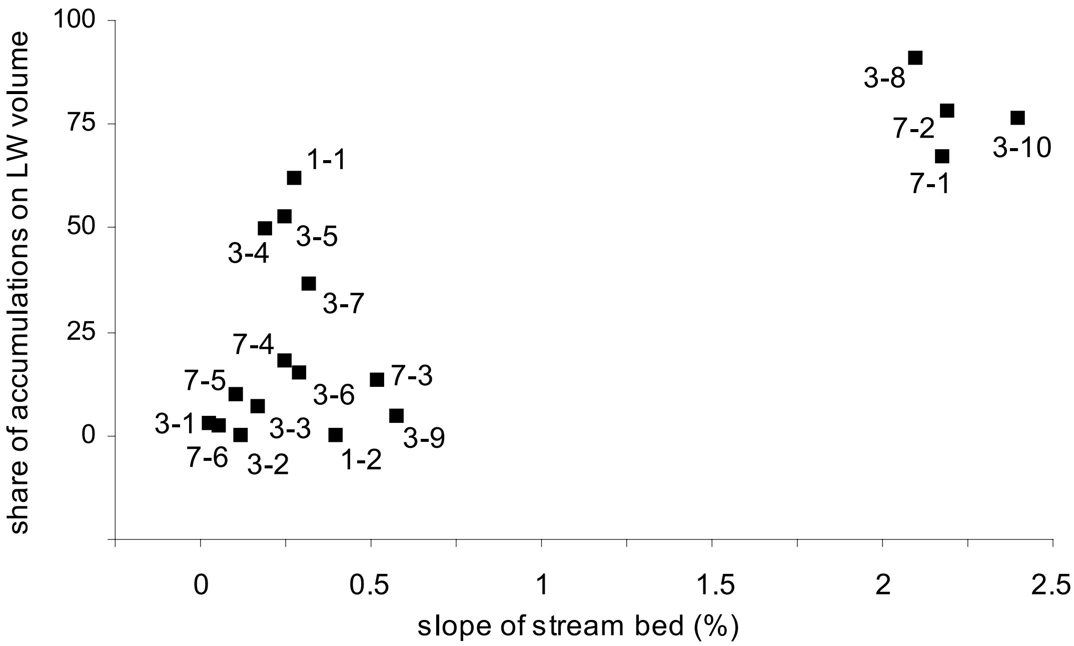

Figure 2.4: Scatterplot of slope (stream bed, %) vs. share of accumulations on volume of large wood (LW, %). Stream numbers correspond to the numbers in Table 2.1.

2.5.3 Size class distribution

In 27 stream sections, size class was recorded for each individual log. This data source comprises 967 logs of > 0.1 m diameter. For 933 of these logs, total length was also measured, while for the other logs only the length which is located in the bankfull channel is known. From these data, the distribution of size classes was examined. 69.5% of the logs have a mean diameter of 0.2 m or less (Figure 2.5). Only 1.5% of all logs (n = 14) have a diameter > 0.5 m. Considering the distribution of length classes, the majority of the logs (78.8%) has a length of 3 m or less, while only 23 logs exceed a length of 10 m (2.5%) (Figure 2.6).

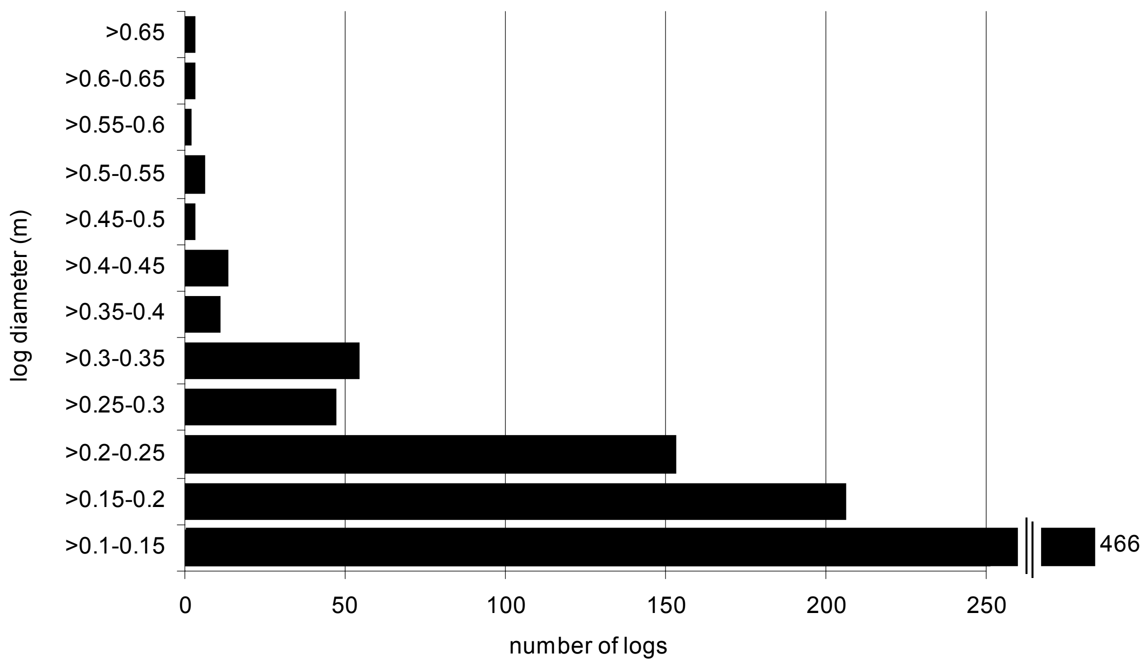

Figure 2.5: Size class distribution of log diameter (m). Only logs with a diameter > 0.1 m are regarded.

A small part of the logs for which diameter and length were measured (n = 933) can be classified as "small fallen trees" (8%, n = 74). These logs have a diameter >0.2 m and a length > 3 m. This corresponds to a spacing of 21 small fallen trees per 1 km stream length, if all stream sections for which stream length is known are considered (total stream length = 2890 m, 60 of 776 logs). Single logs, which exceed a diameter of 0.5 m and a length of 10 m, classified as "large fallen trees", are missing completely. Because of the methods used in the investigations, it is possible that such large logs were considered as parts of accumulations and thus not measured and listed separately.

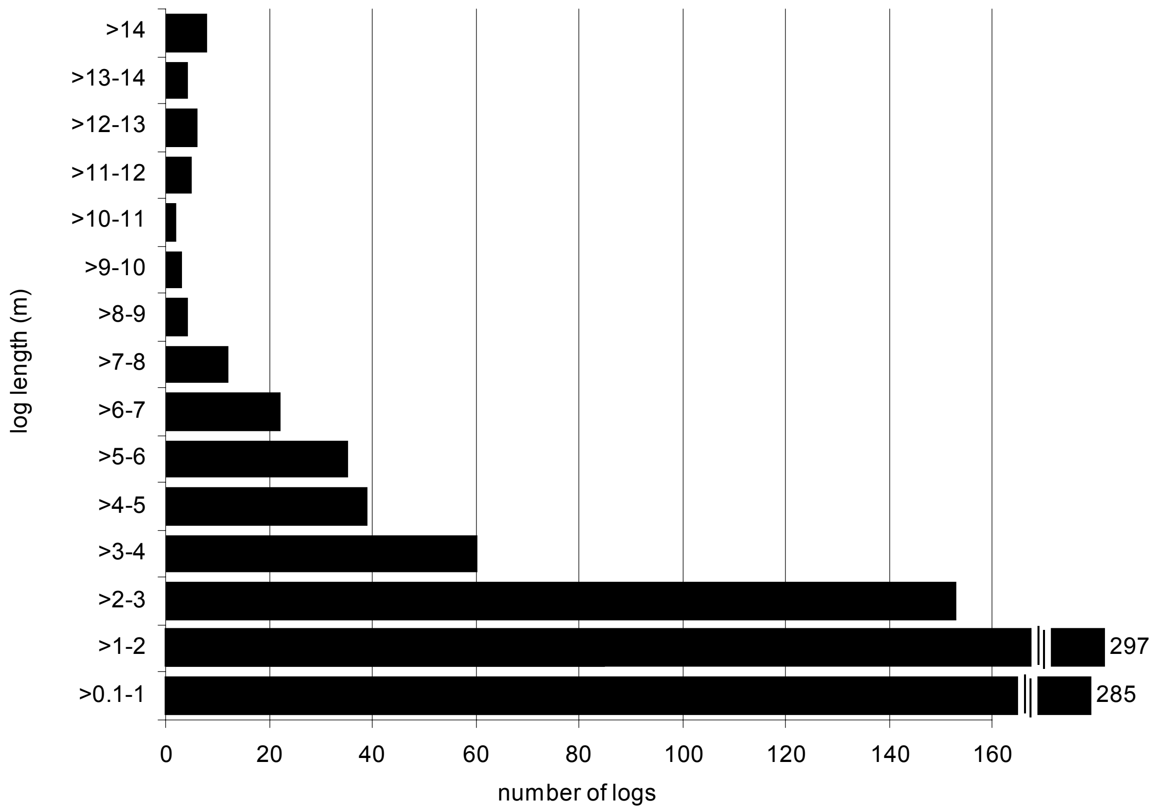

Figure 2.6: Size class distribution of log length (m). Only logs with a diameter > 0.1 m are regarded.

2.5.4 Quantity of large wood in different ecoregions

For further analysis, the streams were roughly grouped according to the ecoregion they are located in (see Figure 2.1 for borders of ecoregion): lowland streams (17 stream sections), streams in lower mountain areas (9 stream sections), and alpine streams (8 stream sections). Streams in different ecoregions are expected to differ in amount and distribution of large wood.

Median volume of large wood (related to section length) of lowland streams (15.6 m^3 km^{-1}) and streams in the lower mountain area (28.6 m^3 km^{-1}) show no significant difference (Figure 2.7), but variability is higher for the lower mountain stream sections (Siegel-Tukey rank dispersion test, $p < 0.01$). Due to insufficient data, this value was not calculated for alpine streams. The volume of large wood related to bottom area in alpine streams (2 m^3 ha^{-1}) is significantly lower compared to the median volume in lowland streams (41.8 m^3 ha^{-1}) and for streams in the lower mountain area (36.9 m^3 ha^{-1}, Mann-Whitney-U-test, $p < 0.05$). Moreover, variability is higher for the lower mountain stream sections compared to the lowland sections (Siegel-Tukey rank dispersion test, $p < 0.01$).

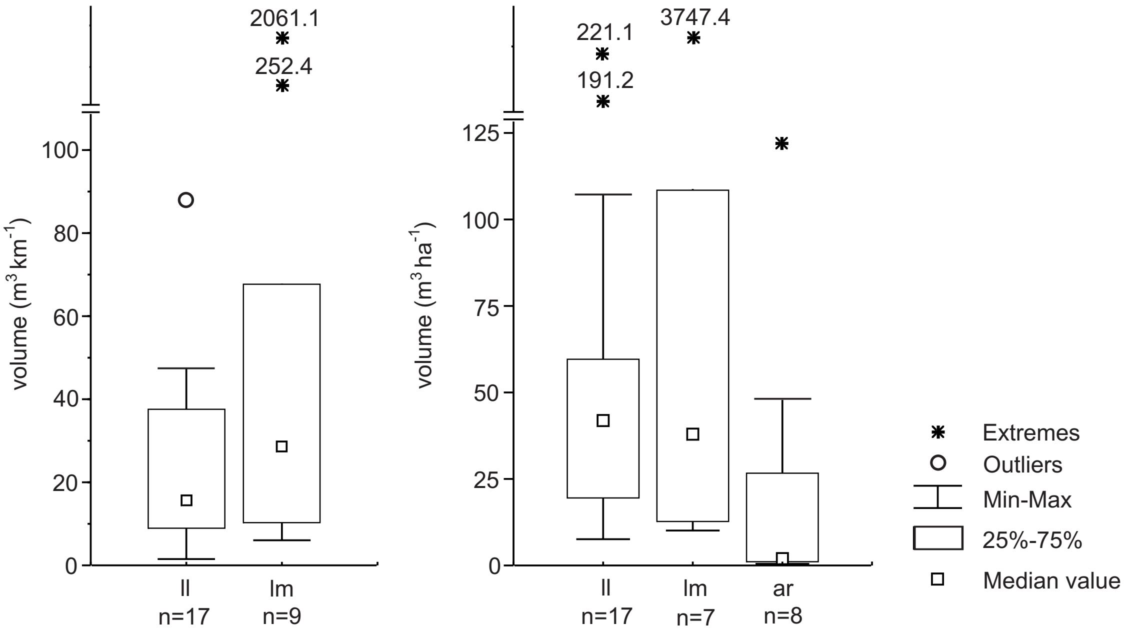

Figure 2.7: Volume of large wood related to section length (left) and bottom area (right) of streams, which are located in the ecoregions lowland (ll), lower mountain area (lm) and alpine region (ar). Extremes, outliers (extreme coefficient = 3, outlier coefficient = 1.5), maximum, 3. quartile, median, 1. quartile and minimum value are shown. Only the volume of logs with a diameter > 0.1 m and volume of accumulations is regarded.

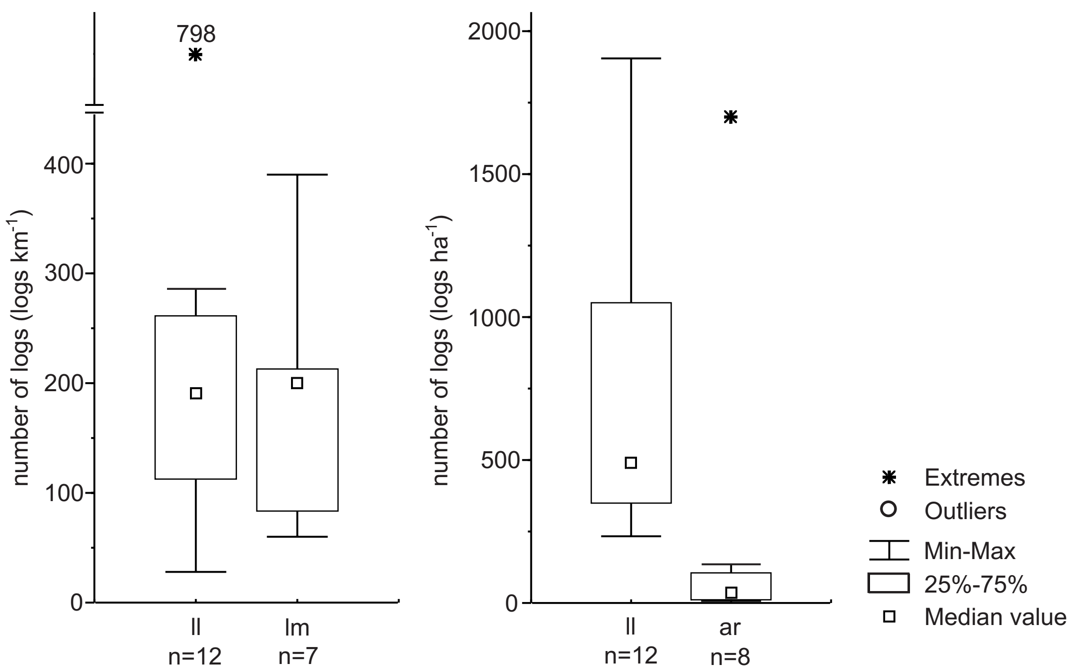

Figure 2.8: Number of logs related to section length (left) and bottom area (right) of streams, which are located in the ecoregions lowland (ll), lower mountain area (lm) and alpine region (ar). Extremes, outliers (extreme coefficient = 3, outlier coefficient = 1.5), maximum, 3. quartile, median, 1. quartile and minimum value are shown. Only logs with a diameter > 0.1 m are regarded.

The median number of logs (related to section length) hardly differ between lowland streams (191 logs km^{-1}) and streams in the lower mountain area (200 logs km^{-1}) (Figure 2.8). The number of logs in the lowland and lower mountain streams corresponds to an average spacing of about 5 m. There is an insufficient number of stream sections to calculate median number of logs related to section length for the alpine streams. Related to bottom area, the mean number of logs in the alpine streams (35 logs ha^{-1}) is significantly lower compared to the lowland streams (491 logs ha^{-1}, Mann-Whitney-U-test, $p < 0.05$). There is an insufficient number of lower-mountain streams to support an estimate.

2.6 Discussion

In this discussion, the term "pristine conditions" is not used, since the term is not applicable for a cultural landscape such as Central Europe. Since the end of the Pleistocene ice age man has continuously altered the entire Central European landscape, thus making descriptions of pristine conditions impossible. Instead, the term "potential natural state" is used, which is defined as the condition that would develop from the current situation without further human impact (see section 1.4). Such a hypothetical picture is frequently used as a reference for stream assessment purposes in Central Europe (Deutscher Verband für Wasserwirtschaft und Kulturbau 1996) and can serve as a reference and target condition in stream restoration projects. In the following section it is discussed if the observed quantities of large wood allow estimations of the amount of large wood that should be present in a particular stream type in the potential natural state.

2.6.1 Variability of the large wood standing stock and supply

Over long time-periods and wide geographic areas the average amount of large wood is probably constant (Murphy and Koski 1989). However, local variability of large wood standing stock in streams is considered to be high under natural conditions due to small and large scale disturbances and long-term forest cycles (Harmon et al. 1986; Gurnell et al. 1995, Nakamura and Swanson 2003). Therefore, a heterogeneous distribution of large wood is typical for natural streams.

Nevertheless, some factors equally influence all streams of a particular ecoregion and differ between ecoregions: First, forest productivity determines the supply of large wood (Lienkaemper and Swanson 1987; Scherzinger 1996). Second, different input mechanisms (e.g., bank erosion, windthrow, fire, downhill sliding, avalanches, debris torrents, transport from upstream) deliver large wood to the stream (Keller and Swanson 1979; Gurnell et al. 1995; Swanson 2003), which differ in importance depending on the geographical setting (Nakamura and Swanson 2003). Third, distribution and stability of large wood is largely dependent on the stream order (Keller and Swanson 1979; Piégay and Gurnell 1997; Marcus et al. 2002) and hydrological regime. Fourth, stream geochemistry influences decomposition rates (Kaushik and Hynes 1971; Melillo et al. 1983). Fifth, at least for North American species, decomposition rates are far lower for wood from coniferous trees compared to wood from deciduous trees (Swanson and Lienkaemper 1978; Harmon et al. 1986) and depend on the log diameter (Murphy and Koski 1989). Differences of decomposition rates decrease distinctly if the logs are submerged and saturated compared to logs that are repeatedly wetted and dried as stream level fluctuates, but they still differ by a factor of 1.5 (Bilby et al. 1999). Although only streams flowing through deciduous forests are considered in this study, differences in the decomposition rate probably influences the amount of large wood present in the potential natural state.

Though it seems impossible to accurately estimate the local volume of large wood due to the high variability of large wood standing stock, it should be possible to define different ranges for certain ecoregions. The data on the volume of large wood presented above indicate that the quantity of large wood in alpine streams related to bottom area is less than in lower mountain and lowland streams. Median volume of large wood related to section length was not calculated for alpine streams due to insufficient data, but the values of the three alpine stream sections (22.0 $m^3\ km^{-1}$, 13.7 $m^3\ km^{-1}$, 41.5 $m^3\ km^{-1}$) fall within the range of the other two ecoregions. Therefore, the differences between the ecoregions in respect to the volume of large wood related to bottom area are obviously due to the fact that the channel width of the braided alpine stream sections is much higher compared to the straight to meandering sections of the streams in the lowlands and lower mountain areas.

There is no obvious reason for the higher variability of the volume of large wood in the lower mountain stream sections compared to the lowland sections. The slope of the stream bottom is not known for most of the lower mountain stream sections, but it is probably lower in the lowland sections. Stream sections also differ in respect to section length. But variability of the volume is thought to decrease with section length, because samples taken from longer lower mountain stream sections should result in more representative estimates. Most probably, the differences are an artefact due to differences in methods used and low number of samples.

Regarding only stream sections of the lowland and lower mountain ecoregion, the data reveal a weak relation between slope and percentage of large wood accumulated in debris jams (slope of stream bottom is not known for the alpine stream sections).

2.6.2 Contrasting the study with others

Harmon et al. (1986) compiled data on large wood present in 83 stream sections of unmanaged forests throughout North America. The volume of large wood ranged from 2.5 to 4500 m^3 ha^{-1}, with a median volume of 400 m^3 ha^{-1}. In Canadian boreal forest streams (1st to 6th order) altered by the beaver (*Castor canadensis*), the standing stock of fine wood (0.01-0.1 m diameter) ranges from 0.41 to 1.8 kg/m^2 and the standing stock of large wood (> 0.1 m diameter) ranges from 1.0 to 39.7 kg/m^2 (Naiman et al. 1986). This corresponds to a volume of 20 to 794 m^3 ha^{-1}, if an average density of 0.5 Mg/m^3 is applied.

Most of the streams mentioned above are located in coniferous forests. Because decomposition rates are far lower for coniferous trees compared to deciduous trees, the large wood standing stock of streams flowing through coniferous forest is probably much higher and can not be compared to the volume of large wood in the streams investigated in this study. Data on the volume of large wood in "near-natural streams" flowing through deciduous forests are rare, but data on the wood standing stock of 26 stream sections could be compiled from literature (Table 2.3). The volume of large wood in these stream sections ranges from 0.5 to 576 m^3 ha^{-1}, with a median volume of 126 m^3 ha^{-1}. According to literature, these streams are among the most natural stream sections in the areas investigated, but almost all of the streams are altered in respect to the volume of large wood due to historic or current forest practices and the removal of large wood.

Median large wood standing stock in the streams considered by Harmon et al. (1986) is about 11 times higher compared to the stream sections investigated in this study. If only streams in deciduous forests are considered (Table 2.3), the difference is less striking (~3.3 times higher), but still statistically significant (Mann-Whitney-U-test, $p < 0.01$). The volume of large wood related to bottom area is markedly lower in the alpine stream sections, because the width and bottom area of the braided alpine stream sections is high compared to the lowland and lower mountain study streams. Therefore, differences could be due to the low values of the alpine study streams. But median value of the streams compiled from literature is significantly higher compared to the study streams (~3.0 times higher), even if only the lowland and lower mountain stream sections are considered, which have a median volume of 41.4 m^3 ha^{-1} (Mann-Whitney-U-test, $p < 0.01$).

Table 2.3
Volume of large wood in most natural stream sections flowing through forests dominated by deciduous trees in North America, Australia, Spain and UK. LW = large wood. *stream sections which meet the following criteria were selected from Diez et al. (2001): (a) maturity index 4-5, (b) average width of riparian forest > mean tree height (25 m) or forested floodplain present. In virtually all studies, only large wood within the bankfull channel was considered. A-g = *Alnus glutinosa* (European black alder) C-s = *Castanea sativa* (Spanish chestnut) E-c = *Eucalyptus camaldulensis* (river red gum), HW = hardwood (not further specified), L-s = *Liquidambar styraciflua* (sweetgum), L-sc = *Leptospermum scoparium* (manuka), M-c = mixed deciduous (not further specified), N-a = *Nyssa aquatica* (water tupelo), N-s = *Nyssa sylvatica* (black gum), Q-n = *Quercus nigra* (water oak), Q-spec = *Quercus spec.* (oak), S-spec = *Salix spec.* (willow), T-d = *Taxodium distichum* (baldcypress), T-l = *Tristaniopsis laurina* (water gum).

region	site	reference	dominant riparian tree species	age of forest stand	bankfull channel width (m)	volume of LW (m^3 ha^{-1})
NE / SE USA	Minnie Ball Branch	Harmon et al. (1986)	HW	~200 years	5.7	70
	Pardon Branch			~50 years	3.6	40
	Ekaneetlee Branch			~200 years	5.2	160
	Ramsey Prong			~200 years	6.5	60
	Trillium Creek			~200 years	4.6	300
	Ogeechee River	Wallace and Benke (1984)	T-d, L-s, Q-n, N-s, N-a	heavily forested floodplain	33	148
	Black Creek				21	168
SE Australia, S New Zewland	Pranjip Creek	O'Conner (1992)	E-c	mature forest	unknown	350
	Pranjip Creek				unknown	550
	Rakeahua River	Evans et al. 1993	L-sc	ancient native	3	100.6
	Silverstream		L-sc	~120 years	3.5	71.2
	Thomson River	Gippel et al. (1996)	E-c	unknown	48.1	172
	Tonghi Creek	Webb and Erskine (2003)	T-l	undisturbed	14.5	576
Northern Spain	Cuchillo 1	Diez et al. (2001)	Q-spec., A-g, C-s	mature forest stand*	3.5	226
	Cuchillo 2				3.9	136
	Salderrey				3.8	128
	Cabrerizas				3.2	222
	Perea 1				3.6	124
	Perea 2				4.4	114
	Cuchillo 3				5.8	147
	Agüera 7				13.6	0.5
United Kingdom	New Forest	Gurnell (2004) unpublished	M-d	> 100 years	1.3	76
	New Forest				1.7	36
	New Forest				2.3	50
	New Forest				3.7	58
	New Forest				5.3	116

However, the data presented in this study indicate that under favourable conditions a large wood standing stock comparable to those of pristine North American streams can be obtained, even comparable to those of coniferous forest streams. Currently, such situations are only found in a few very short floodplain sections which border a slope with unmanaged forest.

Historical descriptions of "near-natural" streams can be used as complementary information to deduce the potential natural state of streams, as it has been mentioned in section 2.2. Some historical records of the first European explorers exist that describe the pristine state of North-American rivers before the European settlement. These records reveal that large amounts of wood caused the formation of massive accumulations, which often completely jammed the whole river. In the Willamette River - a 9th order, formerly braided river (catchment area 29,138 km^2) in the Pacific Northwestern U.S.A. – the multiple channel was filled with snags and fallen trees *"too numerous to count"* and some chutes were obstructed by masses of driftwood (Reports of the Secretary of War (1875), cited in Sedell and Froggatt (1984), p. 1830). Even larger debris jams were reported to occur in the Red River, a lowland river in the southeastern U.S.A. (catchment area approximately 236,000 km^2). In the historical records reviewed by Triska (1984) a series of debris jams, the so called "Great Raft", was described, which affected 390-480 km of the main channel and instantaneously blocked approximately 225 km.

Comparable historical records about large wood in pristine Central European streams are missing, because of the long settlement history, but some information about the amount of large wood in historical times (18th century) in the Central European river Oder is given in Herrmann (1930). He reviewed historical records and reported that *"die Oder lag wie mit Eichen bepflastert voll und zeigte mitunter ein Verhack von Hölzern"* („the river Oder was plastered with oak trees and accumulations of logs occurred", Herrmann (1930), p. 18). In 1782, 502 oak trees and 1171 logs were removed from the Oder between Oppeln and Oberwitz, which corresponds to a spacing of 16 oak trees km^{-1} and 38 logs km^{-1} related to reach length. This amount of large wood probably is far less compared to the potential natural state, because (a) large parts of the floodplain were used for agriculture and therefore, the input of large wood was markedly reduced, (b) large wood has been already removed from the river Oder before 1782, and (c) probably only the large wood pieces that hindered navigation were removed to reduce costs of the clearing action. Therefore, the number of 20 trees km^{-1}, which is considered to be the amount of large wood present in the potential natural state in Central

European rivers in one textbook (Landesumweltamt Nordrhein-Westfalen 2001), must be considered to be a conservative estimate.

2.6.3 Explaining the observed differences

For several reasons, the large wood standing stock present in the study streams is probably considerably lower than the amount of large wood in the potential natural state.

First, large logs (> 0.2 m diameter, > 3 m length) are rare and very large logs (> 0.5 m diameter, > 10 m length) are missing completely. If present, such logs comprise a large part of the large wood standing stock (Kail and Gerhard 2003) and distinctly increase the volume of large wood. Very large logs, particularly those with rootwads, act as stable key pieces, which trap floating wood and lead to the formation of debris dams (Collins and Montgomery 2002; Abbe and Montgomery 2003). Therefore, if large stable logs are missing, the volume of large wood additionally decreases, because smaller wood pieces are transported downstream.

Second, median volume of lowland and lower mountain stream sections do not differ. Differences are to be expected in the potential natural state, because several important factors influencing the input and decay of large wood differ between these ecoregions (see 2.6.1). For example, Gurnell (2003) showed that stream sections flowing through different forests differ in the amount of large wood present in these streams.

Third, the volume of large wood is low in comparison to the loadings in other most natural stream sections in temperate forested ecoregions, even if only the lowland and lower mountain study streams are considered. The potential natural volume of large wood in temperate forested ecoregions probably is higher than the values given in Table 2.3, because even these streams have been altered in respect to the volume of large wood due to forest management and the removal of large wood.

Large wood standing stock of the study streams is small, although there is currently no management of the riparian vegetation and no removal of large wood takes place. This is probably due to the fact that the streams have been influenced by man for centuries. Such historic alterations of the channel and the floodplain may still affect the stream in several ways: First, virtually all forests in Central Europe have been managed and economically used in the past. The age distribution of trees differs significantly from that of natural forests even decades after forestry has ended. This may be the reason why logs with a diameter of more than 0.5 m are almost completely absent in the study streams. Such large old trees bear a large potential for large wood supply. Second, large scale disturbances (wildfires, disturbances by wind, floods, insect outbreaks) rarely occur in a cultural landscape like Central Europe. Even small scale disturbances (landslides, erosion, floods) are largely prevented by man. Such catastrophic events are known to deliver large amounts of large wood to streams (Maser and Sedell 1994; Nakamura and Swanson 2003). Third, large wood was probably removed during earlier times, and cessation of management is too short for an accumulation of large wood. Fourth, though the beaver (*Castor fiber*) has been re-introduced in some parts of Central Europe (Nolet 1997), it is still too rare to enhance large wood supply on a large scale.

As a result of all these factors, none of the study streams receives a "potential natural" supply or boasts a respective large wood standing stock. This is probably true for virtually all streams in Central Europe. Even in nature reserves, it may take centuries to end the effects of these alterations on large wood supply and standing stock.

2.6.4 Modelling the amount of large wood

As it has been stated above (section 2.2), models of wood dynamics can potentially be used to simulate the number and volume of large wood pieces present in the potential natural state of streams and rivers. The large wood standing stock essentially depends on (a) forest productivity (Lienkaemper and Swanson 1987; Scherzinger 1996), (b) processes and mechanisms affecting the amount of wood delivered to the channel (stand dynamics, tree mortality, direction of tree fall, bank erosion, windthrow, wildfire, insect outbreaks, downhill sliding, avalanches, landslides, mass failure, transport from upstream), and (c) processes controlling the depletion of wood (breakage, mechanical abrasion, downstream transport, decomposition) (Keller and Swanson 1979; Gregory et al. 2003b; Nakamura and Swanson 2003; Swanson 2003).

Most of these processes have been integrated at least in some of the 14 models, which have been developed so far (see review in Gregory et al. (2003b)). Virtually all of these models have been developed and applied in North America to (a) investigate processes that influence the amount and distribution of large wood, (b) to predict the amount and distribution of large wood resulting from different forest management practices, and most of the models have been described in open literature (Murphy and Koski 1989; McDade et al. 1990; Van Sickle and Gregory 1990; Malanson and Kupfer 1993; Beechie et al. 2000; Bragg 2000; Downs and Simon 2001; Welty et al. 2002; Benda and Sias 2003; Meleason et al. 2003).

All three authors who have carried out a sensitivity analysis reported that parameter values for the overall depletion rate or the decay rate strongly influenced the outcome of the models

(Welty 2002; Benda and Sias 2003; Meleason et al. 2003). Decay rates are markedly lower for submerged wood pieces compared to terrestrial rates and higher for wood, which is repeatedly wetted and dried as stream level fluctuates (Cederholm et al. 1997; Bilby et al. 1999). Therefore, decay rates differ in dependence on the vertical location of the wood pieces. Moreover, decay rates of submerged logs are known for some North-American tree species (Bilby et al. 1999), but comparable investigations are rare for Central Europe. So far, decay rates were reported only for small wooden cubes (1 cm^3) of beech wood (*Fagus sylvatica*) (Hendel and Marxsen 2000), which have a high surface to volume ratio and thus, can not be compared to decay rates of large logs. Investigations on the decomposition of different tree species in dependence on their vertical location within the bankfull channel are necessary to allow for the modelling of wood dynamics in streams and for estimating the wood volume present in the potential natural state.

2.7 Conclusion

The data presented in this section reflect the current knowledge on the amount of large wood in some of the most natural Central European streams. The streams examined were regarded as being "near-natural" according to Central European standards.

The range of the volume covered by the study streams can be seen as the minimum volume of wood that should be present in a "near-natural" Central European stream. However, it is hard to estimate how closely these values relate to natural conditions. Presumably, large discrepancies exist, as is suggested by the lack of large size classes, the absence of differences between streams in different ecoregions, the comparison with most natural streams in other temperate forested ecoregions, and the anthropogenic alterations mentioned above.

Nevertheless, the data reflect the current upper range of large wood standing stock in Central European streams. Most streams receive a far lower supply and large wood is regularly removed. Thus, in the majority of Central European streams, hardly any logs can be found.

This compilation leads to the conclusion that large wood is still an important substrate in some Central European stream sections. The values presented should be considered as the minimum volume targets to be obtained in restoration projects for streams and riparian areas. A potential natural stream morphology and community would probably boast a much larger amount of large wood. Therefore, stream restoration projects should aim to increase the input of large wood, even in the most natural stream sections.

3 Influence of large wood on mesoscale channel morphology in Central European streams

3.1 Summary of the section

The impact of large fallen trees on channel form is described for six short stream sections in Central Europe influenced by large wood (LW sections), five of which are compared to nearby reference sections free of large wood (reference sections). Three-dimensional models of streambed topography were generated by surveying cross sections with a spacing of one per 1/15 channel width. Parameters derived from digital terrain models and cross sections compared between LW sections and reference sections include the extent of pools, bars, and cut banks, streambed and bank complexity, cross-sectional area, width, depth, and cross-section complexity as described by Andrle's (1994) 'angle-measurement-technique' (AMT-Analysis), a measure of the deviation of a cross-section line from a straight line.

Structural diversity is greater in LW 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 LW section where the fallen tree is oriented parallel to flow, the ratio of pool volume to bed planimetric area ranges from 424 to 693 $m^3\ ha^{-1}$, which is in the upper range reported for small, high-gradient streams in Oregon, Northwest America (229 to 755 $m^3\ ha^{-1}$, Carlson et al. (1990)). Pool volume of LW 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 LW sections and reference sections indicate a strong morphologic control of large wood in these Central European stream sections.

3.2 Scope of the section

The influence of large wood 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 (see section 1.2). Comparable investigations are rare for Europe, where the impact of large wood is far less obvious. But 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 large wood dams on channel morphology in small to medium sized streams in Southern England. Piégay et al. (1998) described changes in channel topography and sedimentation in a 6th-order river (Ain River, France) characterised by complex wood accumulations. Accumulations of large wood 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 two recent studies - one that quantified the effect of large wood on channel depth and width in two small Central European streams (Gerhard and Reich 2000), and one that described the topography of a sand-bed stream with a high wood loading (Mutz 2000) - little is known about the impact of large wood on channel morphology in Central European streams and rivers.

In this section, small-scale channel morphology of six Central European stream sections influenced by single large fallen trees is described, and five of these sections are compared 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 cut banks; 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 wood.

This study focuses on small-scale channel morphology instead of a reach-scale for three reasons. First, morphological features associated with single pieces of large wood are easy to interpret. Second, appropriate study stream sections with high wood loadings on a reach-scale are rarely found in Central European streams. Third, the influence of single large fallen trees on channel morphology is of special interest, because single trees are increasingly used in Central European river restoration projects to alter channel hydraulics, initiate natural channel dynamics, and enhance structural diversity. The main objective of the study is to quantify the effect of single large trees on channel morphology to assess the changes that can be expected to occur in restored stream sections in which such single large trees are used.

3.3 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 (see section 2). Stream managers usually remove large wood 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) (Figure 3.1), 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 mountain areas, primarily consisting of argillaceous shale.

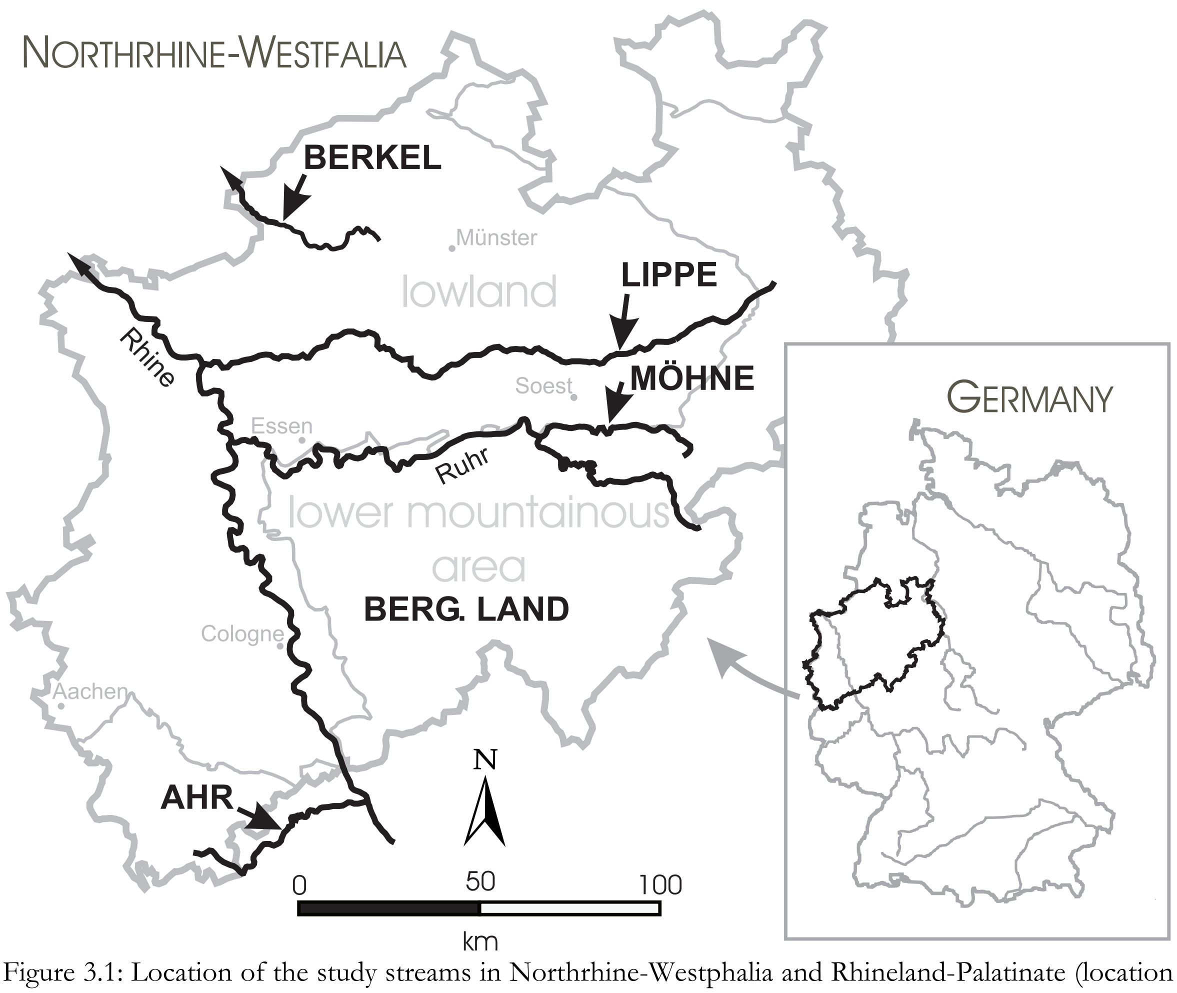

Figure 3.1: Location of the study streams in Northrhine-Westphalia and Rhineland-Palatinate (location of the Ahr study stream), Germany. The author is under a legal obligation not to exactly locate the Berg. Land stream section.

Table 3.1
Data on the investigated stream sections and the investigated large wood pieces (LW), RS = reference section, LW = LW section.

study streams	Berkel1		Berkel2		Lippe
	RS	LW	RS	LW	LW
stream characteristics					
catchment area (km^2)	247.5		247.5		1906
mean section width (m)	12.0	17.8	15.4	16.8	40.5
slope of water level (%)	0.05	0.07	0.05	0.05	0.04
length (section mapped, m)	28.0	50.5	33.5	28.5	44.0
stream type	lowland		lowland		lowland
bed material	sand		sand		sand/silt/ marl
bank material	sand		sand		sand/silt
riparian vegetation	sparse poplar		sparse poplar		sparse willow
section sinuosity	straight		straight		bend
peculiarity of section	deeply entrenched		deeply entrenched		bend
bankline riprap (bankline length %)	50	10	0	0	0
LW characteristics [a]					
date of input [b]	1998		1995		1997
diameter at breast height (m)	75/65/65		50/75		75
horizontal orientation (°) [c]	100/115/115		85/0		0
vertical orientation [d]	ramp/ramp/on bed		ramp/bank		on bed
individual tree volume (m^3) [e]	7.19/4.14/3.55		2.13/2.44		9.68
length / channel width	>1		>1		~0.3
blockage ratio [f]	0.48		0.13		0.05
rootwad anchored in bank	no/yes/yes		yes/no		cabled
LW input	natural		natural		restoration project
discharge (m^3 s^{-1})					
mean annual discharge					
mean low flow		0.368		0.368	7.09
mean discharge		2.83		2.83	23.98
mean high flow		31.4		31.4	110.4
peak flow		59		59	178
discharge since LW input [g]					
mean low flow		0.471		0.347	6.84
mean discharge		3.80		3.10	24.08
mean high flow		43.2		32.7	113.2
peak flow		48		48	178
peak flow recurrence interval		10yr		10yr	10yr

Table 3.1
(continued)

study streams	Ahr		Möhne		Berg. Land[h]	
	RS	LW	RS	LW	RS	LW
stream characteristics						
catchment area (km^2)	538		275		180.5	
mean section width (m)	22.7	31.3	18.1	20.3	18.1	16.0
slope of water level (%)	0.3	0.1	0.2	0.2	0.1	0.6
length (section mapped, m)	41.8	67.0	38.0	54.0	30.0	30.0
stream type	lower mountain		lower mountain		lower mountain	
bed material	gravel/cobble/ boulder		gravel / cobble		gravel / cobble	
bank material	gravel/cobble/ boulder		clay		gravel/cobble/ clay	
riparian vegetation	sparse poplar, willow		sparse alder, willow, ash		dense beech, oak, alder	
section sinuosity	straight		meander		straight	
peculiarity of section	riffle		meander		near-natural	
bankline riprap (bankline length %)	0	20	30	30	0	0
LW characteristics[a]						
date of input[b]	01/1999		03/1998		not known	
diameter at breast height (m)	115		40/60		125	
horizontal orientation (°)[c]	75		90/65		95	
vertical orientation[d]	on bed		ramp/ramp		above bed	
individual tree volume (m^3)[e]	5.4		1.1/5.14		12.34	
length / channel width	~ 0.7		>1		>1	
blockage ratio[f]	0.21		0.36		0.34	
rootwad anchored in bank	no		yes/yes		no	
LW input	natural		natural		natural	
discharge (m^3 s^{-1})						
mean annual discharge						
mean low flow		0.458		0.847		0.472
mean discharge		4.78		4.22		3.39
mean high flow		74.2		42.1		46.0
peak flow		149		96		112
discharge since LW input[g]						
mean low flow	mean discharge data not available			0.782	date of LW input not known	
mean discharge				4.31		
mean high flow				39.6		
peak flow				51		
peak flow recurrence interval	2yr			5yr		

Table 3.1
(continued)
[a] Characteristics of large wood pieces are given for individual trees (several values) or for entire large wood (single value).
[b] Date of input is assessed by means of an consultation of local stream managers, stream ecologists and residents.
[c] Horizontal orientation according to Robison and Beschta (1990a) with 0° the rootwad pointing upstream, 90° perpendicular to flow and 180° the root-wad pointing downstream.
[d] Vertical orientation was classified: "ramp position", rootwad inside the channel and the other end supported on the opposite bank – "on bed", resting on the stream bed – "bank", single large fallen trees lie between top of bank and mean water level parallel to flow – "above bed", inside the bankfull channel but completely above low-flow water level.
[e] Tree volume inside bankfull channel.
[f] Blockage ratio is the cross-sectional area blocked by the single large fallen trees according to Gippel et al. (1996a).
[g] Discharge data since the input of the single large fallen trees are not available for the year 2000 at the Berkel and Möhne study streams.
[h] The author is under a legal obligation not to exactly name the stream investigated.

Figure 3.2: Downstream view at the Berkel1 LW section at mean flow to high flow. Two large fallen trees in the foreground are mainly submerged at mean flow; tree with rootwad in the background is located above mean flow water level.

For five of the study streams, a section influenced by 1-3 fallen trees (LW section) and a nearby reference section without large wood were selected (for details concerning the selection of reference sections see 3.4.1). No comparable reference section could be found within the short restored reach of the Lippe River in which the LW 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 LW 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 (LW sections and reference sections) are characterised in Table 3.1. In order to further illustrate the characteristics of LW sections, a photo of the Berkel1 LW section is given in Figure 3.2.

3.4 Methods

3.4.1 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 wood (LW sections) with nearby reference sections free of large wood (reference sections).

The LW sections were demarcated based on the extent of the large fallen trees and the morphological features (pools, bars, cut banks, channel widening) in the area of the fallen trees 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.

LW 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 LW 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 LW 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.

3.4.2 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 LW stream section with a point density of 3.1 p m^{-2} (which is assumed to represent mesoscale morphology) was progressively thinned to a density of 0.5 p m^{-2}. Terrain models were computed for each data set and compared to the original surface (Figure 3.3). No clear limit was noticeable, but errors increase rapidly when point densities are < 1 p 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 p m^{-2}. Topographic breaks in slope of particular geomorphological importance (e.g., bank top, cut banks, 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 large wood and reference sections of most study streams. Differences in point densities between LW sections and corresponding reference sections are less than 10%, except the Möhne

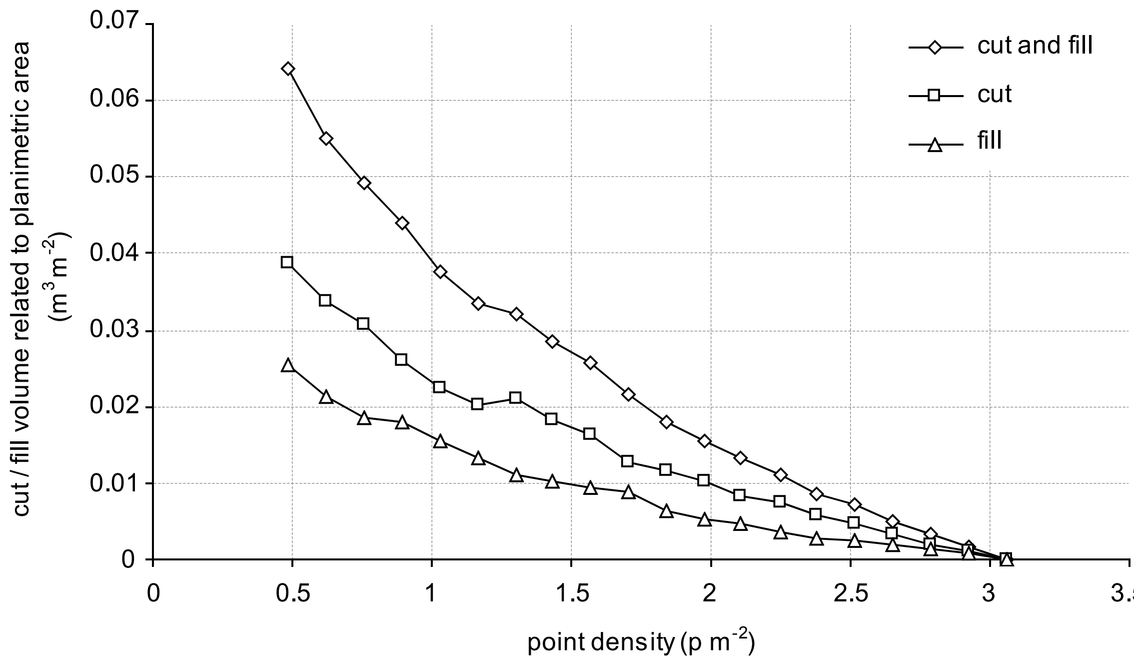

Figure 3.3: Terrain model surface error (per unit stream area) against survey point density.

stream (29%). In the Möhne LW 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 per square meter 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 LW sections is high compared to 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.

3.4.3 Terrain models

Three-dimensional terrain models were computed from the field data using the GIS "ArcView 3D-Analyst" to describe the stream morphology of LW sections and reference sections (Figure 3.4). Surfaces were created as TINs (triangulated irregular networks) 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 stream bed, are defined as bars. Pool and bar volume was computed for single morphological features using the ArcView 3D-Analyst tool "Area and Volume Statistics". Pools and bars were classified according to Church (1992).

Non-vegetated areas of the bank steeper than 65° and above the mean water level were defined as cut banks. The outlines of these cut banks 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).

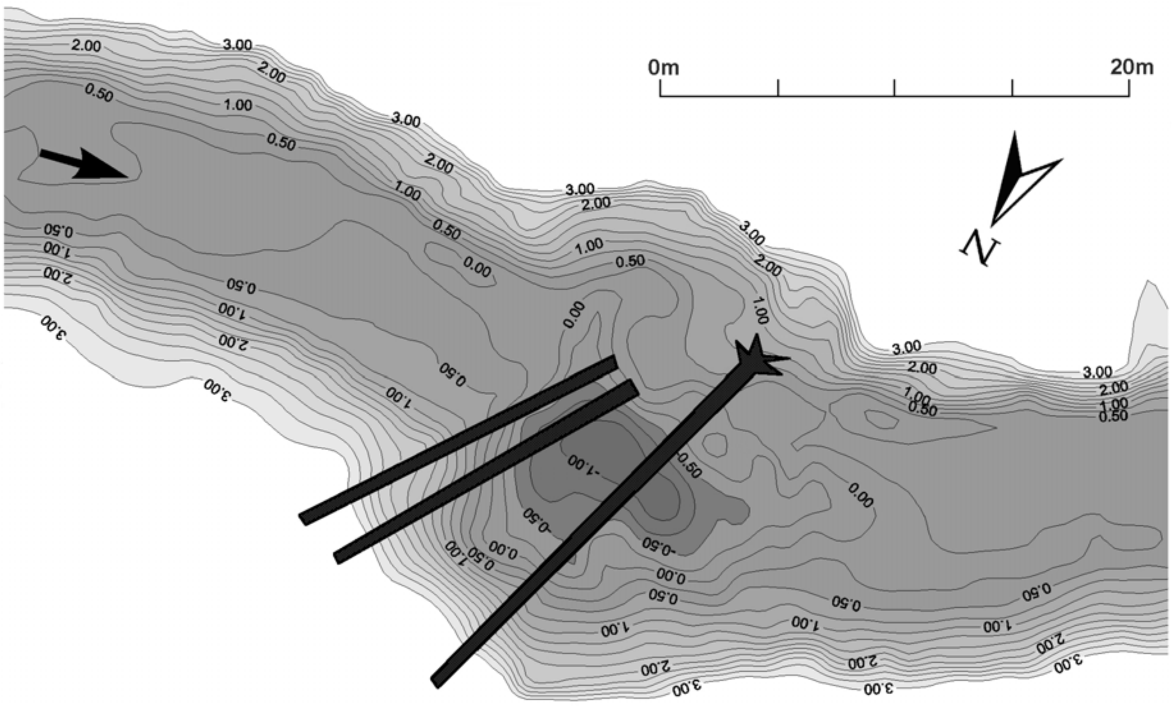

Figure 3.4: Contour map of Berkel1 LW section 3D-model. Height above / below mean stream bed height is given in meters. Stream bed area one standard deviation above / below mean depth of stream bed (0.5 m) is defined as bar and pool respectively. Pool is located downstream of the first large fallen tree, which is located on the stream bed. Sketch of the large fallen trees is not to scale; flow is from left to right.

3.4.4 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 large wood 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 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 bankfull 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).

Habitat diversity is assumed to increase with the variability of the cross-section parameters.

Therefore, an increase of the variability is considered to be an appropriate measure for the ecological effect of the large fallen trees, and hence, cross-section variability is investigated in addition to the absolute value (median).

3.4.5 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 (Figure 3.5). 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.

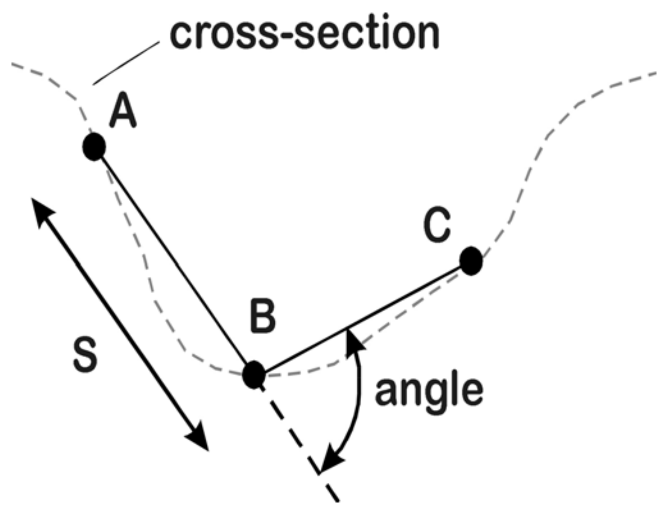

Figure 3.5: Measurement of cross-section angle for AMT-Analysis.

Because mean angle increases markedly with the entrenchment of the channel, AMT-Analysis was restricted to the stream bed. Otherwise, differences in entrenchment of the streams would mask differences in stream bed 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.

3.5 Results

3.5.1 Terrain models

Large pools are associated with the large fallen trees in all LW sections except the Lippe (Table 3.2). Median pool volume ($m^3\ ha^{-1}$) is higher in the LW sections than in reference sections (Mann-Whitney-U-test, $p < 0.01$, $n = 29$). Differences are greatest in the LW sections of the lowland streams Berkel2 and Berkel1, which have pool volume 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 LW sections. In spite of the later date of large wood input, pool volume is markedly higher in the Berkel1 LW section, which is possibly due to the higher blockage ratio (see Table 3.1).

Table 3.2
Qualitative and quantitative description of morphological features present at LW sections (LW) 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 large wood' (c.a. with LW).

stream section	morphological feature	volume (m^3)	planimetric area (m^2)	max. depth/height (cm)	surface area (m^2)	pool / bar volume ($m^3 ha^{-1}$)	cutbank area ($m^2 100m^{-1}$)	c.a. with LW
Berkel1 LW	pool	16.8	51.4	75		593.5		+
	side bar	~2	~21	~22		53.0		
	cut banks				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 LW								
	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		+
	cut bank				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		

Table 3.2
(continued)

stream section	morphological feature	volume (m^3)	planimetric area (m^2)	max. depth/height (cm)	surface area (m^2)	pool / bar volume ($m^3 ha^{-1}$)	cutbank area ($m^2 100m^{-1}$)	c.a. with LW
Ahr LW	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 LW	pools	59.6	143.1	98		692.7		
		0.5	11.4	16		5.8		
	point bar	~49	~154	~87		568.3		
	cut bank				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		
	cut bank				67.6		177.4	
Berg. Land LW	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 LW	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		
		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		+
	cut bank				26.1		59.0	

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 side bars and point bars is largely dependent on the delineation of river bed and banks. Small differences in the extent of river bed 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 LW sections of the Berkel2, Ahr, and Lippe. The mid-channel bar volume is 29 times higher in the Berkel2 LW 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 single large fallen trees 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 cut banks is restricted to LW 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). Cut-bank area is nearly the same in the Möhne study sections indicating that the large fallen trees at the LW section did not increase cut-bank area.

Increase in stream bed surface area compared to planimetric area indicates topographic complexity of the stream bed. High values indicate a rough stream bed surface and, therefore,

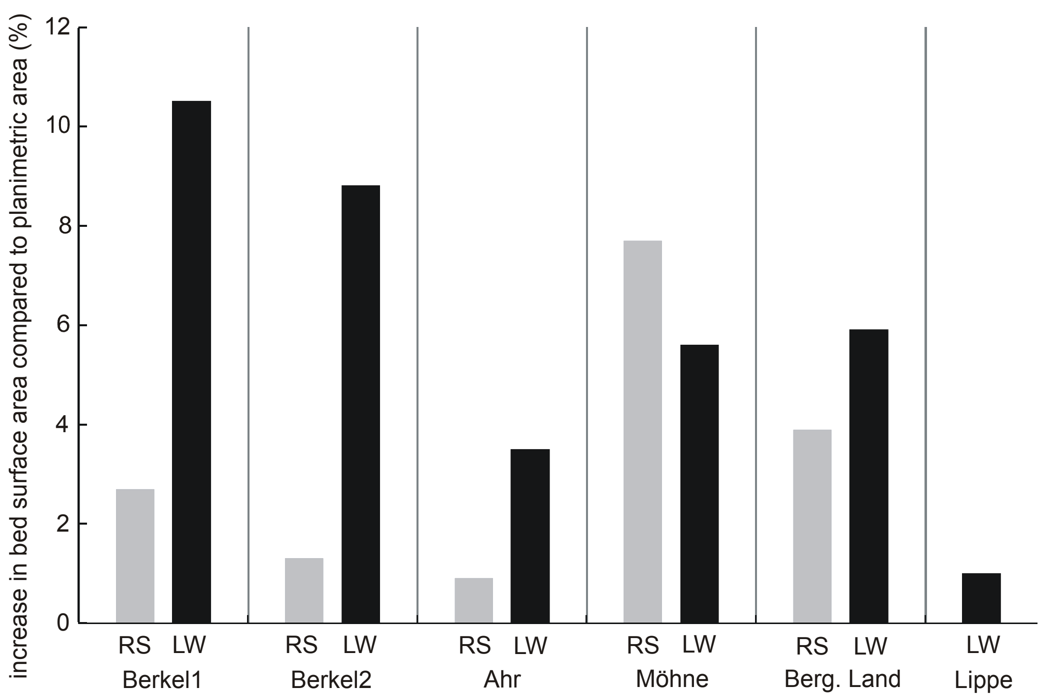

Figure 3.6: Increase in bed surface area compared to planimetric area (%). RS = reference section, LW = LW section.

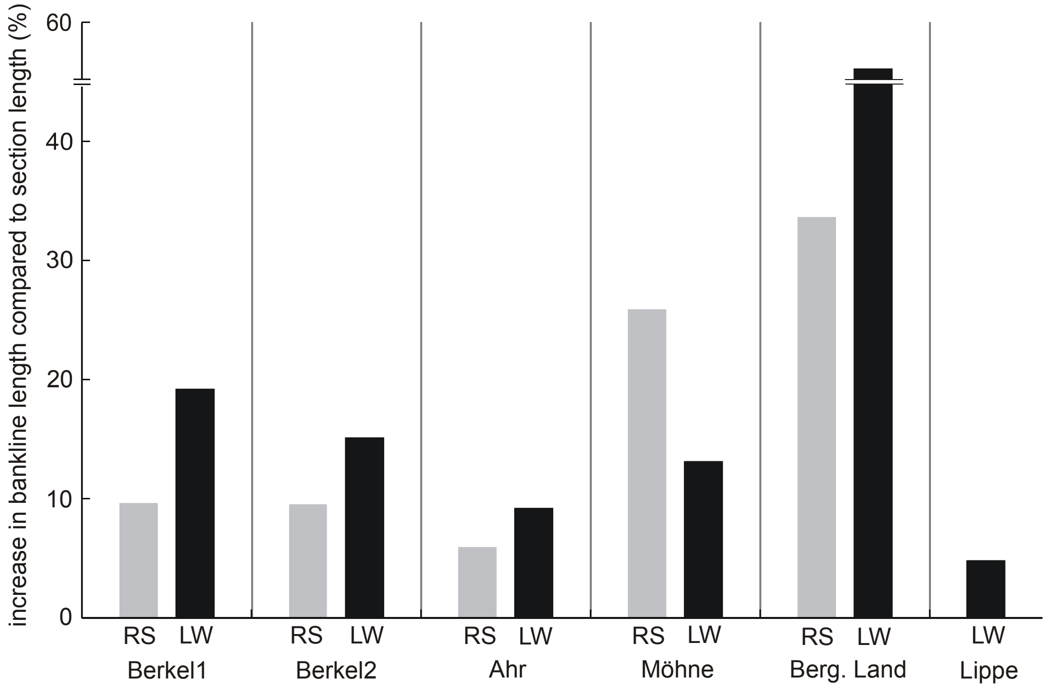

Figure 3.7: Increase in bankline length compared to section length (%). RS = reference section, LW = LW section.

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 LW sections (Figure 3.6). 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 (fourfold higher).

Increase in bank line length compared to section length is a measure of bank line complexity. Bank line length is higher at all LW sections compared to the corresponding reference sections (Figure 3.7) 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 LW sections and reference sections are due to the channel widening induced by large wood (lowland stream Berkel1 and Berkel2, respectively, 2 and 1.6 fold higher in LW 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 LW section (1.6 fold higher) is not apparent.

3.5.2 Cross-section parameters

Considering the quartiles of all values, a distinct increase in variability of cross-sectional area was noted at the Berkel1 LW section (Figure 3.8A). Here, widening of the channel caused by bank erosion and a deep scour pool increased the area of single cross sections dramatically. Differences in cross-section area variability are less pronounced but still statistically significant at the Berkel2, Ahr, and Möhne stream sections (Siegel-Tukey rank dispersion test, $p < 0.01$). Median cross-sectional area is greater at the lowland sand bed LW 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 LW sections and corresponding reference sections at the lower mountain streams Ahr, Möhne 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 LW sections causes differences in cross-sectional area variability at the lowland sand bed LW stream sections Berkel1 and Berkel2 and the lower mountain stream Möhne compared to corresponding reference reaches (Figures 3.8B, 3.8C, 3.8D). Median cross-section width is higher at all LW sections compared to 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 LW 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 (Figure 3.8C). This is also true for the variability of mean depth, which indicates that pools in most LW sections cover a large part of the cross sections and are not restricted to a narrow thalweg (Figure 3.8D). 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 LW sections (sample A) and reference sections (sample B) was tested using the inter-quartile coefficient as a measure of dispersion. Variability of cross-section area and cross-section max. depth is higher at the LW 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 don't differ between LW sections and corresponding reference sections, except the Ahr stream, in spite of an evident change in

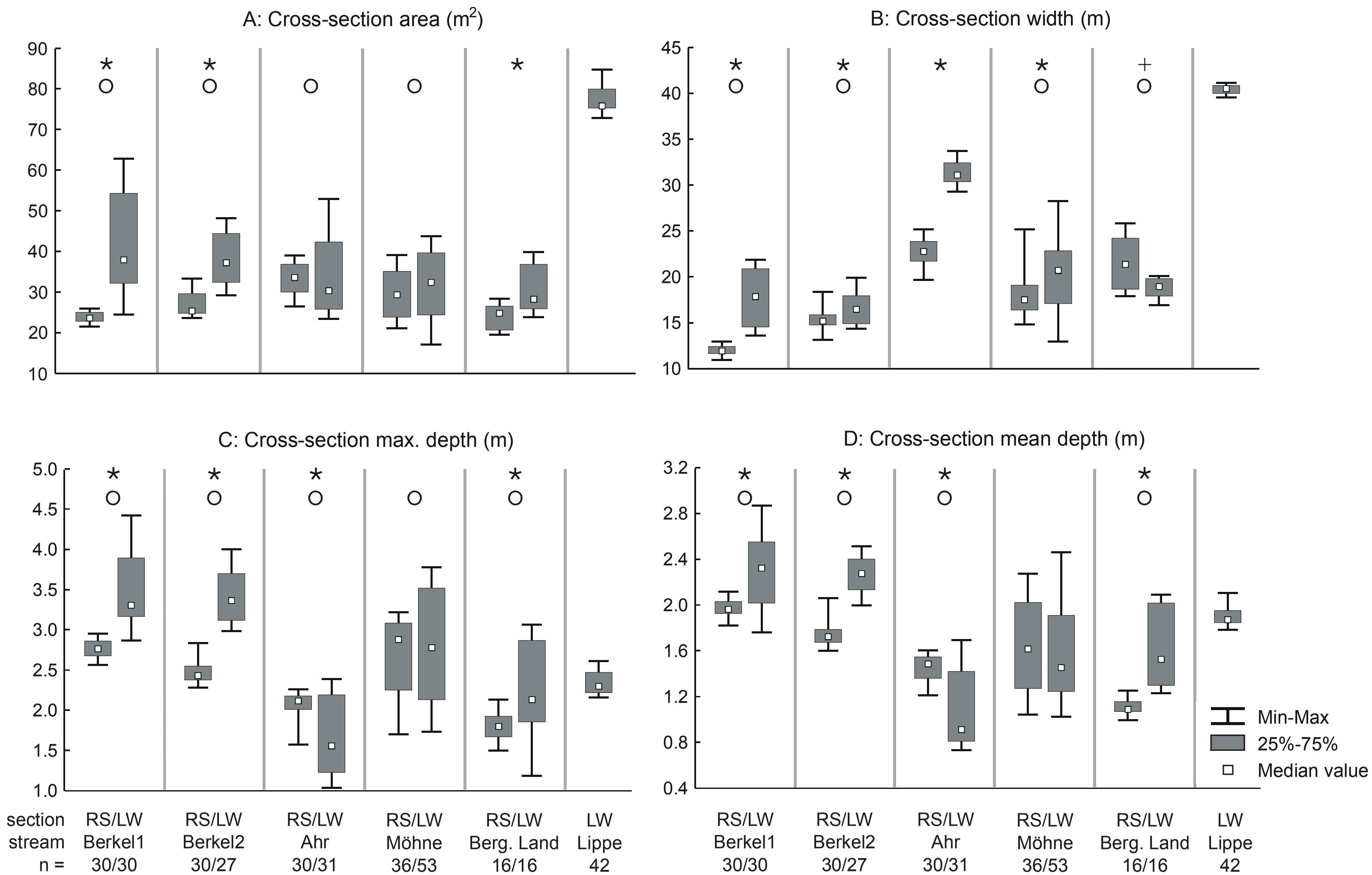

Figure 3.8: Median and variability of cross -section parameters (A: area; B: width; C: maximum depth; D: mean depth) at reference sections (RS) and LW sections (LW). Min-Max, 25%-75%, and median are shown; n = number of cross sections investigated, significant differences between median of LW section and corresponding reference section (Mann-Whitney-U-test): * - $p < 0.01$, + - $p < 0.05$, significant differences between variability of LW section and corresponding reference section (Siegel-Tukey rank dispersion test): o – $p < 0.01$.

channel morphology. Low variability of width/depth ratio at the LW 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 no appropriate measure to describe the effects of large wood on channel morphology at the stream sections investigated in this study.

3.5.3 AMT-Analysis

Median angle of each spatial scale *S* was calculated based on cross-sectional mean angle data for each stream section (Figure 3.9). The median angle of LW sections is significantly greater compared to the reference sections at all scales, with the exception of the 0.3-, 0.4-, 0.7-, and 0.8-m scales (Mann-Whitney-U-test, $p < 0.05$).

Stream sections may be roughly grouped into three categories according to the results of the cluster analysis presented in Figure 3.10. Group A consists of the Ahr, Berkel1, and Berkel2 reference sections, and the Lippe LW 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 (a) the Berg. Land reference section, which shows an increase in median angle up to about 6° at the

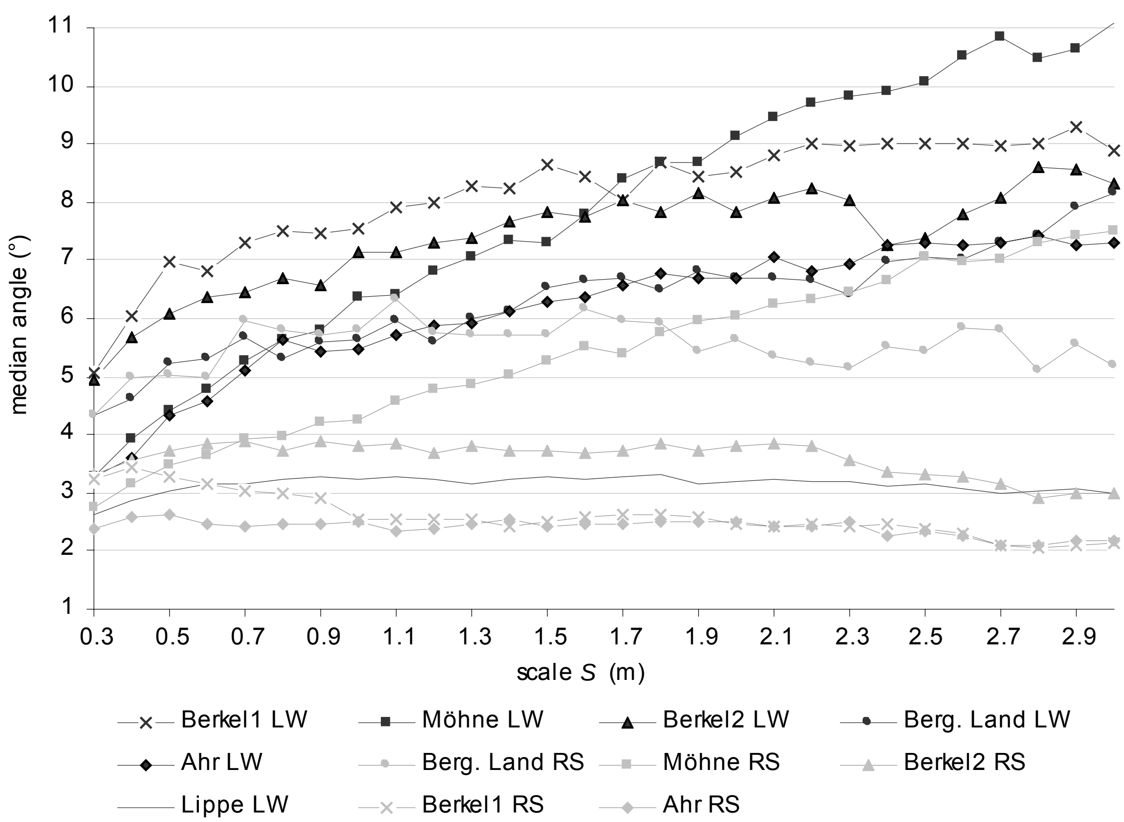

Figure 3.9: Median of mean angle of cross sections at scales S ranging from 0.3-3.0 m. Study sections in legend are listed according to the mean angle over all scales S. RS = reference section, LW = LW section.

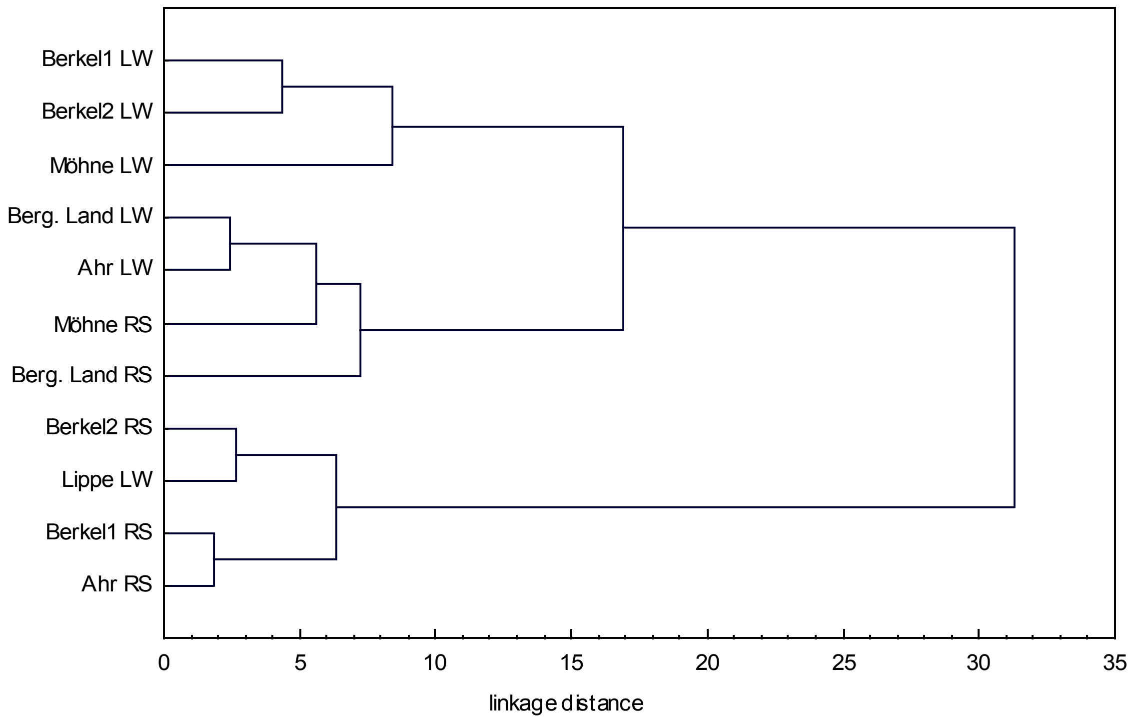

Figure 3.10: Cluster analysis of reference sections (RS) and LW sections (LW) according to the median of mean angle at scales ranging from 0.3 to 3.0 m. Cluster analysis was performed using Euclidian distance and complete linkage, because variables have the same dimension (°) and clusters should rather be naturally distinct groups than elongated trees.

scale of 0.8 m and a slight decrease at larger scales, and which is the member of group B being most similar to group A; (b) the Möhne reference section with an approximately linear increase in median angle from 2.8° to 7.4°; and (c) the Berg. Land and Ahr LW sections, which show a rapid increase up to about 5.5° at the scale of 0.8 m and a moderate, approximately linear increase at larger scales. Group C consists of (a) the Berkel1 and Berkel2 LW sections where the course of the curve can be described as a saturation curve, approximating to angles of about 9° and 8.5°, respectively; and (b) the Möhne LW section, which shows an approximately linear increase similar to the Möhne reference section, but with a steeper slope.

In comparing LW sections with the corresponding reference sections, greater median angles at the LW 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 (2.8, 2.9, and 3.0 m), 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 LW 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.

3.5.4 Relating stream morphology to large wood and stream characteristics

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

Pool volume of LW 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. (1996a). 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.

3.6 Discussion

3.6.1 Power of parameters to describe change in channel morphology

Differences between LW 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 3.4). However, only differences in distinct morphological features such as pools, bars, and cut banks could be detected. This is due to the experimental design of comparing LW 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.

3.6.2 Characteristics of single large fallen trees

It can be assumed that nearly all trees investigated are located where they entered the channel and changed little in position because either (a) they are still anchored in the bank with their root-wad, (b) the cut bank caused by the uprooting of the tree remains in close vicinity to the tree, or (c) 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 ± 25°), which indicates that trees did not rotate at high flows (e.g., Q2 to Q10 floods which have been recorded since the wood entrance). In addition, re-mapping 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 large wood on channel morphology changed little over time and large wood characteristics listed in Table 3.1 represent the conditions that influenced channel morphology since the input of the single large fallen trees. 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 rootwads 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 rootwads, 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 rootwad.

The volume of large wood 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 compared to the number of trees, which can be assumed to be present in the potential natural state (see section 2). The main reasons for the low wood loading in the streams investigated are sparsely vegetated banks (see Fig. 3.2) and the removal of large wood by stream managers. Even in nature reserves stream managers are under a legal obligation to remove large wood, 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.

3.6.3 Comparing observed scour patterns with those described in literature

The pool at the Ahr LW 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 large wood jams at the apex of bars in a large alluvial river. This is possibly a typical scour pattern at wood obstructions located on the stream bed in the middle of the channel, either nearly perpendicular or parallel to flow, if peak flows don't 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 LW section occurs downstream of one of the large fallen trees, which is oriented perpendicular to flow (Fig. 3.4). 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 LW 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.

3.6.4 Assessing the morphological influence of single large fallen trees investigated

Pool volume of the LW 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^{-1} (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 LW 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 (cut-bank 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., cut-bank area increases with channel entrenchment). Meander morphology and local geomorphic controls such as local geology are likely to mask the influence of large wood 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 3.2).

Considering the extent of morphological features at LW sections compared to reference sections, the effect of the large fallen trees on channel morphology is evident in most study streams (Table 3.2, Fig. 3.6-3.10). Although sample size of paired sections is small ($n = 5$) and reference sections vary in structural diversity, the differences between LW 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 LW sections and reference sections could partly be caused by morphological differences that existed prior to large wood input. Comparability of LW 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 doesn't 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 re-mapped in 2001. The results show that considerable changes in channel morphology occurred in all LW 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, side bars expanded), but others diminished (e.g., pools filled, mid-channel bars eroded). Although channel morphology before the first mapping in 2000 and prior to large wood input is not known, and morphological changes observed over a one 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 re-mapping in 2001 suggests), and morphological differences described are strongly dependant on channel conditions (channel morphology, discharge, sediment supply) and large wood characteristics, transferability of the results is limited. However, given similar channel conditions and large wood characteristics, differences between LW sections and stream sections free of large wood of the same order of magnitude are to be expected in Central European streams.

4 Using large wood for stream restoration in Central Europe: quantification of potential use and simulation of effects

4.1 Summary of the section

The potentials for the use of large wood in stream restoration projects are quantified for streams in Central Europe (total stream length assessed 44,880 km). Six different scenarios were investigated differing in the method of stream restoration and in the land uses that have to be restricted to allow for lateral movement of the channel. Hydromorphological data were used to identify stream sections to which the six restoration scenarios can be applied. A hydromorphological quality index was calculated for the pre- and post-restoration state to assess the effects of the "placement" (anthropogenic input of large trees) and "recruitment" (restoring natural recruitment of wood) of large wood. The three recruitment scenarios are suited for only a small percentage (~1% each) of the total channel length in the study area. The potential use of the placement of large wood is much higher (6.5%, 20.2% and 32% of the total channel length if the land uses "forest land, fallow land", "pasture, meadows" and "cropland" are successively restricted). There are differences between (a) the lower mountain area, where a large number of channel segments can be restored, yielding an improvement from a moderate/good to a good/excellent morphological status and (b) the lowlands, where only a small number of channel segments can be restored, yielding an improvement from a bad to a moderate morphological state. The latter upgrading might be sufficient to reach a "good ecological status" as defined by the EU Water Framework Directive (European Commission 2000). The results of this study show the suitability of the recruitment and placement of large wood as appropriate measures to restore a large proportion of the streams in the study area.

4.2 Scope of the section

Large wood is a key feature of stream ecosystems in temperate forested ecoregions. It influences stream hydrology, hydraulics, sediment budget, morphology, and biota across a wide range of spatial and temporal scales (see 1.2). Considering its beneficial effects on stream morphology and biota, large wood can be used for many objectives in stream restoration projects (see 1.3). Many such projects have focused on the placement of artificial, wood structures in the stream in order to improve fish habitat (e.g., Crispin et al. (1993), Cederholm et al. (1997)). According to Kauffman et al. (1997) and Bisson et al. (2003) the placement of large wood can be called "active restoration". Most of these artificial wood structures have been fixed using boulders, cables or wooden earth anchors, which can be considered to be conventional bio-engineering methods and are called "hard engineering" according to Bisson et al. (2003). Such hard engineering restoration measures lead to a short-term improvement of aquatic habitat on the reach scale and are particularly suited if land use rather tightly constrains the options for stream restoration. Alternatively, artificial log jams, which span the entire channel at the downstream end of restored stream reaches, can be installed in order to trap floating wood, as it has been proposed by Gerhard and Reich (2001). Upstream from these barriers large wood can simply be placed into the stream without costly fastening in a technical way. The upstream logs then can be moved by floods, thus allowing for the development of natural instream structures. Such placement of large wood without additional anchoring can be considered to be a "soft engineering" method according to Bisson et al. (2003). Subsequently, this method will be referred to as "**placement**". Placement is suited to restore longer reaches or even whole watersheds, because it is rather inexpensive.

Artificial placement can be regarded as an interim measure prior to the establishment of a riparian forest providing natural input of large wood (Cederholm et al. 1997; Roper et al. 1998, Collins and Montgomery 2002; Bisson et al. 2003). However, restoration tied to "placement" does by itself not support natural input of wood from the riparian forest into streams. Thus, on a long-term basis, restoring processes that sustain large wood recruitment are regarded to be more suitable and less costly, simply because the restoration then is undertaken by the riparian forest (Crispin et al. 1993; Cederholm et al. 1997; Collins and Montgomery 2002; Kondolf 2000; Roni et al. 2002). According to Kauffman et al. (1997) and Bisson et al. (2003) restoration methods like the recruitment of large wood can be called "passive restoration". In the following, restoration based on long-term processes that sustain the input of large wood is referred to as "**recruitment**".

In Europe, there is presently a strong demand for cost-effective stream restoration, because the "European Water Framework Directive" recently enacted by the EU requires a good ecological status of all European rivers to be achieved by 2015. In Central Europe, the main problem is the poor hydromorphological status of most streams, while severe pollution, obvious effects from toxic substances, and acidification have almost vanished in the past decades (Brookes 1987; Lorenz et al. 2004; Verdonschot and Nijboer 2004). The two methods of stream restoration mentioned above - placement of large wood without additional anchoring ("placement") and restoring potentials for large wood recruitment ("recruitment") – are candidate measures potentially suited for a large-scale improvement of hydromorphological river quality. However, the placement and recruitment of large wood can only be applied, if certain conditions are met. Within a reasonable time frame the recruitment of large wood can be a successful strategy only if native riparian stands are already present. Both methods can only be applied if there is no risk of damage to bridges or other works, and if land use does not impose tight restrictions to the degree of achievable stream dynamics. In densely populated areas like Central Europe, virtually all floodplains are used for silviculture and agriculture, or built-up areas (settlements and traffic infrastructure) are located in the floodplain. Therefore, the question arises whether the recruitment and placement of large wood can actually be used in restoration projects implemented to enhance or to restore the majority of streams in Central Europe.

The objectives of this study are: (a) to quantify the potential use of large wood in stream restoration projects in Central Europe and (b) to assess and discuss the potential enhancement of stream morphology by the placement and recruitment of large wood. Pre-existing data on hydromorphology are used to identify stream reaches that allow for the potential application of restoration measures linked to large wood. Results of a hydromorphological survey are used to simulate the potential effects of the placement and recruitment of large wood on hydromorphology.

4.3 Study area

The study area is located in western Germany and includes three federal states, namely Northrhine-Westphalia (NRW), Rhineland-Palatinate (RP), and Hesse (H) (Figure 4.1). The total study area is 74,979 km^2 (21% of the German territory); population density in the study area is about 370 p km^{-2}.

Mainly for reference purposes in the context of the Water Framework Directive, 23 "stream types" have recently been defined in Germany (Schmedtje et al. 2001; Pottgiesser and Sommerhäuser 2004). Each "type" comprises streams that are comparable in size, ecoregion, altitude, and catchment geology, and are characterised by a homogeneous biocoenosis (Tables 4.1 and 4.2).

The study area comprises both lowlands and lower mountains areas, thus reflecting the geomorphological situation in Germany as a whole (Figure 4.1). A total of 16 of the 23 German stream types are present in the study area. The lowland parts of the study area

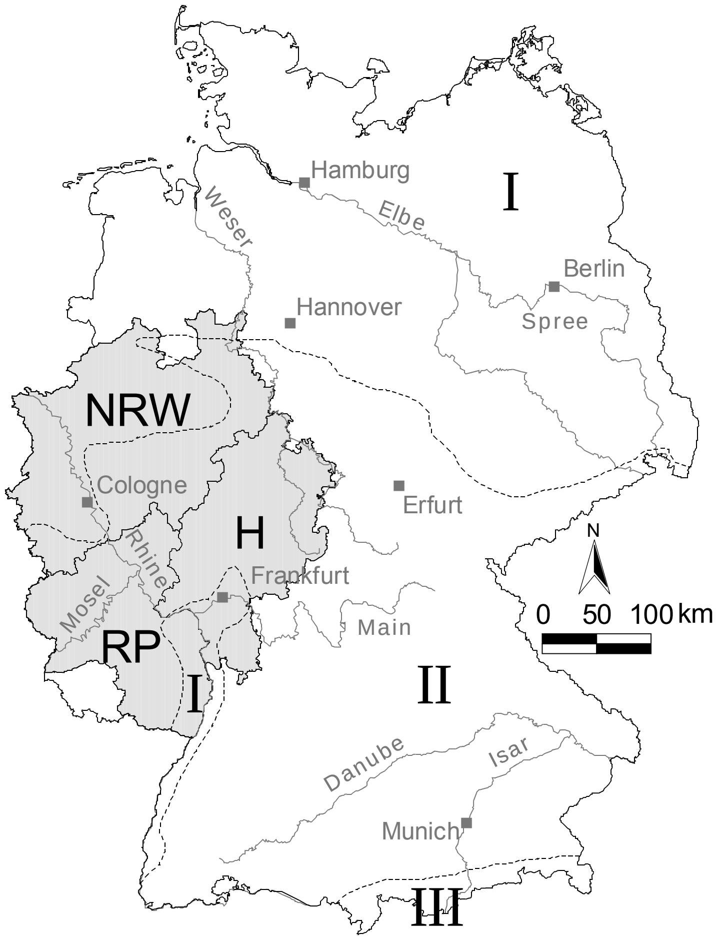

Figure 4.1: Location of the study area in Germany. The study area (grey area) encloses three federal states, Northrhine-Westphalia (NRW), Rhineland-Palatinate (RP) and Hesse (H). Ecoregions are bordered by dotted lines (according to Illies (1978), modified according to Briem (2003)): I – lowland, II – lower mountain area, III – alpine region.

(ecoregion 14 according to Illies (1978), modified after Briem (2003)) are characterized by terraces (24%), gravely-sandy floodplains (23%), loess areas (13%), cretaceous sandstone, mudstone, and marl (12%). In addition, moraines and dunes/drift sand cover small areas. Settlements and traffic infrastructure (18%) and cropland (55%) are the most important land use categories, whereas grassland (9%) and forest (12%) are restricted to small fragmented areas. The most densely populated region of Germany, the "Ruhrgebiet", is located in the northwestern part of the study area (~ 1200 p km^{-2}), while population density in other parts of the ecoregion is lower (~ 250 - 500 p km^{-2}).

The lower mountain parts of the study area (ecoregion 9 according to Illies (1978), modified after Briem (2003)) are dominated by shale (45%), new red sandstone (20%), and mafic volcanic rocks (6%). In comparison to the lowland ecoregion, forests cover a larger part

Table 4.1
Reference conditions of stream types in the study area according to Pottgiesser and Sommerhäuser (2004) (small streams, catchment area < 100 km²).

name of stream type spreading	substrate	channel form	valley slope
T 14 - small sand-dominated lowland rivers			
sander, sandy parts of moraines and terraces	dominant: sand, in addition: gravel / clay	heavily meandering with point bars and cutbanks, shallow cross profile, pools associated with large wood	2 - 7‰
T 16 - small gravel-dominated lowland rivers			
gravelly parts of moraines and terraces	dominant: gravel / cobble, in addition: sand / loam	winding to meandering with pools and riffles, undercut banks, shallow cross profile, minor point bars and cutbanks	3 – 25‰
T 18 - small loess and loam-dominated lowland rivers			
loess areas	dominant: loess / loam plates, in addition: organic material / marl	winding to meandering, entrenched u-shaped cross profile, minor pools and riffles	2 - 12‰
T 19 - small streams in riverine floodplains			
floodplains and terraces of larger streams	dominant: organic material, in addition: grain sizes present	winding to meandering, partly anastomosing, very shallow cross profile, very low gradient	< 2‰
T 5.1 - small fine substrate dominated silicious highland rivers			
new red sandstone	dominant: sand / gravel, in addition: cobble	winding to meandering with point bars, cutbanks, pools and riffles, shallow u-shaped cross profile	4 - 50‰
T 5 - small coarse substrate dominated silicious highland rivers			
shale, granite, gneiss	dominant: cobble / gravel, in additon: fines	in dependance on valley form straight to winding and partly braided, very shallow cross profile	10 - 50‰
T 6 - small fine substrate dominated calcareous highland rivers			
loess areas, Cretaceous sandstone, mudstone and marl	dominant: loam / sand, in addition: gravel / cobble	winding to meandering, entrenched u-shaped cross profile, undercut banks	4 - 30‰
T 7 - small coarse substrate dominated calcareous highland rivers			
calcareous rocks, chalk	dominant: cobble, in addition: fines / organic material	straight to winding, minor pools and riffles, partly intermittent	10 - 50‰

Table 4.2
Reference conditions of stream types in the study area according to Pottgiesser and Sommerhäuser (2004) (medium-sized to very large streams, catchment area > 100 km²).

name of stream type spreading	substrate	channel form	valley slope
T 15 - mid-sized and large sand and loam-dominated lowland rivers			
sander, sandy parts of floodplains, moraines and terracces	dominant: sand / loam, in addition: gravel / clay / marl	winding to meandering with point bars and cutbanks, shallow cross profile, several small floodplain channels	0.2 - 2‰
T 17 - mid-sized and large gravel-dominated lowland rivers			
gravelly parts of moraines and terraces	dominant: gravel, in addition: sand / cobble	winding to meandering with point bars and cutbanks, predominant shallow cross profile, mid-channel bars	0.5 - 1.5‰
T 12 - mid-sized and large organic substrate-dominated rivers			
sander, floodplains, terracces	dominant: organic material, in addition: sand / gravel	anastomosing, very shallow cross profile, very low gradient	<0.5 - 1.5‰
T 20 - very large sand-dominated rivers			
e.g., downstream part of Rhine, Elbe	dominant: sand / gravel, in addition: cobble	winding to meandering, single or multiple channel, wide and shallow cross profile	0.07 - 1‰
T 9 - mid-sized fine to coarse substrate dominated silicious highland rivers			
shale, new red sandstonge, gneiss, granite, other volcanic rocks	dominant: cobble / boulder , in addition: gravel / sand	in dependence on valley width and slope straight to meandering and single to multiple channel, shallow cross profile, pools and riffles, large bars	2 - 6‰
T 9.1 - mid-sized fine to coarse substrate dominated calcareous highland rivers			
calcareous rocks, chalk, marl, mudstone, sandstone, loess areas	dominant: boulder / cobble / gravel, in addition: sand	winding to meandering, partly multiple channel, pools and riffles, shallow to slightly entrenched	0.7 - 4‰
T 9.2 - large highland rivers			
large floodplains of the river	dominant: cobble / boulder, in addition: sand	winding to meandering, in dependence on valley slope single to multiple channel, large banks, shallow cross profile	~3‰
T 10 - very large gravel-dominated rivers			
e.g., downstream part of Danube	dominant: cobble / gravel, in addition: gravel / sand	winding to meandering, shallow cross profile, islands, partly multiple channel	0.2 - 2‰

(43%), grassland (16%) is nearly twice as dominant, whereas settlements and traffic infrastructure (7%) and cropland (27%) cover less area as compared to the lowlands. Population density is significantly lower (~ 50 – 250 p km^{-2}); nevertheless, most streams and rivers have been altered by man (e.g., straightening, bed and bank fixation).

4.4 Methods

4.4.1 Hydromorphological survey

This study is based on a large hydromorphological data set that has been compiled from regional authorities in Northrhine-Westphalia, Rhineland-Palatinate, and Hesse. Since the mid-1990's, hydromorphological surveys have been conducted in most parts of Germany, mainly by regional authorities. However, only in the three federal states mentioned above the hydromorphological survey covered almost all the streams present. Therefore, this study is restricted to the three federal states, where the surveys can be assumed to best represent the overall status of stream morphology.

Slightly different methods have been applied in surveys performed by the individual states. The methods applied so far have not been internationally published in any detail, but essentially correspond to the field survey method of the "Länderarbeitsgemeinschaft Wasser" (LAWA) briefly described by Raven et al. (2002). The LAWA method is described in more detail to enable a full understanding of the data upon which this study is based.

The results of the LAWA hydromorphological survey method can be analysed and interpreted at different levels of resolution: the attributes listed in Table 4.3 are recorded and grouped into six "main categories", further aggregated into three "higher categories" (stream bed, stream bank, floodplain) and finally into a single value.

All attributes are recorded along 100 m channel segments and compared to a reference condition, which is defined as the "potential natural state" of the stream (the condition that would result naturally without further human intrusion, see 1.4). The assessment results of the individual attributes are used to calculate a result for each of the six "main categories". These results are finally gauged by the expert (surveyor) in relation to the presumed reference condition. Possible results range from unchanged (only minor deviations from the reference condition, class 1) to heavily degraded (class 7).

A slightly different method was used to survey larger rivers in Northrhine-Westphalia and Rhineland-Palatinate. The main differences are: (a) a list of attributes specifically applicable to

Table 4.3
Attributes of morphological quality assessment of streams and rivers: *only recorded for streams and rivers in Hesse and small to medium sized streams in Northrhine-Westphalia and Rhineland-Palatinate, **only recorded for large streams and rivers in Northrhine-Westphalia and Rhineland-Palatinate.

higher category	- *main category* attribute
stream bed	- *development of stream course*
	planform
	erosion at bends
	bars*
	features indicating natural channel dynamics (e.g., woody debris, islands)
	- *longitudinal profile*
	artificial barriers limiting continuity of flow, sediment and migration for biota
	culverts
	artificial impoundments
	riffles and steps
	flow-diversity*
	depth-variability*
	flow-diversity and depth-variability**
	diversion hydropower**
	- *river-bed structure*
	substrates
	bed-fixing
	substrate-diversity
	channel-features (e.g., scour and backwater pools, rapids, cascades)
	alteration of river-bed (e.g., navigation, groins, sediment placement)**
stream bank	- *cross-section profile*
	cross-section form
	cross-section depth
	bank erosion (indicating widening of channel)
	cross-section width variability
	bridges
	widening / narrowing**
	- *bank structure*
	riparian vegetation
	revetment / bank protection
	bank features (e.g., woody debris, cutbanks)
	alteration of river-bank (e.g., hydropower peaking)**
floodplain	- *floodplain*
	land-use
	riparian buffer
	floodplain features (e.g., oxbow lakes, high-flow channels)**
	features hindering lateral channel migration (e.g., roads, dumping sites)

characteristics of larger rivers (see Table 3.3); (b) some attributes are recorded using aerial photographs rather than field records (e.g., planform, channel- width variability); and (c) the length of surveyed stream segments is not always 100 m, but dependant on channel width, ranging from 100 m (channel width 5-10 m) to 1 km (channel width > 160 m).

The total length of the surveyed stream sections (n = 431,886) adds up to 44,880 km.

4.4.2 Quantifying the potential use of large wood

To assess the applicability of the two restoration measures ("placement" and "recruitment"), the following criteria were defined. Both restoration measures are only applicable if the lateral movement of the channel is permissible, thus restricting land use in the floodplain. Consequently, both methods will only be applied if the benefit of stream enhancement is considered to be greater than the cost incurred by restrictions on land use. The cost resulting from land-use restrictions is considered to increase in the following order: "natural non-woody vegetation", "forest land", "fallow land", "pastures and meadows" (subsequently referred to as "grassland"), "cropland". It is further assumed that some types of land use can not be restricted (e.g., built-up areas, parks, sport grounds). Consequently, for both methods, "placement" and "recruitment", three scenarios were discerned differing in the land-use types considered to be dispensable (Table 4.4).

Channel segments which meet the preconditions in Table 4.4 and those listed below are

Table 4.4
Requirements for channel segments to be considered as restoration segments, separately given for the six scenarios. Additional requirements for restoration segments of all six scenarios are given in the text.

	scenario	possible land uses of floodplain (>10%)	woody debris recruitment
recruitment	RS-Forest	forestry, natural non-woody vegetation, fallow land	riparian vegetation: native hardwood forest, land use of floodplain: native hardwood forest or natural non-woody vegetation > 50%
	RS-Grass	forestry, natural non-woody vegetation, fallow land, grassland	
	RS-Crop	forestry, natural non-woody vegetation, fallow land, grassland, agriculture	
placement	PS-Forest	forestry, natural non-woody vegetation, fallow land	no requirements
	PS-Grass	forestry, natural non-woody vegetation, fallow land, grassland	
	PS-Crop	forestry, natural non-woody vegetation, fallow land, grassland, agriculture	

subsequently referred to as „restoration segments". The more extensive scenarios always include all restoration segments of the less extensive scenarios (e.g., if cropland is considered to be dispensable, grassland is dispensable, too).

Further requirements for the applicability of the scenarios include: First, only hardwood forest bordering the channel is assumed to ensure a near-natural input of large wood, and thus, meet the preconditions for recruitment, because forest dominated by coniferous trees is not part of the natural vegetation in the study area (Ellenberg 1996). Second, no "features hindering lateral channel migration" (e.g., roads, dumping sites, fish farms) must be present in the restoration segment, since they would be at risk to be damaged. Structures within a distance from the channel of 40% of the floodplain width were used as exclusion criteria (these data were only available for streams in Northrhine-Westphalia). Third, no bridges and culverts serving as bridges must be present within the restoration segment. Fourth, it is assumed that single channel segments (100 m in length), which meet the conditions mentioned above, are too short to be restored. Therefore, the total length of connected restoration segments must be at least 300 m (subsequently referred to as "restoration reach").

The hydromorphological survey for streams in Northrhine-Westphalia and Rhineland-Palatinate does not distinguish between the adjacent land uses "cropland" and "coniferous forest". Thus, data from another source (Corine-Land-Cover) were used to separate between these two types of land use. Because the resolution of the Corine-Land-Cover data is low (25 ha), this must be considered a rough estimate.

4.4.3 Spatial distribution of restoration segments

Three different procedures were applied to describe the spatial distribution of restoration segments: First, for each scenario, the share of segments that are suitable for restoration within a watershed is compared to the share of segments that are suitable for restoration within the whole study area. This comparison of watersheds reveals whether restoration segments are evenly distributed or clumped. Only watersheds with a minimum length of 0.3 km surveyed streams km^{-2} are considered, thus, some watersheds with low data density were excluded from the analysis (3.3% of the total channel length). Overall, 868 out of 1140 watersheds were included in the analysis. Similar comparisons were performed for (2) stream types and (3) stream sizes to investigate if particular stream types or sizes are more or less suited for restoration with large wood.

4.4.4 Simulating the potential enhancement of stream morphology

The precise effect of the placement and recruitment of large wood can not be predicted, because it depends on local conditions. However, the potential for hydromorphological enhancement of the restoration segments can be based on the following general assumptions:
First, the standing stock of large wood in Central European streams is restricted due to the management of riparian forests and the removal of wood from channels. However, in small streams, debris dams are still present and the formation of debris dams is more likely if large wood is added through stream restoration projects. Due to the lack of large key-pieces, the formation of debris dams is unlikely to occur in larger rivers, even if some channel reaches are restored with large wood. Thus, the effect on channel morphology depends on the relative size of the wood pieces and decreases with increasing stream size (Piégay and Gurnell 1997). Hence, in order to assess effects, it seems necessary to distinguish between different stream sizes.

Second, according to data presented in section 2, the frequency of large logs (> 20 cm diameter and > 3 m length) in the most natural Central European stream sections is 21 logs per kilometre (mostly fallen trees). Even these most natural stream sections are far from the potential natural state with respect to large wood standing stock. Therefore, for the assessment of effects, this value is considered to be the minimum input from unmanaged riparian forests.

Third, even single fallen trees can cause the formation of large pools within a time period of one to several years (Kail (2003), section 3). This is considered to be the "minimum effect" of a single fallen tree on channel morphology.

Based on the above assumptions/conditions and the addition of 2 trees per 100 m stream segment, the following predictions are made to describe the potential changes of channel morphology due to "placement" and "recruitment" of large wood. Each tree yields at least one large pool in streams with a channel width of less than 20 m and one small pool in larger streams (relative to channel width). Furthermore, flow and substrate diversity, and depth variability increase. Thus, changes in the values of five hydromorphological attributes are predicted (more or less strongly, dependent on stream size) due to the "placement" and "recruitment" of large wood, according to the hydromorphological survey method for small streams (Table 4.5) and larger rivers (Table 4.6), respectively. The index of hydromorphological quality assessment was re-calculated for each restoration segment considering these predicted changes in channel morphology.

Table 4.5
Proposed effects of restoration. Changes of attribute values for small streams due to the recruitment and placement of large wood described for the different scenarios. In the individual federal states slightly different values have been used to describe attributes (e.g., the highest possible score for the attribute "channel feature" is defined for the value "many" in Northrhine-Westphalia and for the value "> 3" in Hesse). All values used in the individual countries are listed and separated by a backslash. *Since the impact of large wood is dependent on stream size, different simulations have been used for small streams (< 20 m average width) and large streams (> 20 m average width) for the hydromorphological data from Northrhine-Westphalia and Rhineland-Palatinate. However, the hydromorphological data from Hesse do only separate between stream sizes > 10 m and < 10 m average width; thus, in this case 10 m average width is used as a threshold value for the different simulations. The new attribute values are used to re-calculate the morphological quality assessment.

attribute *attribute value*	description	new attribute value of section* channel width < 20 m, < 10	 channel width > 20 m, > 10
features indicating natural channel dynamics			
many \ > 3	features indicating natural channel dynamics (e.g., woody debris, islands, widening, narrowing) of large extent are counted	many \ > 3	many \ > 3
several \ 3		many \ > 3	many \ > 3
two		many \ > 3	many \ > 3
one		several \ 3	several \ 3
low extent		two	two
no		two	two
flow diversity / depth variability / substrate diversity			
very high	> three flow conditions / depth categories / substrate types, three of them of large extent	very high	very high
high	three flow conditions / depth categories / substrate types, two of them of large extent	very high	high
moderate	three flow conditions / depth categories / substrate types, two of them of low extent	high	high
low	two flow conditions / depth categories / substrate types, one of them of low extent	high	moderate
no	one flow condition / depth category / substrate type	high	moderate
channel features			
many \ > 3	channel features (e.g., pools, rapids, cascades) of large extent are counted	many \ > 3	many \ > 3
several \ 3		many \ > 3	many \ > 3
two		many \ > 3	several \ 3
one		several \ 3	two
low extent		two	one
no		two	low extent

Table 4.6
Proposed effects of restoration. Changes of attribute values for larger rivers due to the recruitment and placement of large wood described for the different scenarios. *Since the impact of large wood is dependent on river size, different simulations have been used for small rivers (< 20 m average width), medium sized rivers (20-60 m average width) and large rivers (> 60 m average width) in Northrhine-Westphalia. However, the hydromorphological data from Rhineland-Palatinate do only separate between stream sizes 10-50 m, > 50 m average width; thus, in this case 50 m average width is used as a threshold value to differentiate between medium-sized and large rivers. In Hesse, streams with a width > 10 m are not further differentiated between different size classes; therefore attribute values listed in Table 4.5 were used for all Hessian streams. **According to the hydro-morphological survey method for larger rivers, the instream structures are not simply counted as it is done for small streams, but the respective attribute value (e.g., "many") is only given if all types of instream structures (large wood, island, widening) are frequently occurring. Thus, an increasing number of logs leads to a smaller improvement of the hydromorphological assessment result than in small streams. The new attribute values are used to re-calculate the morphological quality assessment.

attribute *attribute value*	description	new attribute value of section* with a a channel width of		
		< 20 m	20-60 m, 10-50 m	> 60 m, > 50 m
features indicating natural channel dynamics				
many	all types of features indicating natural channel dynamics (e.g., woody debris, islands, widening) are present to the extent described by the attribute value**	many	many	many
several		many	many	many
few		several	several	several
low extent		few	few	few
no		few	few	few
flow diversity / depth variability / substrate diversity				
very high	> three flow conditions / depth categories / substrate types	very high	very high	very high
high	three flow conditions / depth categories / substrate types, two of them of large extent	very high	high	high
moderate	three flow conditions / depth categories / substrate types, two of them of low extent	high	high	moderate
low	two flow conditions / depth categories / substrate types, one of them of low extent	high	moderate	moderate
no	one flow condition / depth category / substrate type	high	moderate	moderate
channel features				
many	channel features (e.g., pools, rapids, cascades) of large extent are counted	many	many	many
several		many	several	several
few		several	several	few
low extent		several	few	low extent
no		few	few	low extent

4.5 Results

4.5.1 Potential use of the recruitment and placement of large wood

The total length of the 431,886 channel segments mapped is 44,880 km (subsequently referred to as "total channel length"). A patchy distribution characterises the stands of native riparian forest required to ensure a natural recruitment of large wood. Therefore, a large proportion of the channel reaches that are generally suited for the recruitment of large wood according to the land use in the floodplain are too short for effective restoration measures (42% < 300 m in length) and hence, neglected. In contrast only 22%-28% of the channel reaches that are generally suited for restoration linked to placement are less than 300 m in length.

For each of the three recruitment scenarios, the restoration segments comprise about 1% of the total channel length (Figure 4.2). This is mainly due to the lack of riparian forest stands along streams. However, even at 1% the total length of these restoration segments is always approximately 500 km. The similarity between the three recruitment scenarios is probably due to the fact that riparian vegetation is needed for the recruitment of large wood; the floodplain of sections with riparian vegetation is usually covered by forest to a larger extend and rarely additionally covered by grassland or cropland (only 6.7% and 2.3% of the total channel length, respectively). Therefore, only few channel segments can additionally be classified as restoration segments in the less rigorous scenarios RS-Grass and RS-Crop.

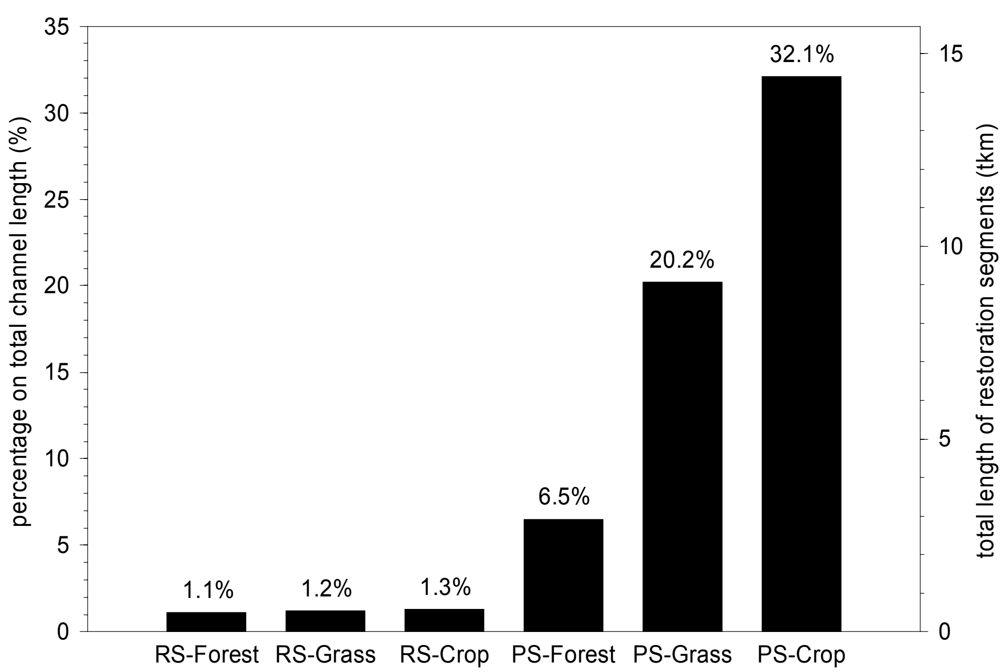

Figure 4.2: Restoration segments' percentage on total channel length and total length of restoration segments for the six scenarios investigated.

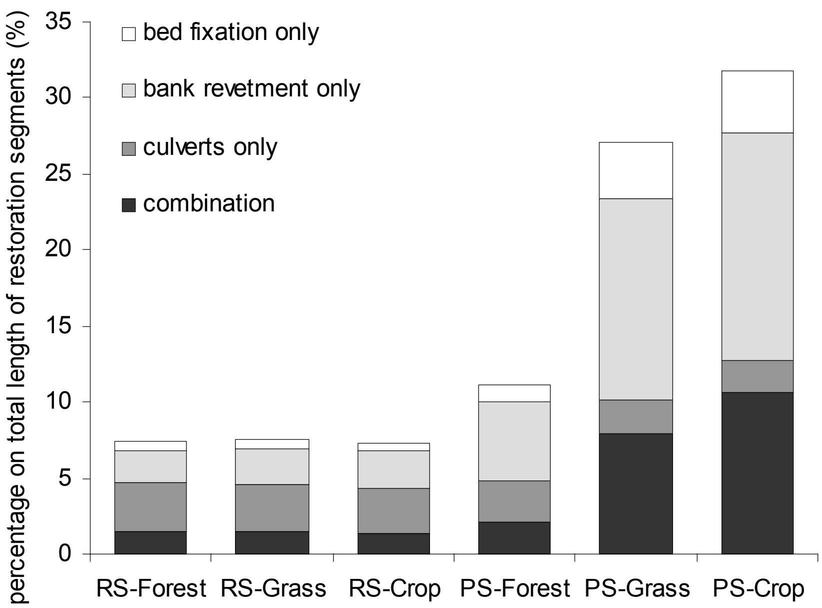

Figure 4.3: Percentage of restoration segments, which need additional removal of engineered instream structures (bed fixation, bank revetment, culverts and combination of these types).

In contrast, the extension of potential restoration segments in the three placement scenarios is much higher, and there are marked differences between the scenarios. Assuming that silvicultural land use can be restricted, 6.5% (~ 3000 km) of the total channel length could be restored by the placement of large wood. Assuming that in addition the land uses "grassland" and "cropland" can be restricted, the percentage markedly increases to about one fifth (~ 9000 km) and almost one third (~ 14000 km), respectively.

In some cases, the removal of engineered instream structures such as bed fixation, bank revetment, and culverts is a necessary precondition for successful restoration (e.g., to facilitate lateral movement or the development of channel features). Additional measures are required for about 8% of the restoration segments (all three recruitment scenarios), 11% of the PS-Forest scenario, 27% of the PS-Grass scenario, and 32% of the PS-Crop scenario, respectively (Figure 4.3). A high proportion of these PS-Grass and PS-Crop sections (33%) can be classified as "heavily fixed" (combination of engineered instream structures present) compared to those of the three recruitment scenarios (~20%).

In general, the placement scenarios allow for longer restoration reaches as compared to the recruitment scenarios. Because the data on the length of restoration reaches are strongly skewed to the right, minimum length of restoration reaches (300 m), lower quartile (300 m), and median (400 m) do not differ between the six scenarios, but upper quartile and maximum length are higher for the placement scenarios (Table 4.7).

Table 4.7
Length of restoration reaches (upper quartile, maximum length and number of restoration reaches). Minimum length (300 m), lower quartile (300 m) and median length (400 m) do not differ between the six scenarios.

	RS-Forest	RS-Green	RS-Crop	PS-Forest	PS-Green	PS-Crop
upper quartile (75%)	500	500	500	600	600	700
maximum	4600	4600	4600	4700	6000	7200
n (restoration reaches)	1073	1134	1229	5403	16107	24458

Few long restoration reaches can comprise a large part of the total restoration segments length. To consider this, the share of different length classes on the total restoration segments length is regarded in addition. The share of restoration segments belonging to long restoration reaches (at least 500 m in length) is greater for the placement scenarios than for the recruitment scenarios (Figure 4.4) and slightly increases within the placement scenarios (PS-Forest < PS-Grass < PS-Crop).

Restoration segments, which are part of very short restoration reaches (300 m and 400 m in length), comprise nearly half of the restoration segments of the recruitment scenarios (48%), but only 29%-34% of the restoration segments of the placement scenarios. Peaks at reach length classes 1 km and 2 km are due to the length of surveyed channel sections in larger

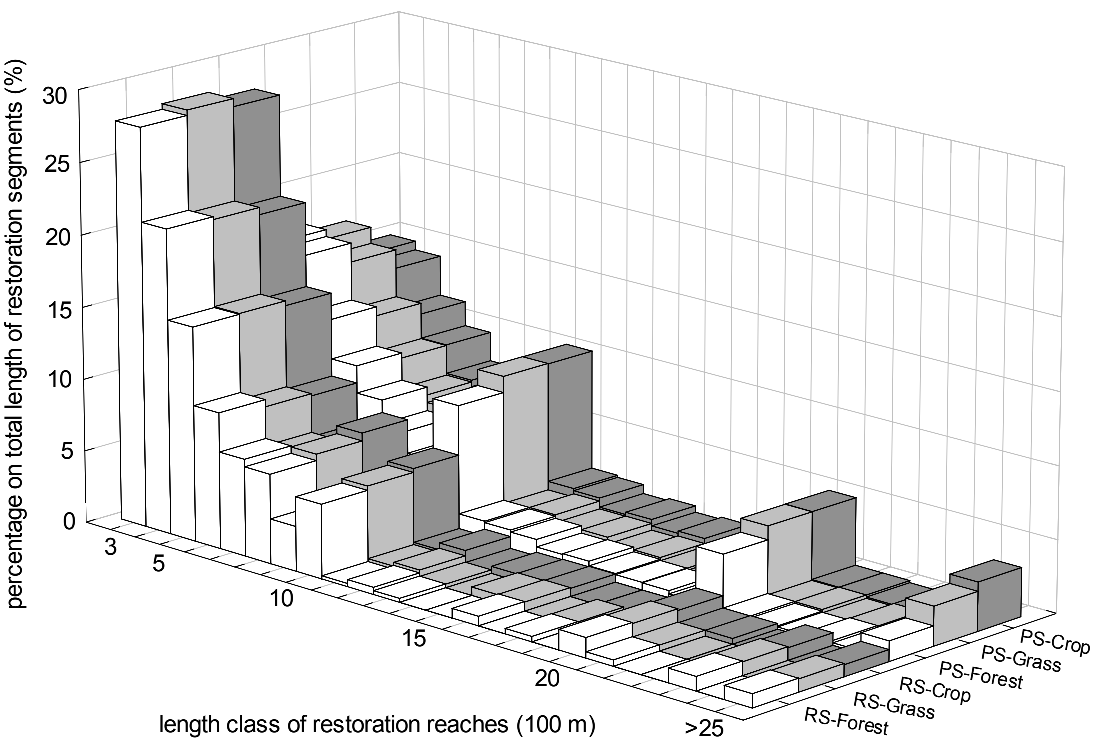

Figure 4.4: Restoration-reach length classes as a percentage of total length of restoration segments (separately given for each scenario, percentages of length classes sum to 100% for each scenario).

rivers, which often was 1 km. Differences between the distributions are statistically significant if all six scenarios are considered and within the recruitment and placement scenarios, respectively (chi-squared test for homogeneity, $p < 0.01$).

4.5.2 Spatial distribution of restoration segments

For each scenario, the share of restoration segments was calculated separately for the lowlands and the lower mountain areas. For all scenarios, the percentage of restoration segments relative to total channel length is higher in the lower mountain areas as compared to the lowlands (chi-squared crosstabulation, $p < 0.01$, Figure 4.5).

The differences between the two ecoregions are small for the PS-Crop scenario. The share of restoration segments for the PS-Crop scenario is 31.8% in the lowlands compared to 32.6% in the lower mountain area, which corresponds to a difference of 2.5%. Differences are much higher for the other scenarios (18.2% - 124.5%). Thus, the land use "cropland" restricts the use of large wood for stream restoration in the lowlands.

The maximum share of restoration segments relative to total channel length within a single watershed is 25% for all recruitment scenarios, 47% for PS-Forest, and 100% for PS-Grass and PS-Crop. The share of restoration segments for the recruitment scenarios ranges between 4.1% and 4.6% in those watersheds with the largest share of restoration segments comprising in total 5% of the study area. For the placement scenarios, the respective values are much higher (PS-Forest > 19.6%, PS-Grass > 44.9%, PS-Crop > 56.9%).

Broken down to stream type level, the following stream types are under-represented in all scenarios in most cases, except for PS-Crop (Figure 4.6): (a) small streams in fertile and intensively farmed regions (T18, T19), (b) medium-sized streams in the lowlands (T15, T17), and (c) large rivers (T9.2, T10, T20). In contrast, small and medium-sized streams in regions with poor soils, which are mainly used for silviculture (stream types T5, T5.1, T9, T12), are over-represented in most scenarios.

According to size classes, streams with a channel width > 10 m (large streams) are under-represented in all restoration scenarios. Large streams comprise about 9.6% of the total channel length in the study area, but only 4.1% to 5.2% relative to the total length of restoration segments in the different scenarios, except the PS-Forest scenario. Here, the percentage of restoration segments with a channel width > 10 m relative to total length of restoration segments is extremely low (1.9%), since floodplains of larger streams are wider and more often used as grassland or cropland. Large streams are under-represented even in the

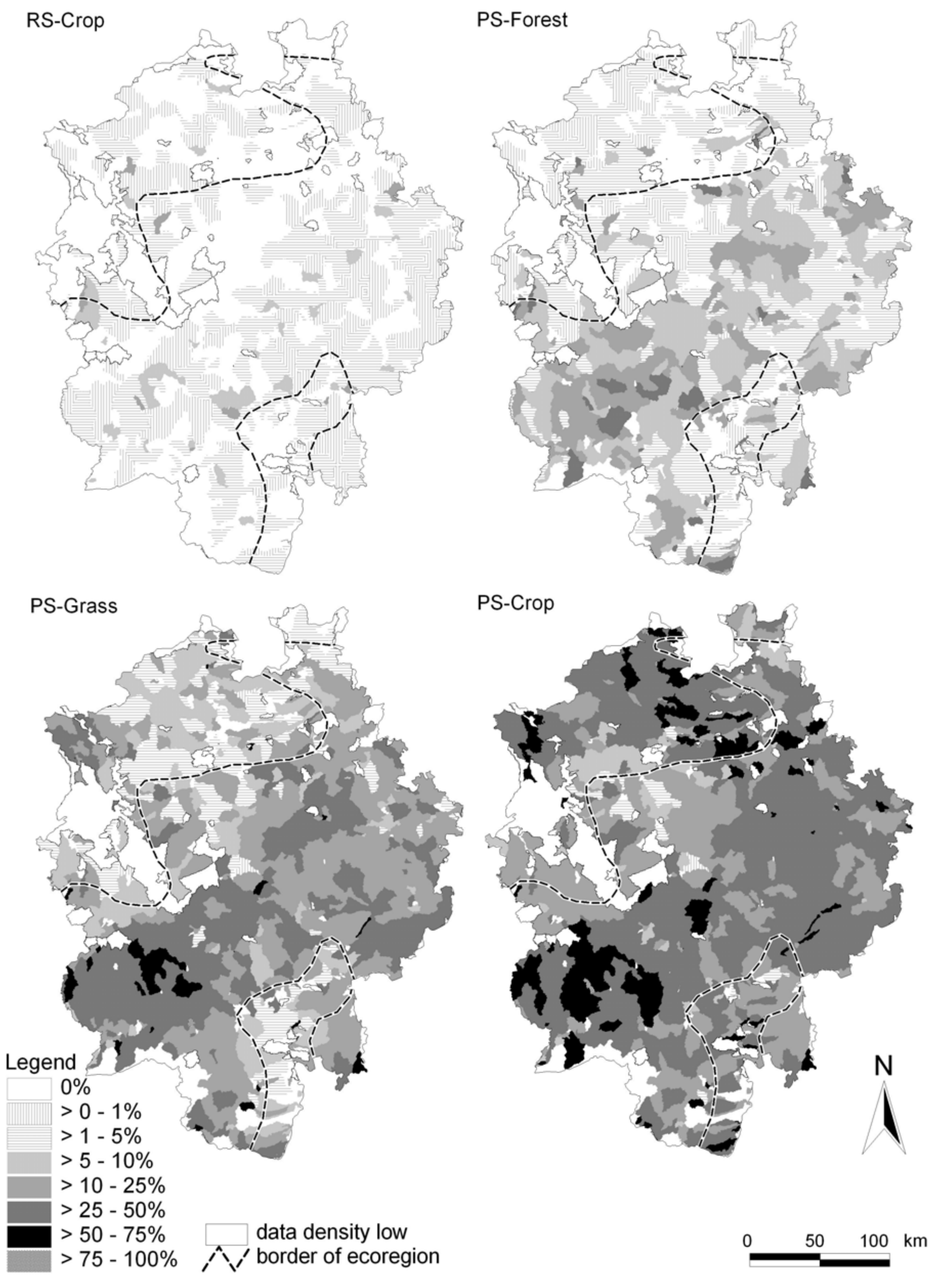

Figure 4.5: Spatial distribution of restoration segments in the study area. Percentage of restoration segments on total channel length in each watershed is given. Watersheds, where survey channel length is less than 0.3 km km^{-2} were not considered (data density low). Lower mountain area (centre) and lowlands (margins) are separated by the dotted line (see also Figure 4.1 for borders of ecoregions). Results for scenarios RS-Forest and RS-Grass are not given, because they do not markedly differ from the RS-Crop scenario.

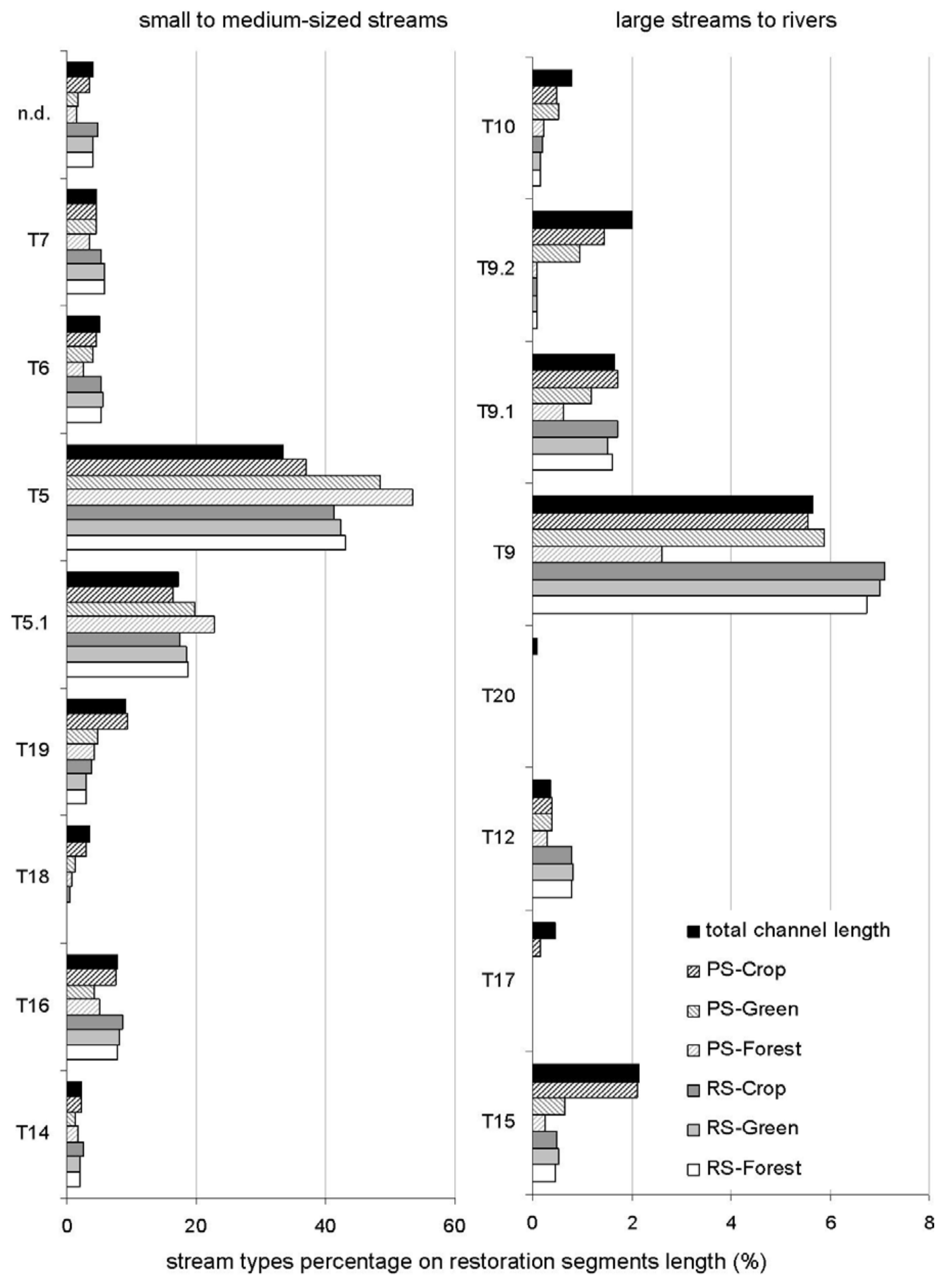

Figure 4.6: Percentage of different stream types for small to medium-sized streams (left) and large streams to rivers (right) on total restoration segments length compared to the percentage of the different stream types on total channel length (see Table 4.1 for description of stream types, n.d. = stream type not determinable). Separately given for each scenario.

PS-Crop scenario (5.2% as compared to 9.6%); thus, in addition to the land uses differentiating between the scenarios other exclusion criteria, such as built-up areas, parks, sports grounds or bridges, restrict the use of large wood in larger streams.

The relationship between the share of restoration segments and the population density of the districts in the study area was assessed using the Pearson product moment correlation. Only districts with a minimum stream density of 0.3 km surveyed streams km^{-2} were considered ($n = 106$), and both variables were transformed to normality. For the three placement scenarios human population density is correlated to the share of restoration segments (r for the PS-Forst, PS-Green, PS-Crop is $r = -0.38$, $r = -0.58$, and $r = -0.72$ respectively, $p < 0.01$). No such statistically significant correlation could be found for the three recruitment scenarios.

4.5.3 Simulating the potential enhancement of stream morphology

For each restoration segment, current hydromorphological assessment results were compared to results to be expected after restoration. The overall assessment of a segment results from the aggregation of the categories "stream bed", "stream bank", and "floodplain". The category "stream bed" (see Table 4.3) improved for all restoration segments due to the assumed changes in channel morphology. This general improvement in one category has a significant impact on the overall assessment results for the restoration segments (Figure 4.7).

The final hydromorphological assessment result is given as one out of seven possible ranks (I1-I7). For each of the six scenarios, the frequency of the ranks changes significantly if restoration is simulated (chi-squared test for homogeneity, $p < 0.01$). The effects of the three recruitment scenarios on the final assessment results hardly differ (chi-squared test for homogeneity, $p > 0.9$). All recruitment scenarios lead to an increase of segments assessed to have a high hydromorphological quality (I1) by the factor 1.8 and to a decrease of segments with a poor hydromorphological quality (I3 to I7). The percentage of restoration segments classified worse than I4 decreases by at least 50% in all six scenarios. Data of 98 benthic macroinvertebrate samples showed that 90% of the sites with a hydromorphological quality worse than I4 fail the "good ecological status", and approximately two thirds of the sites with a hydromorphological quality I4-I1 reach the "good ecological status" defined by a AQEM multimetric score > 3.5 (a macroinvertebrate assessment score that meets the requirements of the Water Framework Directive and has been developed in the context of the EU-funded project AQEM, see Hering et al. (2004)).

The restoration segments affiliated with the recruitment scenarios are already in a favourable

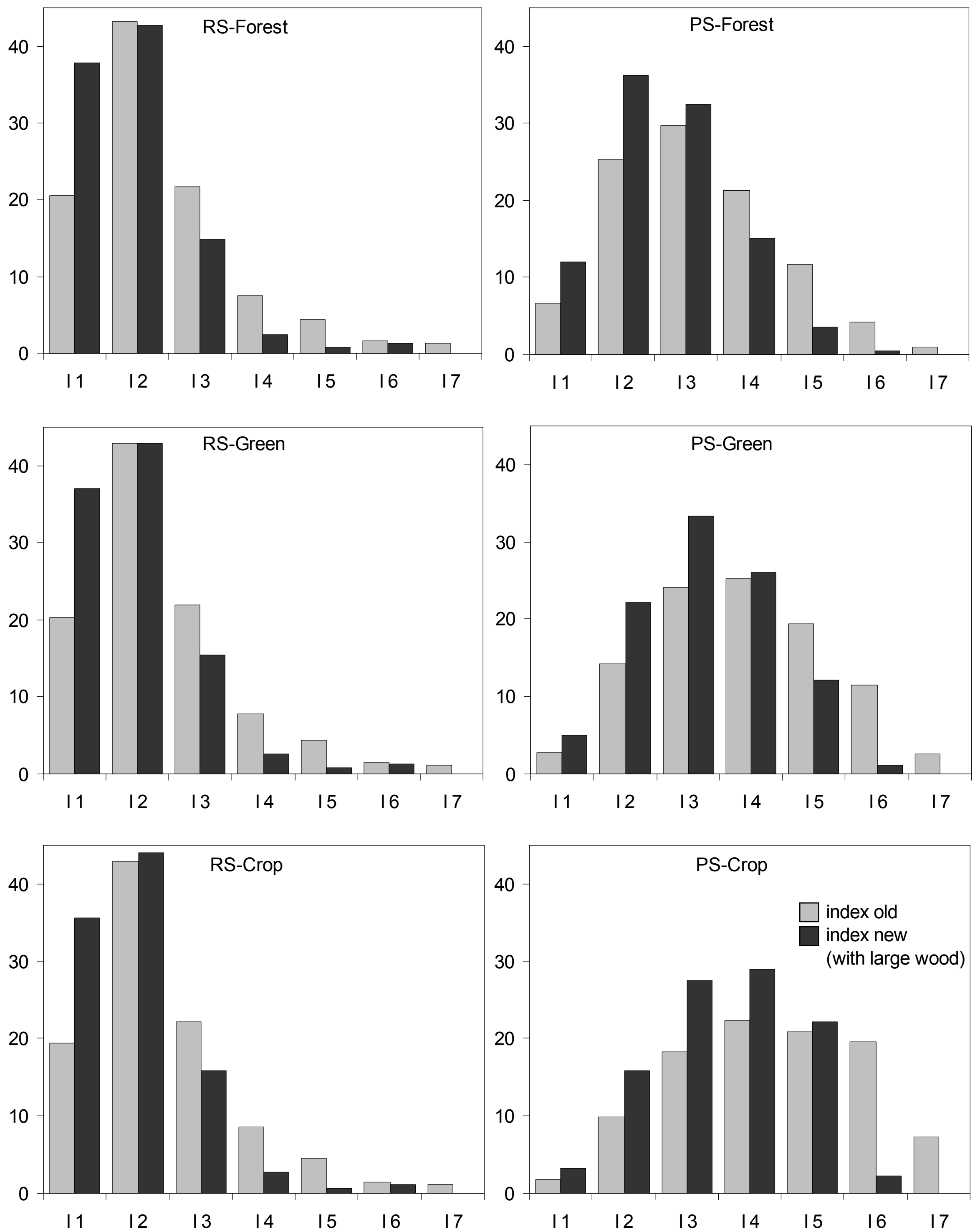

Figure 4.7: Hydromorphological assessment (including assessment of stream bed, stream bank and floodplain) of the restoration segments, prior ("old index") and after ("new index") the simulated restoration. Percentage of the seven ranks (from "I1" – unchanged, only minor deviations from the reference condition to "I7" - completely changed) on restoration segments total length is given for each scenario.

morphological state prior to the simulated restoration (only 7% are ranked worse than I4). Therefore, the total number of restoration segments that improve to a score better than I5 due to restoration is rather small. This is particularly true for restoration segments from stream types in the lower mountain areas: for stream types T5, T5.1, T6, and T7, the share of sections with a poor hydromorphological condition (I5-I7) decreases from 1%-8% to 0%. In the lowlands, a larger part of the restoration segments are ranked worse than I4 prior to the recruitment of large wood, and the share of these segments decreases by 10%-40% following the simulated restoration (stream types T14, T16, T18, T19). In contrast to the recruitment scenarios, many restoration segments in the placement scenarios are in a poor hydromorphological condition (PS-Forest: 17%, PS-Green: 34%, PS-Crop: 48%). These values decrease to 4%, 13%, and 24%, respectively, following restoration. No difference specific to stream type was detected for the placement scenarios.

An upgrading of the restoration segments leads to an increase of those channel segments that will likely reach a "good ecological status", even if this improvement is calculated relative to all channel segments rather than to the restoration segments, only (percentage of channel segments better than I5 on total channel length mapped). In the placement scenarios, this percentage increases from 40% to 41% (PS-Forest), 44% (PS-Green), and 47% (PS-Crop), respectively (chi-squared crosstabulation, $p < 0.01$)

4.6 Discussion

4.6.1 Potential use of the recruitment and placement of large wood

A main objective of this study was to quantify the potentials for the use of large wood in Central European stream restoration projects. The results indicate that (a) more than 20% of the channel segments can be restored with large wood, provided that "grassland" use can be restricted, and (b) the share of restoration segments is particularly high in the lower mountain areas compared to the lowlands and for small streams compared to larger streams and rivers. No data are available on the total length of streams that have already been restored in the study area. However, since in the past most restoration projects have been limited to short channel segments (e.g., Smukalla and Friedrich (1994)), it is likely that even the recruitment scenarios account for much more restoration potential (~ 500 km) as compared to the stream length that has actually been restored so far. There is no study on the potential for the use of large wood in Central European stream restoration projects to which the results of this study can be compared.

This study provides a minimum length of stream sections suitable for restoration projects with large wood. For three reasons the actual length might considerably exceed that estimated in this study. First, some of the structures restricting the use of large wood (e.g., small bridges and culverts) are probably not used any longer or are dispensable. Second, for some segments, it might be cheaper in the long run to modify existing bridges rather than to continue the removal of large wood (Lassettre and Kondolf 2000), which currently is done regularly in almost all Central European streams. Thus, restrictions do not necessarily arise from the wood, but from the size of bridges or culverts. Third, management practices described in the literature could be applied in channel segments with minor restrictions (e.g., rotation of large logs in longitudinal direction to reduce the effect on water level, Gippel et al. (1996a), Gippel et al. (1998), Hilderbrand et al. (1998), Gerhard and Reich (2001)) to enable the use of large wood in the restoration of channel segments with minor restrictions. Since no data on these options were available for the study area, they were not included in the scenarios.

Length of the restoration reaches (see Figure 4.4, Table 4.7) would probably increase too, if these options could be taken into consideration. Median length of the restoration reaches of the six scenarios would increase from 400 m to 500 m, if all reaches separated by a single channel segment not fulfilling the requirements of the scenarios would be connected.

4.6.2 Potential enhancement of stream morphology and biota

The second main objective of this study was to assess the potential for the enhancement of stream morphology by the placement and recruitment of large wood. The results indicate the potential benefit of restoration measures that are based on large wood. Considering restoration segments from the grassland scenario only, the share of restoration segments with a moderate to high hydromorphological status (I1-I4) would increase from 66% to 87% (scenario PS-Green). Considering all channel segments, the scenario PS-Green alone increases the share of restoration segments with a moderate to high hydromorphological status from 40% to 44%. Although the latter appears to be a minor effect, it might nevertheless contribute significantly to meet the quality goals defined in the EU Water Framework Directive, since many of the remaining sections that can not be restored are likely to be classified as "Heavily Modified Water Bodies" (channel segments that are substantially modified due to human induced physical alterations and that can not achieve a good ecological status without technically unfeasible or disproportionately costly measures). Such heavily modified water bodies do not have to reach the good ecological status.

The results stress the difference between (a) the lower mountain areas, where potentially a large number of channel segments can be restored, yielding an improvement from a moderate/good to a good/excellent morphological status and (b) the lowlands, where potentials for restoration are limited to a small number of channel segments, mostly yielding an improvement from a bad to a moderate morphological state, and hence, fostering achievement of a "good ecological status" as defined by the Water Framework Directive.

For three reasons the simulated morphological improvement is a conservative estimate: First, only the enhancement of the channel morphology that is directly related to the input of large wood was included in the re-calculation of the morphological quality score. Other measures, which might supplement stream restoration projects (e.g., removal of bed and bank fixation), were not considered. Second, only short term effects that will probably show within the first years after the input of large wood were considered; long-term effects like changes in channel form due to bank erosion were disregarded. Third, the overall hydromorphological quality score was used to compare the restoration sections prior and after potential restoration. The effect on the score for the category "stream bed" is much more pronounced, because all attributes assumed to change belong to this category.

According to new European legislation the quality of rivers and streams is mainly defined based on the biota. Hydromorphology is regarded as an "additional parameter" only. Thus, it is relevant to gauge the changes in the biotic communities expected to result from simulated restoration measures. It is focused on benthic macroinvertebrates, because data from a large number of samples (n = 194) collected by regional authorities and in the course of research projects are available for the study area. Multiple linear regression analysis was performed to evaluate the relationship between biological quality and hydromorphological attributes. Due to a lack of harmonised data sets, I did not succeed in simulating the impact of the restoration measures on the biota; thus, interpretation of restoration effects remains speculative.

While chemical parameters linked to organic pollution and acidification predominantly affect the benthic invertebrate fauna, hydromorphological alterations produce responses, too. For example, the impacts of dams (Marchant and Hehir 2002), reduced discharge (Brunke et al. 2001), habitat composition (Buffagni et al. 2001), fine sediment cover (Mebane 1999), and logging (Fore et al. 1996) on benthic macroinvertebrates have been described in detail. For the ecoregion investigated Lorenz et al. (2004) indicate that certain indices such as diversity, number of taxa, and composition of functional groups are highly impacted by hydromorphological parameters, such as bed- and bank fixation or the removal of the riparian vegetation.

Therefore, at each of the sites that have been previously analysed the restoration scenarios considered might directly affect the benthic invertebrate fauna: the generation of pools adds to habitat and substrate diversity and thus, to the creation of niches for certain species. Similar effects can be expected from the increase of flow- and substrate diversity and depth variability. Finally, the addition of logs adds a new habitat for specialised taxa (Hoffmann and Hering 2000). Thus, depending on the scenario applied, positive effects on the fauna can be expected for at least 1% (recruitment scenarios) up to almost one third of the total channel length (PS-Crop scenario).

However, it is questionable how persistent such local effects are and how they will affect the quality assessment for a whole stream or river. While positive effects resulting from changes in the hydromorphology might be readily observed on local scales (Rolauffs 2003), they are far more pronounced in longer, homogeneous stretches, in particular. Local improvement might have positive effects even for rather removed downstream reaches (Sponseller et al. 2001; Rolauffs 2003; Weigel et al. 2003). Thus, in addition to the local effects, a long-term substantial improvement of the fauna can be assumed for long restoration reaches (e.g., > 1km length, which comprise between 0.1% and 9.6% of the total channel length).

4.6.3 Generalisation of results

The area considered in this study includes the two most common ecoregions in Germany (lowlands and lower mountain areas). The dominance of these ecoregions in the study area mirrors the situation in Germany. Therefore, the general results are considered to be transferable to Germany as a whole. However, population density, which is negatively correlated to the abundance of restoration segments (see section 4.5.2), is high in the lowland part of the study area as compared to other German lowlands (e.g., lowland of Mecklenburg Western Pomerania < 50 p km^{-2} compared to ~ 250 - 500 p km^{-2} in the lowland part of the study area). Thus, there may be more restoration segments in other parts of the German lowlands.

No alpine streams were investigated. Likely, the potentials for the use of large wood for restoring alpine streams are quite different, since unit stream power is much higher, yielding an increased risk of damage to structures caused by drifting wood. However, there are few alpine streams in Central Europe compared to streams in lowlands and lower mountain areas.

The results of this study show that the recruitment and placement of large wood are appropriate measures to restore a larger part of the streams in the study area and probably in Germany and the neighbouring countries. It would be of great interest to conduct comparable studies in other countries with large data sets on stream hydromorphology (e.g., River Habitat Survey – UK, Système d'Evaluation de la Qualité du Milieu Physique – France) in order to develop a European perspective on the use of large wood in stream restoration projects.

5 Experiences gained from Central European stream restoration projects in which wood has been used

5.1 Summary of the section

Wood is increasingly used in Central European restoration projects to improve the hydromorphological status of streams and rivers. A mail survey was started to summarize the experiences that have been gained so far to provide information for the design of future projects. The survey revealed the following aspects:

First, wood has been used successfully in many restoration projects, mainly to increase structural complexity by initiating natural channel dynamics with fixed wood structures. Failure rate of the wood structures is low (8%), and preliminary monitoring results indicate that the hydromorphological status improved rapidly in most projects. From an ecological point of view, there is potential for improvement in regard to the amount of wood and the size and type of wood structures. The amount of wood placed in the streams (median volume 27.9 m^3 ha^{-1}) is low compared to the amount in some of the most natural streams in Central Europe (41.4 m^3 ha^{-1}) and in other temperate forested ecoregions comparable to those investigated (126 m^3 ha^{-1}). The size and the potential effect of some wood structures on stream hydraulics and morphology is low and can be increased without inferring with local restrictions. Furthermore, in most of the cases, complex natural shaped wood structures could have been used instead of bare cylindrical logs to benefit from positive side effects.

Second, in some projects, large natural shaped wood structures without additional anchoring were used. Because the data on the restoration projects investigated indicate that costs can be markedly reduced and positive side effects are to be expected, it is highly recommended to use such soft engineering methods in future projects whenever possible.

Third, the effect of wood structures on stream morphology is strongly dependant on the natural setting, problems occurring during the implementation of the projects are generally site specific, and therefore, schematic project designs are not applicable to most specific restoration sites.

Fourth, the potential effects of wood placement must be evaluated within a watershed and reach-scale context. Otherwise, the wood placement can have adverse effects on stream morphology and biota.

Fifth, there is a lack of knowledge on the use of wood in stream restoration, an urgent need to

improve the monitoring programs of future restoration project and a strong need to communicate the monitoring results.

5.2 Scope of the section

Restoration of stream channels, which have been degraded in terms of hydromorphology, has become a widely accepted social objective in developed nations and the scientific interest in stream restoration has been steadily increasing over the last two decades (Shields et al. 2003). Because wood is an important component of ecosystems in temperate forested ecoregions, which influences stream hydrology, hydraulics, sediment budget, morphology, and biota across a wide range of spatial and temporal scales (see section 1.2), it is often used in stream restoration projects (see section 1.3). Most of these restoration projects have been carried out in the northwestern U.S. to restore fish habitats by the placement of artificial instream structures such as log weirs. Several authors pointed out that careful monitoring is necessary to evaluate the effectiveness of these projects and to use the collected information to improve future projects (Bryant 1995; Kondolf 1995, 1996, 1998; Bash and Ryan 2002). But only few of the restoration projects in the northwestern U.S. have been monitored, and it is doubtful whether the monitoring effort is sufficient to adequately evaluate the effectiveness of the restoration projects (Larson et al. 2001; Bash and Ryan 2002). In addition to above mentioned monitoring of single restoration projects, some studies have examined the effectiveness of the placement of wood and the durability of these structures in stream restoration projects in the northwestern U.S. systematically (Frissell and Nawa 1992; Roper et al. 1998; Larson et al. 2001).

In contrast to North America, the relevance of wood for stream ecosystems has long been overlooked in Central Europe, presumably because it is rarely found in Central European streams due to the long term human impact on streams and the extensive management of virtually all forests over many centuries. However, the data presented in section 2 indicate that under favourable conditions a wood standing stock comparable to those of pristine North American streams can be obtained, and even single large fallen trees can act as a strong morphologic control in Central European streams (Kail (2003), section 3). Although wood could potentially be used to restore a large part of the streams in Central Europe (see section 4), it is rarely used in stream restoration projects, mainly because (a) the beneficial role of wood in stream ecosystems and its application in stream restoration are still not well-known, (b) project managers are afraid of wood structures being transported downstream, damaging bridges and other works and of rising the water level, thus increasing flood probability upstream. Transferability of the monitoring results of North-American studies is limited, because land-use pressure is particular high in Central Europe and the natural setting (e.g., discharge, geology, vegetation) and restoration objectives differ from those in North-America.

Recently, Reich et al. (2003) reviewed restoration projects from North America (n = 18) and Germany (n = 11), which are described in literature and compared them in regard to project objectives, adjacent land use, population density, year of restoration, and the type and extent of wood measures. However, it was not the objective of Reich et al. (2003) to gain a representative overview about Central European stream restoration projects. The 11 German projects described in this study are not entirely representative since, (a) only few of the restoration projects implemented are described in literature (probably this is especially true for projects that failed or experienced severe problems), (b) 10 out of the 11 projects are located close together in the federal state of Hesse and only represent streams of this lower mountain area, (c) some new projects have been implemented in the last years.

Therefore, this study started with a complementary mail survey to summarize the experiences gained in Central European stream restoration projects, in which wood has been used. Aim of this study is to examine project objectives, types and extent of measures, costs, monitoring efforts, problems during planning, approval, and implementation of the projects, and preliminary monitoring results. Although the number of restoration projects, which can be investigated, is still limited, the results may provide important additional information for the design of future projects.

5.3 Methods

5.3.1 Data collection

A preliminary survey was carried out to identify restoration projects in which wood has been already used. Local and regional authorities, stream managers, and stream ecologists in Central Europe were consulted in the initial phase of this study (n = 112); they named 53 restoration projects, which were further addressed. The study is based on a mail survey, which was developed and pre-tested according to standard survey techniques (Noelle-Neumann and Petersen 2000) and addressed (a) general description of restoration projects, (b) description of wood measures, (c) description of streams after restoration, (d) description of streams prior to restoration, (e) general description of streams, and (f) personal data (Table 5.1). Twenty-eight

Table 5.1
Structure and content of the questionnaire.

general description of restoration project
- state of knowledge about the stream (judgement of project manger)
- general project goals
- restrictions / planning conditions
- physical measures other than wood placement
- description of monitoring
- total cost of planning and implementation
description of wood measures
- length of restored reach
- date of restoration
- cost of planning and implementation of wood measures
- objectives of wood placement
- type and number of wood structures
- diameter and length of wood structures
- fixation of wood structures
- orientation to flow
- blockage ratio according to Gippel et al. (1996a)
- state of knowledge about the drawbacks and opportunities of using wood in stream restoration at the time of restoration and today (judgement of project manager)
- modification of future project designs due to the experiences gained
- experiences and problems related to planning, approval and implementation of wood measures
- state of knowledge about the drawbacks and opportunities of using wood in stream restoration at the time of restoration and today (naming source of information)
description of stream after stream restoration (at the time of the survey)
- discharge since wood placement
- failure of wood structures (damage, rotation, downstream transport)
- (preliminary) results of monitoring
description of stream prior to stream restoration
- sinuosity
- bed and bank fixation
- entrenchment
- adjacent land uses
general description of stream
- bankfull width
- slope
- discharge
- total length of restored reach
- bed and bank material
personal data
- profession
- activities in nature conservation

project mangers, which planned and implemented a total of 41 restoration projects, agreed to participate in the survey and 22 questionnaires were returned. Because most of the project mangers, who were in charge of several restoration projects, returned information on a single project only, the survey resulted in data on 23 projects.

5.3.2 Data analysis

Due to missing data, a lower number of data sets ($n < 23$) were used for some steps of evaluation. Some data were given separately for several groups of wood structures per project (e.g., diameter and length of wood structures) and hence, sample size is > 23 for other steps of evaluation.

Closed questions (single or multiple choice) were used in most cases, generally with the category "other" to allow for answers not listed. Open questions were used in two key areas – questions about the monitoring results and the problems that occurred during planning, approval, and implementation of the projects - to encourage the respondents to express their experiences freely and because a wide range of responses of different level of detail, which hardly can be categorised, was expected. Therefore, these sections of the questionnaire were mainly analysed qualitatively.

Three sections of the questionnaire were structured for response on a five-point Likert scale: (a) general project objectives, (b) objectives of wood placement, and (c) modification of future project designs due to the experiences gained. Each respondent rated the parameter values of these sections on a Likert scale from 1 to 5 (e.g., the general project objective "flood protection is rated on the scale ranging from 1 = no importance to 5 = most important project objective). These scores were used to calculate a mean score for each parameter value.

One objective of the survey was to relate the durability of wood structures to stream and wood characteristics (e.g., recurrence interval of high flows; maximum specific stream power since the placement of wood, fixation of wood structures). Therefore, the questionnaire included questions on the number of wood structures, which were damaged, rotated or transported downstream, and on discharge data since the placement of wood. Only few respondents were able to provide all of these information (4 out of 23), but data on the number of wood structures transported downstream were given by most of the respondents (21 out of 23).

5.3.3 Study streams

The project managers were assured that the data set is analysed anonymously and projects are not named explicitly to increase the willingness of project managers to report the failure of a

Table 5.2
Data on the restoration sites. Number in first column corresponds to numbering in Figure 5.1. Width:depth ratios are classified: A = < 3:1, B = 3:1 to 4:1, C = 4:1 to 6:1, D = 6:1 to 10:1, E = >10:1. Sinuosity is classified: a = straightened, b = straight, c = slightly curved, d = distinctly curved, e = meandering, f = heavily meandering. Adjacent land use is classified: past = pasture, crop = cropland, fallow = fallow land, nn-forest = non-native forest, n-forest = native forest, urban = low-density areas, n-veg = natural non-woody vegetation. Other abbreviations used: nd = no data, revet = bank revetment, organic = organic material.

number	bankfull width (m)	width:depth ratio	slope (%)	mean flow ($m^3 s^{-1}$)	mean high flow ($m^3 s^{-1}$)	sinuosity	dominant bed material	dominant bank material	dominant adjacent land use
1	5-10	B	0.01	0.751	4.76	b	sand	sand	past / crop
2	5-10	D	0.5	10	125	b	sand	sand	past
3	20-40	A	0.3	13.2	53	d	sand	sand	fallow / past
4	20-40	A	0.3	13.2	53	d	sand	sand	fallow / nn-forest
5	1-5	C	0.3	0.02	0.5	c	sand	sand	n-forest
6	1-5	B	1-2	0.08	2	b	sand	sand	past
7	3	B	1-2	nd	nd	f	sand	clay	n-forest
8	1-5	nd	~0.1	nd	nd	nd	nd	nd	nd
9	3	B	1-2	nd	nd	c	cobble	sand	past /urban
10	10	C	nd	4.5	44	a	gravel	clay	past / nn-forest
11	5-10	C	0.1-0.5	0.175	1.5	d	gravel	clay	past
12	10-20	D	1-2	1.09	19.8	e	gravel	clay	nn-forest
13	9	C	4	1.3	17.6	c	cobble	clay	past
14	9	B	0.6	1.3	17.6	c	cobble	clay	n-forest / past
15	5-10	A	0.5	0.3	12	b	clay	clay	crop
16	16	B	3.2	3.9	53.9	b	cobble	revet	n-forest / past
17	2	B	~0.1	0.06	2	a	clay	clay	past
18	20-40	B	0.3	8	124	b	gravel	gravel	fallow
19	1-5	B	~0.1	nd	nd	a	sand	sand	n-veg
20	200	E	0.2	90	420	c	gravel	revet	parks
21	>40	D	0.5-1	19	130	a	gravel	gravel	n-veg / urban
22	28	D	0.2	9.1	93	e	gravel	organic	past
23	12	C	0.06	4.92	nd	a	gravel	revet	past

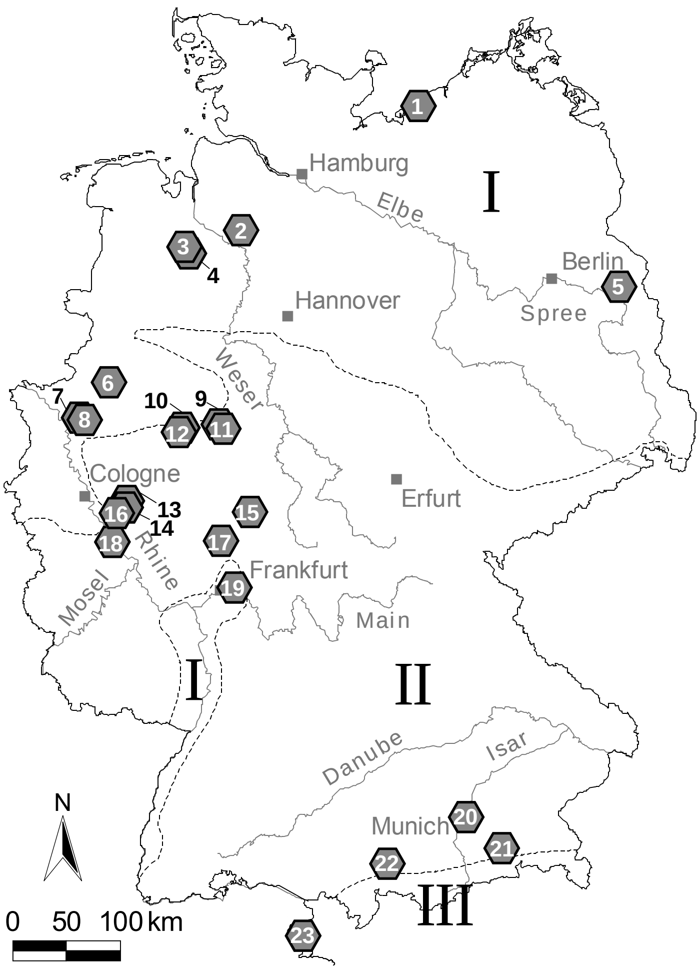

Figure 5.1: Location of restoration sites in Germany and Liechtenstein, numbering of the sites corresponds to the numbers in Table 5.2. Ecoregions are bordered by dotted lines (according to Illies (1978), modified according to Briem (2003)): I – lowland, II – lower mountain area, III – alpine region.

project or problems during planning, approval, and implementation. Virtually all restoration projects are located in Germany, except one project implemented in Liechtenstein (Figure 5.1). The restoration sites represent a wide range of natural settings in the lowland, lower mountain, and alpine ecoregion (Table 5.2). Most of the streams are bordered by pasture or forest, and even the two stream reaches partly bordered by low-density areas can not be described as urban streams.

5.4 Results

5.4.1 Objectives of restoration projects

The questionnaire distinguished between "general project objectives" and "objectives of wood placement". Three different types of general project objectives were listed in the questionnaire: (a) non-ecological objectives, (b) general ecological objectives, and (c) selective ecological objectives, where respondents had to name the specific species or channel features that should be protected or created (Figure 5.2).

The rating of the general project objectives by the respondents on a five-point Likert scale reveals two aspects. First, virtually all projects were implemented to approach the potential natural state and hence, meet the definition for "restoration" given in section 1.4. All non-ecological objectives are rated low, especially the objective "conventional engineering" (mean Likert score 1.4). The objectives rated high by respondents (mean Likert score > 3) are the general ecological objectives "increase general structural complexity" and "initiate lateral channel migration", with mean Likert scores of 4.0 and 3.8, respectively. Furthermore, only one of the projects was solely focussed on non-ecological objectives (single Likert scores 4 to 5). Here, wood was used to control bank erosion. Second, the overall objective of the restoration projects are rather non-specific. The selective ecological objectives have medium and low mean Likert scores, respectively ("creation of specific channel features" mean Likert score 2.4, "protect specific species" mean Likert score 1.3). Both selective ecological objectives were rated low (single Likert scores 1-3 in 13 out of 23 projects). Moreover, only

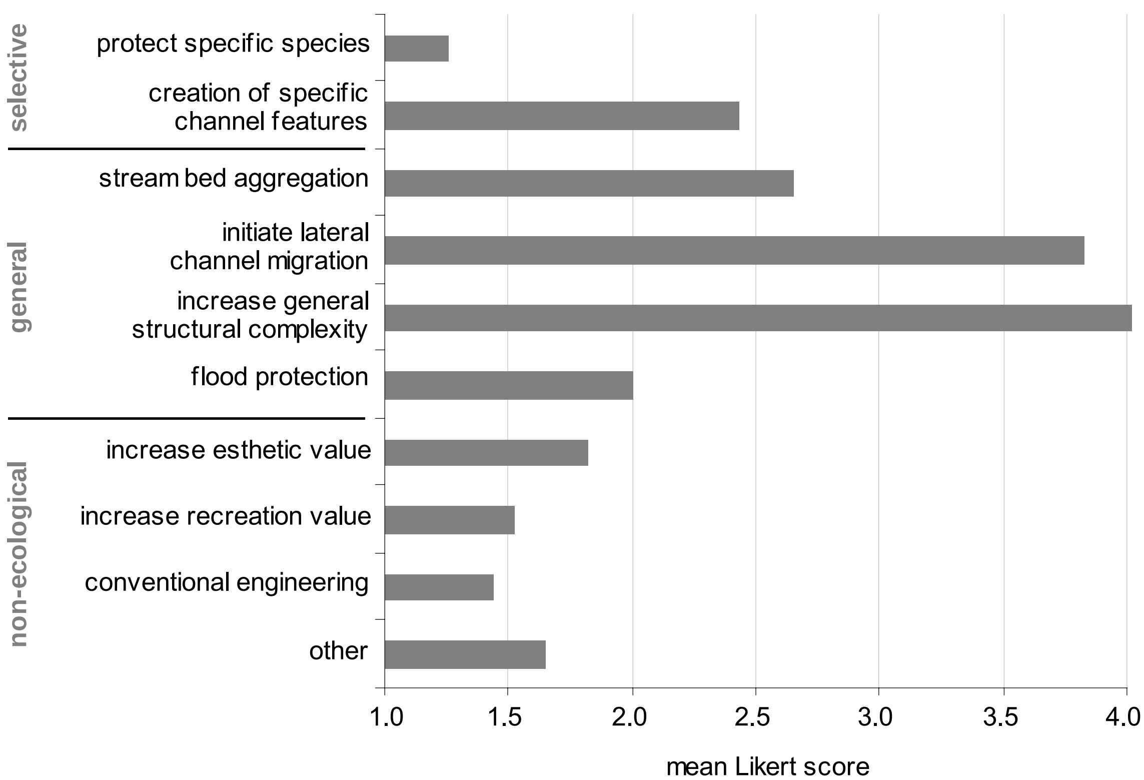

Figure 5.2: Mean Likert scores of the general project objectives.

three projects have a specific overall project objective, on which the respondents solely rated high a single objective (single Likert scores 4 or 5): "conventional engineering" (control bank erosion), "stream bed aggregation" (control incision of stream bed), and "increase general structural complexity"; the latter rather indicating a non-specific overall project objective.

The objectives of wood placement listed in the questionnaire were also classified into non-ecological, general, and selective ecological objectives (Figure 5.3). The rating of the objectives shows: First, overall objective of wood placement in almost all projects is stream restoration rather than conventional engineering. In accordance with the rating of the general project objectives, the non-ecological objective "bank protection" is rated low (mean Likert score 1.4). Second, none of the ecological objectives is of special importance. Four general and selective ecological objectives were rated high by the respondents (mean Likert score > 3), but differences between these four objectives are minor. Furthermore, only two respondents solely rated high one single objective (single Likert scores 4 or 5), namely "stream bed aggregation" and "initiate lateral channel migration".

The placement of wood is one out of several different measures that were applied in the restoration projects. Some of these measures are necessary to support the objectives of the wood placement (e.g., removal of engineered instream structures such as bed fixation or bank

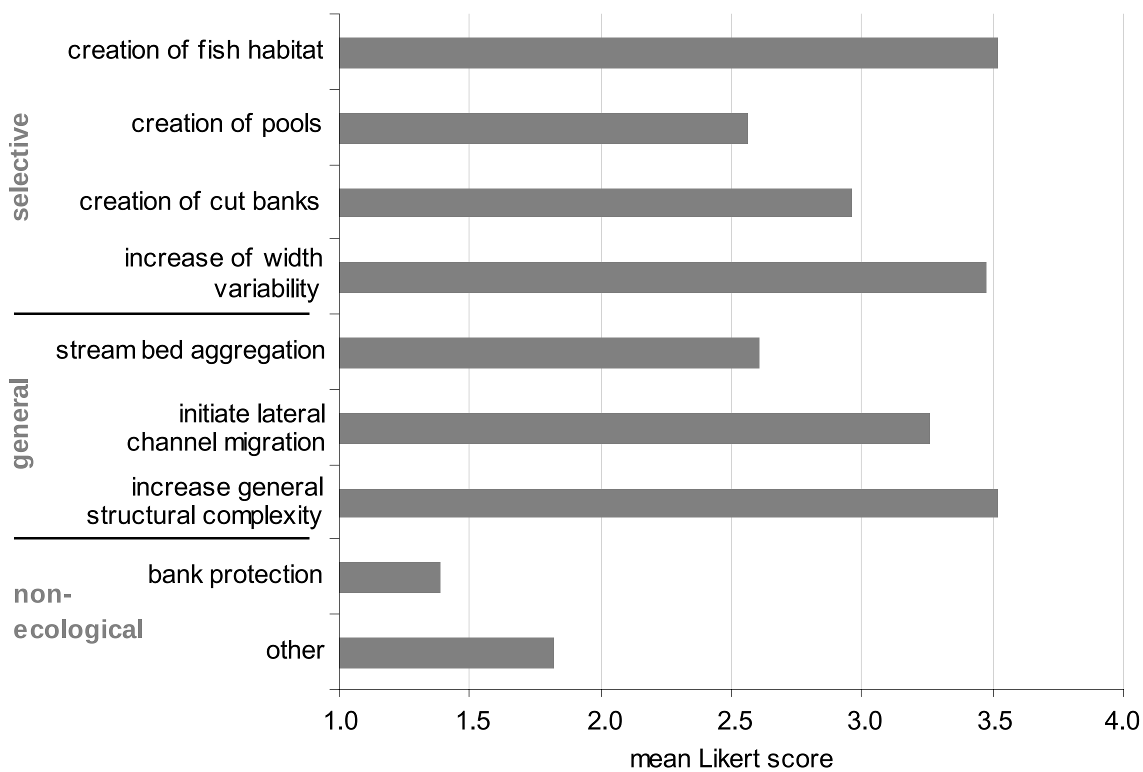

Figure 5.3: Mean Likert scores of objectives of wood placement.

revetment to facilitate the development of channel features caused by wood, purchase of adjacent land to allow for lateral migration of the channel). In addition, more than half of the projects (13 out of 23) include measures other than those related to wood placement (e.g., widening of cross sections, building channel features like pools or cut banks, replacing weirs by glides).

5.4.2 Nature and extent of measures

The projects differ in respect to the length of the restored reaches and the amount of wood placed in the streams (Figure 5.4), but most reaches are short (median length 800 m) and the extent of the wood measures in the single projects is small compared to North American restoration measure (median number of wood structures n = 8, median total volume 10.2 m^3).
Differences are less pronounced, if the number and volume of wood structures in the single projects is related to reach length and bottom area (median number 28 wood structures km^{-1} and 22 wood structures ha^{-1}, median volume 15.2 m^3 km^{-1} and 27.9 m^3 ha^{-1}). A weak but significant negative correlation exists between the mean volume of wood structures and the time since wood placement (Spearman rank correlation, $r_s = -0{,}54$, $p < 0.01$, $n = 21$), indicating that larger wood structures are increasingly used in recent projects.
The size of the wood structures is small, both absolute and related to stream size. Mean diameter, length, and volume is 0.36 m, 5.7 m and 1 m^3 respectively, but because data on the length of wood are strongly skewed to the right, half of the wood structures have a length and volume of less than 2.5 m and 0.35 m^3, respectively (n = 38 groups of wood structures, for which diameter and length were given separately by the respondents, representing a total number of 481 wood structures).
To assess the potential influence of the wood structures on stream hydraulics and morphology, the size of the structures must be related to stream size. The percentage of the cross-section area, which is blocked by the wood structures, is used as a measure for the proportion of wood and stream size (blockage ratio *B* according to Gippel et al. (1996a)). Although size of the wood structures is small, blockage ratio is at least 0.1 for 69% of the structures (Figure 5.5), because mainly small streams have been restored (78% of the structures were placed in streams with a bankfull width less than 10 m). About one third of the wood structures (31%) have blockage ratios ≤ 0.1, which is too low to significantly effect stream hydraulics and cause a detectable upstream afflux (Gippel 1995; Gippel et al. 1996a). About half of the wood structures (51%) with $B \leq 0.1$ were used in restoration projects, which

are under no restrictions (rise in water level was not named as a restriction for stream restoration). Only 15% have blockage ratios with $B > 0.3$.

Blockage ratio and drag coefficient, which determine the effect on stream hydraulics and the rise in water level besides Froude number (Gippel et al. 1996a), could be increased for a larger

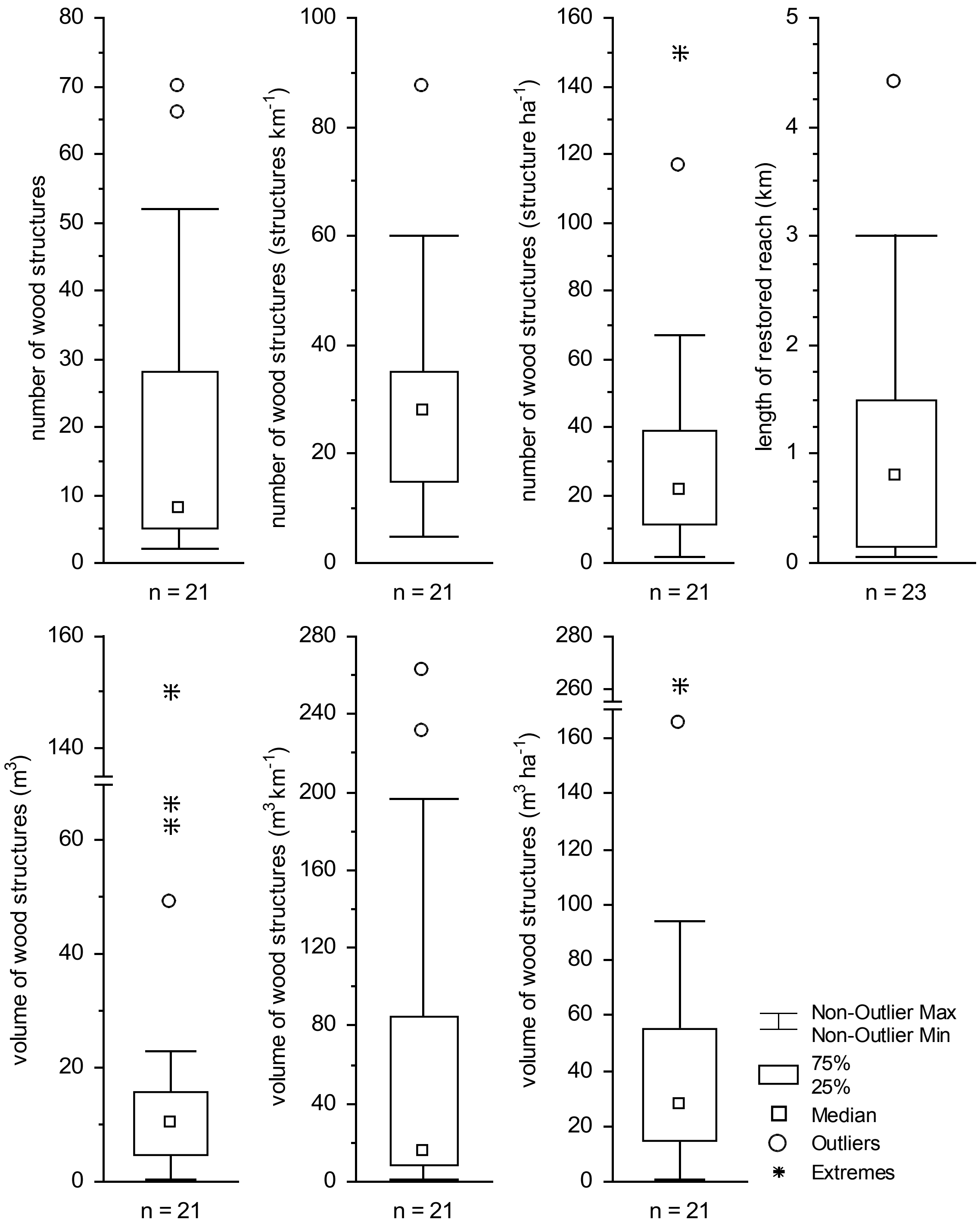

Figure 5.4: Variability and median of restoration project characteristics. Non-outlier maximum and minimum, 25 – 75%, median, outliers (outlier coefficient = 1.5) and extremes (extreme coefficient = 3) are given.

part of the wood structures by rotating them perpendicular to flow. Some wood structures are rather round than elongated (n = 68, e.g., rootwads), but orientation to flow can be determined for the vast majority of the structures. About half of the wood structures, for which the orientation to flow was given (n = 332), were placed nearly perpendicular (~90°) to flow (25%) or with an angle from 60° to < 90° (28%). A larger part of the structures has an angle to flow from 30° to < 60° (19%) or is located nearly parallel (0° to < 30°) to flow (28%). The drag coefficient of cylindrical logs is known to sharply decrease for angles < 60° and is low for angles < 30° (Gippel et al. 1996a). About half of the wood structures (59%) with angles < 60° were used in restoration projects, which are under no restrictions, and hence, wood structures could have been placed perpendicular to flow. But it is not possible to rule out that the objectives of these restoration projects do require the wood structures to be placed in the stream with a specific angle to flow < 60°.

The questionnaire listed nine types of wood structures, which can be grouped into two categories: (a) logs of cylindrical shape and (b) wood of natural shape (Figure 5.6).

The majority of the wood structures are natural shaped, both related to the number (64%) and volume (74%) of wood pieces. The most important type of natural shaped wood structures are single trees, which act as key-pieces for the formation of wood accumulations in natural stream reaches and hence, strongly influence stream morphology. The percentage of single trees on the number and volume of natural wood structures is 47% and 49%, respectively.

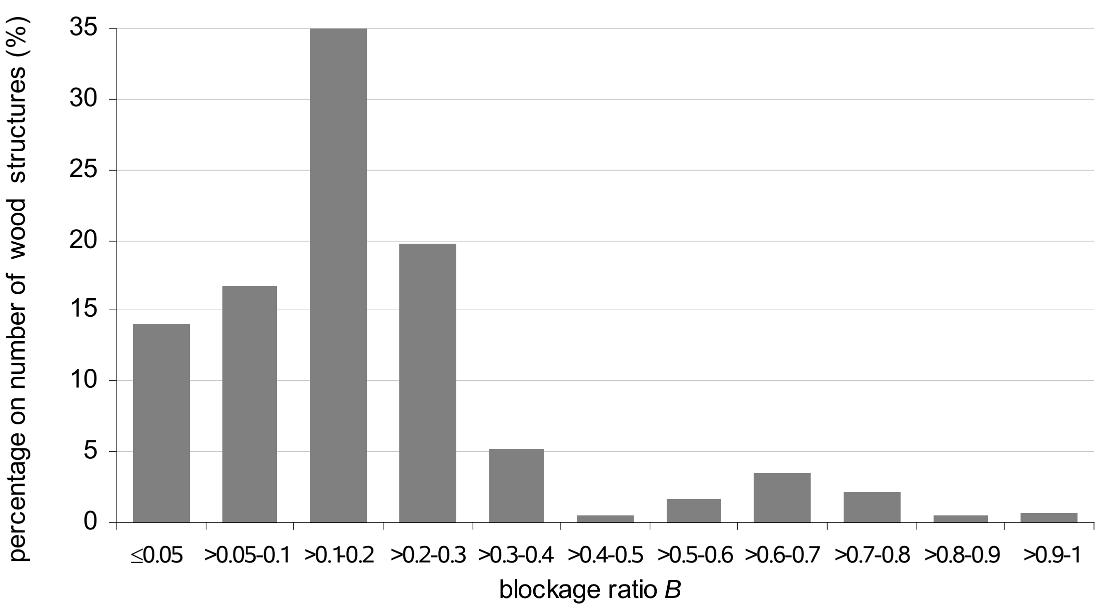

Figure 5.5: Blockage ratio of the wood structures (n = 48 groups of wood structures for which blockage ratio was given separately by the respondents, representing a total number of 400 wood structures.

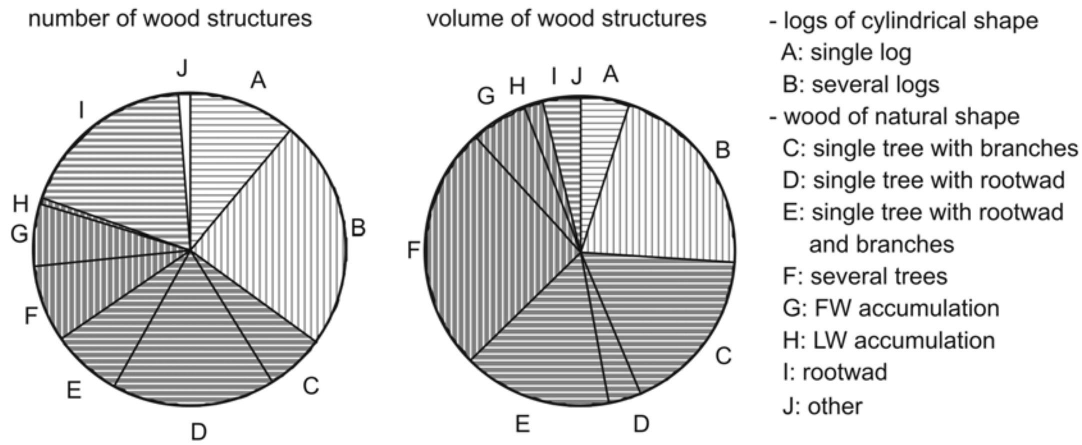

Figure 5.6:Types of wood structures used in the restoration projects related to number and volume. FW = fine wood (diameter approximately < 0.1 m), LW = large wood (diameter approximately > 0.1 m).

Mean diameter and length of the single trees (n = 121) is 0.32 m and 7.6 m, respectively, but the size of most trees is low compared to stream size. Blockage ratio is ≤ 0.3 for 88% of the trees and tree length is less than bankfull channel width for 55% of the trees. Besides single trees, accumulations (several trees, wood accumulations, large wood accumulations) comprise a larger part of the natural shaped wood (percentage on number and volume of natural shaped wood is 23% and 45%, respectively). Logs of cylindrical shape comprise about one third of the wood structures (35%) and one fourth of the wood volume (26%). There is no obvious reason for the use of simple cylindrical logs instead of complex natural shaped wood structures for about half (54%) of the cylindrical logs (restoration projects are under no

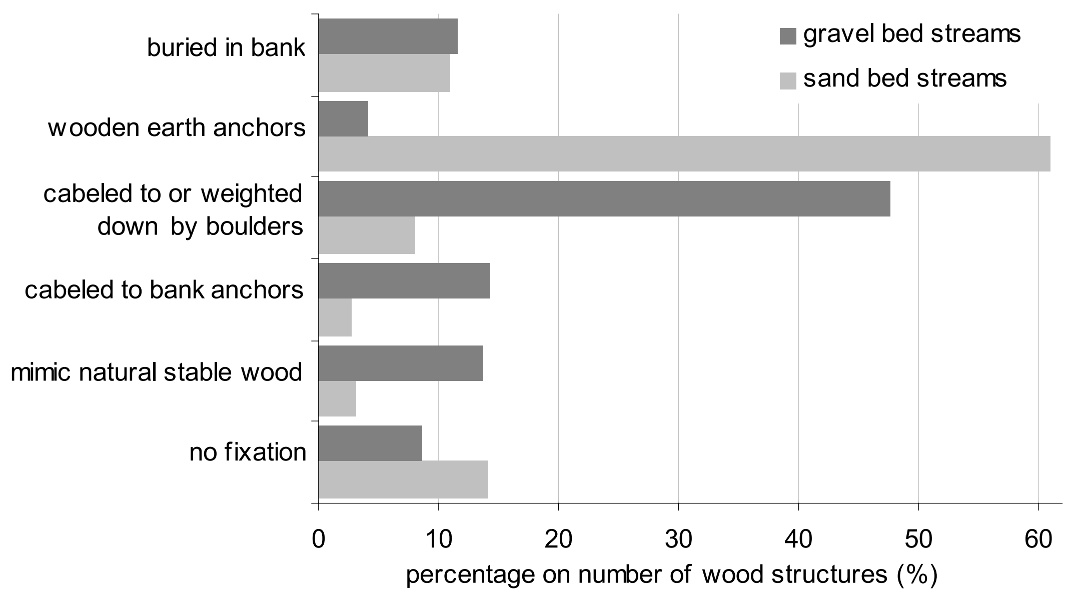

Figure 5.7: Methods used for the fixation of the wood structures in gravel bed and sand bed streams (a total of n = 400 wood structures were considered).

restrictions, rise in water level was not named as a restriction for stream restoration).

The vast majority of the wood structures (89%) are fixed, with most of the structures either being fixed with boulders (28% cabled to or weighted by boulders) or fixed in the stream bed with wooden earth anchors (33%). Some structures are buried in the bank (11%) or cabled to bank anchors (9%) (e.g., trees on bank), the latter method of fixation especially being used for tree revetments (trees aligned parallel to the bank for bank protection). Few of the structures are fixed using methods, which mimic natural stable wood (8%) (e.g., wood structures partly placed on stream bank, wedged between trees on the banks) and only 11% of the structures are not fixed and potentially can move freely at high flows. Only two respondents reported the use of an artificial log jam at the end of the restored reach according to Gerhard and Reich (2001), which traps floating wood upstream of works that are at risk to be damaged and therefore, allows for natural wood movement in the restored reach. Sand and gravel bed streams differ in the methods used, the majority of the wood structures in sand bed streams (61%) being fixed in the stream bed by wooden earth anchors and the majority of the structures in gravel bed streams (48%) being cabled to or weighted by boulders (Figure 5.7).

5.4.3 Costs of stream restoration with wood

The questionnaire distinguished between the costs for planning and implementation of the wood structures. The costs for planning were related to the number of wood structures, because costs are considered to be dependant on the extent of the project. Costs for planning are relatively low and do not differ markedly between projects ($n = 10$) with an inter-quartile range of about 80 € per wood structure and median costs of 125 € per wood structure. Because costs for implementation are considered to be dependant not only on the number of wood structures but also on their volume, the costs for implementation were related to wood volume. Costs for implementation (placement and fixation of 1 m^3 wood volume) differ markedly between projects ($n = 18$) with an inter-quartile range of about 930 € m^{-3} and median costs of 464 € m^{-3}. Costs for implementation are significantly lower for the projects, where wood structures were not heavily fixed (not fixed at all, installation of log jam at the end of the restored reach to trap floating wood, mimic natural stable wood) compared to the projects, where wood structures were partly buried in the stream bank or fixed using cables, boulders or wooden earth anchors (Mann-Whitney-U-test, $p < 0.05$, $n = 18$). In correspondence with these results, fixation represents a large portion of costs for the implementation of the wood structures (median portion 70%, $n = 11$).

5.4.4 Monitoring effort and results

A monitoring is carried out in the majority of the projects (19 out of 23), but the measures used for monitoring as well as monitoring intensity differ markedly, and monitoring intensity is extremely low in some cases. Most respondents use cross profiles to monitor changes in channel morphology (10 out of 19), some use macroinvertebrates (8 out of 19) or fish (8 out of 19) as biological quality measures and 5 out of 19 carry out a detailed hydromorphological survey. Most of the respondents, who named other measures than those listed above, use photographs to document morphological changes (5 out of 8). In the majority of the projects, at least two different measures are used, which generally correspond to some of the project objectives. Some respondents reported the use of only one single measure (6 out of 18), which is qualitative in nature in most cases (5 out of 6, e.g., photographs). A discrepancy exists between the objective of wood placement "creation of fish habitat" and the monitoring measures. Half of the respondents, who monitor the project's success and rated high the objective "creation of fish habitat" (Likert score 4-5) do neither monitor the fish fauna nor do they monitor morphological changes to an extent that allows the generation of fish habitat to be detected (6 out of 12).

Because most projects have recently been implemented (lower and upper quartile of time since wood placement 9 and 36 months, respectively), only preliminary monitoring results were reported. Monitoring results differ in the level of detail and are predominantly qualitative in nature. Therefore, besides some general conclusion presented in the discussion part, only two aspects can be investigated quantitatively. First, local morphological changes generally start with the first high flows after wood placement (e.g., sorting of bed material, creation of pools, bars, cutbanks). Almost all respondents, who carry out a monitoring and assessed the influence of wood structures on channel morphology observed morphological changes (12 out of 13). One respondent reported that channel incision of a sand bed stream (bankfull width 3 m, slope 1-2%) was reversed by wood structures and sediment aggregated 0.2 m in height upstream of the structures within three month after wood placement. Second, the vast majority of the respondents monitoring the fish fauna observed positive effects (5 out of 6). But monitoring efforts differ markedly and do not allow for a comparison of the results. One respondent did publish the results of the fish monitoring in detail (Becker et al. 2003).

Downstream transport of wood structures was observed for some projects (9 out of 23), but the number of wood structures which moved (n = 40, 8%) is low compared to the total number of structures placed in the restored reaches. Most of these wood structures (n = 21) shifted on-site and were transported less than 40 m downstream. Return interval of the high flows is known for 11 out of the 23 restored reaches and ranges from 1 to 100 years, with a median return interval of 5 years. It was assessed, if projects, where wood movement was observed, differ significantly from projects with stable wood structures in regard to the following stream and wood characteristics: bankfull width, slope, data on mean annual discharge and discharge since wood placement (mean high flow, specific stream power at mean high flow), return interval of high flows since wood placement, fixation / volume / blockage ratio of wood structures, time since wood placement. Median volume of wood structures is higher ($n = 21$) and median time since wood placement is lower ($n = 23$) for the projects with stable wood structures (Mann-Whitney-U-test, $p < 0.01$). Furthermore, median specific stream power at mean high flow after wood placement ($n = 11$) is higher in those projects where wood moved (Mann-Whitney-U-test, $p < 0.05$). According to two respondents, buoyancy force was underestimated and some wood structures floated and were transported downstream at high flows, because they were too small or the wooden earth anchors used to fix the structures failed.

5.4.5 Assessment of projects by project managers

The majority of project mangers was well informed about stream restoration with wood at the time of project planning and implementation, but there are some exceptions. The questionnaire included questions on the state of knowledge at the time of wood placement and distinguished between seven sources of information (Table 5.3). The mean number of sources, which had been available to the project managers, is relatively high (4.4). About one third of the respondents (8 out of 23) used only one source of information. Virtually all of these project managers (7 out of 8) had read publications on stream restoration with wood in

Table 5.3
Sources of information, which were available to the respondents at the time of wood placement. The number of the respondents who used the specific source of information is given.

source of information	number
internet inquiry on the use of wood in stream restoration	6
in contact with other project managers which already used wood in stream restoration	12
publications on stream restoration with wood in German	20
international publications on stream restoration with wood	12
educational event on stream restoration with wood	5
educational event on stream restoration	15
already carried out at least one stream restoration project	17

German, which are rare and generally only give basic information. Some respondents had already taken part at an educational event on stream restoration with wood (5 out of 23) or had carried out an internet inquiry (6 out of 23).

The questionnaire included open questions on problems during planning, approval, and implementation of the projects, which revealed the following aspects: First, in accordance with the results presented above, four respondents reported that the lack of information on the use of wood in stream restoration projects was a major problem. Second, only two respondents reported problems during approval of the projects. One of these projects had to be modified due to objections of local authorities regarding flood protection. One respondent reported that several project proposals were rejected in the alpine region, especially after the hundred year flood in 1999. Most of the measures (16 out of 23) had the legal status of "Gewässerunterhaltungsmaßnahmen" (stream maintenance works), which do not have to go through an extensive approval procedure compared to "Ausbaumaßnahmen" (waterway construction). According to two respondents, residents and land owners should be informed at an early stage of the planning procedure to avoid problems in the approval of the projects. Third, in some projects (8 out of 23), problems occurred during the implementation phase, which are generally site specific. For example, one respondent reported that the placement of wood structures in a deeply incised stream was difficult, because the excavator which was available hardly reached the stream bed.

The respondents were asked, if they would carry out the projects in the same way today and had to rate their opinion on a five point scale ranging from "exactly the same way" to "not at all", with an additional category "depends on monitoring results". Most of the respondents would carry out the projects in exactly (3 out of 23) or a very similar (9 out of 23) way, while

Table 5.4
Modifications of future projects designs due to the experiences gained. The number of respondents who rated the modification with the respective Likert score is given.

Likert score / modification of	-2 markedly decrease	-1 decrease	0 same extent	1 increase	2 markedly increase
number of wood structures	0	0	18	4	1
volume of wood structures	0	1	16	5	1
fixation of wood structures	0	2	15	4	2
detailed planning	0	0	20	2	1
participation of residents in planning process	0	0	20	3	0
mimic natural wood structures	0	0	20	3	0
other	0	0	20	3	0

according to 7 out of 23 responses, the design of future projects will depend on the monitoring results. The respondents further specified, which modifications they would make on future project designs due to the experiences gained. Seven modifications were listed in the questionnaire and were rated on a five point Likert scale ranging from "markedly decrease" (-2) to "markedly increase" (+2). In accordance with the results presented above, mean Likert scores for most modifications hardly differ from zero. Some respondents would increase the number, volume, and fixation of wood structures in future projects (Table 5.4), resulting in mean Likert scores of 0.3.

5.5 Discussion

5.5.1 Objectives and general project design

The main objective of stream restoration projects in the northwestern U.S. is to provide instream structural habitat for fishes (Roper et al. 1997; Keim et al. 2000; Roni et al. 2002), and in most cases, restoration projects focus on one or two target fish species (Bisson et al. 2003). In a survey conducted by Bash and Ryan (2002) in Washington State (USA), three out of five most important objectives were directly related to fish enhancement. In contrast, the main objectives of the Central European projects investigated are less specific, and the project managers predominantly aim at increasing structural complexity by initiating channel dynamics. This corresponds to the findings of Reich et al. (2003), but in contrast to the results of Reich et al. (2003), the creation of fish habitat is one of the most important objectives of wood placement in the projects investigated (Fig. 5.3). These restoration projects do not focus on single fish species, as reflected by the low mean Likert score of the general project objective "protect specific species".

Restoration projects which have a more generic management approach – like the ones investigated - are considered to be preferable to projects, which have very specific objectives (Beechie and Bolton 1999). Projects, which focus on specific objectives, such as the enhancement of single fish species, are prone to failure, because it is difficult to exactly identify the limiting factor(s) (House 1996; Kondolf 2000), and specific measures that help one species may harm others (Reeves et al. 1991). Moreover, such specific measures may create conditions, which do not correspond to the potential natural state (e.g., placement of boulders in lowland sand-bed streams, Kauffman et al. (1997)). However, in some cases, specific restoration objectives and measures are necessary (e.g., creation of habitat for endangered species).

Many authors have stressed the necessity for local restoration measures to be seen in a watershed context and on a landscape scale (Kauffman et al. 1997; Roper et al. 1998; Beechie and Bolton 1999; Kondolf 2000; Roni et al. 2002). In addition to local modifications of stream morphology (e.g., bank revetment, straightening), men has also altered processes on a landscape scale (e.g., changed stream hydrology, increased input of fines, reduced shade level, reduced wood input). Local restoration measures often only treat the symptoms rather than the causes of stream degradation, because they neglect the processes that cause degradation and hence, are prone to failure (Frissell and Nawa 1992; Kauffman et al. 1997). The restoration of habitat-forming landscape processes, called "passive restoration" (Kauffman et al. 1997; Bisson et al. 2003), is considered to be preferable to the "active" creation of local instream habitats (Kauffman et al. 1997; Beechie and Bolton 1999; Roni et al. 2002).

Wood placement should be considered to be an interim measure to rapidly improve degraded stream reaches prior to the establishment of a riparian forest providing natural recruitment of wood (Cederholm et al. 1997; Roper et al. 1998; Bisson et al. 2003). Moreover, many habitats can only be created and maintained, if natural processes like wood recruitment and transport are restored (Kauffman et al. 1997; Beechie and Bolton 1999). For example, cutbanks, which are caused by fixed wood structures deflecting the flow against the stream bank, will flatten, because stream width progressively increases and hence, shear stress decreases. Thus, wood recruitment or downstream transport of wood should be enabled to serve for a continuous generation of these habitats.

The placement of wood structures, which are not fixed and able to move at high flows, is a preferable restoration method from the ecological point of view compared to the fixation of wood structures (called "soft" and "hard" engineering according to Bisson et al. (2003)). The results presented in section 4 show that soft engineering methods can potentially be used to restore a larger part of the streams in Central Europe, and even passive restoration techniques (wood recruitment) can potentially be applied in Central European stream reaches. Furthermore, the present study revealed that (a) soft engineering methods have already been successfully applied in some restoration projects, generally in combination with an artificial log jam at the end of the restored reach according to Gerhard and Reich (2001), which traps floating wood at the downstream end of the restored section, and (b) fixation is a large part of total costs, and therefore, total costs are extremely low, if soft engineering methods can be applied. Nevertheless, in contrast to the results of Reich et al. (2003), the present study shows that most wood structures were heavily fixed and soft engineering methods are rather the exception than the rule.

5.5.2 Nature and extent of wood measures

Wood placement is a new method in Central European stream restoration, and the projects investigated can be considered to be "pilot projects". Obviously, it was crucial for these projects to prevent any damage by wood structures placed in the stream, because the acceptance by residents as well as the approval of future projects by local and regional authorities strongly depends on the performance of these pilot projects. Moreover, the lack of information about the use of wood in stream restoration was one major problem in planning of the projects. These restrictions surely influenced the design of the wood structures. From an ecological point of view, the results of the survey indicate potential for improvement in regard to the amount of wood and the size and type of the wood structures.

The vast majority of the restored stream sections is located in the lowland and lower mountain ecoregion. The median volume of the wood structures placed in the restored streams (27.9 m^3 ha^{-1}) is markedly lower compared to the amount of wood found in some of the most natural stream sections in Central Europe located in these ecoregions (41.4 m^3 ha^{-1}, see section 2). Even these most natural stream sections are probably far from the potential natural state. Wood volume in other most natural streams in temperate forested ecoregions, which are also altered in respect to the volume of wood due to historic or current forest practices and the removal of wood, is about 4.5 times the volume placed in the restored streams. Therefore, from an ecological point of view, the amount of wood placed in restored stream reaches should be increased in future projects.

The influence of wood structures on stream hydraulics and morphology strongly depends on the blockage ratio. Gippel (1995) and Gippel et al. (1996a) showed the dependence of rise in water level upstream of wood structures from the blockage ratio; almost no effect is detected for $B < 0.1$. The results presented by Kail (2003) indicate that the pool volume caused by single large fallen depends on the blockage ratio. Therefore, the wood structures should block a greater part of the cross-section, if they are intended to significantly affect stream hydraulics and morphology. Blockage ratio of some wood structures used in the projects investigated is low and can be increased by simply rotating the wood structures perpendicular to flow or by the placement of single large wood structures, which are increasingly used in recent projects.

Some of the wood structures investigated are small compared to stream size (see section 3.2).

This is especially important with regard to single trees, which normally act as key-pieces in the formation of wood accumulations in natural stream reaches (Abbe and Montgomery 2003; Abbe et al. 2003) and therefore, strongly influence stream hydraulics and morphology. However, to act as key pieces, such trees must be stable at high flows. The stability of natural wood pieces increases with wood length (Bilby 1984) and is considered to be especially high, if length of wood pieces exceeds bankfull channel width (Bryant 1983; Swanson et al. 1984; Nakamura and Swanson 1994) and for trees with rootwads (Abbe and Montgomery 2003; Abbe et al. 2003). If wood pieces of sufficient dimension relative to channel size are used, no further fixation is necessary (Hilderbrand et al. 1998). Bankfull width is less than 20 m in the majority of the restored reaches (see Table 5.2). In such small to medium-sized streams tree height can exceed bankfull width and hence, single trees which are large enough to be stable without additional anchoring can potentially be placed in these streams. The use of key pieces of appropriate size / shape, which are placed in areas where channel morphology / hydraulics favour stability, should be considered in future projects.

Complex natural shaped wood structures like trees with rootwad and branches or wood accumulations create a higher habitat diversity compared to wood structures of low structural complexity like logs of cylindrical shape (McMahon and Hartman 1989). Data on the wood structures used indicate that about half of the cylindrical logs could have been replaced by complex natural shaped wood structures. Even if the restoration objectives can be reached with wood structures of low structural complexity, natural shaped wood structures should be used in stream restoration projects to enable positive side effects. However, the influence of complex wood structures on stream morphology and hydraulics is less predictable, and in some cases the use of cylindrical logs might be necessary to insure the achievement of specific objectives and to consider local restrictions.

5.5.3 Monitoring

The following conclusions can be drawn from the monitoring results of the restoration projects :

First, most projects have been implemented only recently, but the majority of the wood structures have experienced high flows with a return interval of at least 5 years. The failure rate (8%) is in the lower range of the failure rates reported in literature for artificial instream structures ranging from 0% to 76% (Ehlers 1956; Frissell and Nawa 1992; Crispin et al. 1993; House 1996; Roper et al. 1998; Schmetterling and Pierce 1999). This may be due to (a) different definitions of functioning and failure (Roper et al. 1998; Roni et al. 2002), (b) comparably high peak flows, gradients, and sediment transport rates of the streams described in literature, most of which are located in the Pacific Northwest (USA), and (c) different periods of time since wood placement. The low failure rate indicates that the wood structures were sufficiently fixed, but to finally assess stability, high flows occurring during the life span of such wood structures should be considered.

Second, the effect of wood structures on stream morphology is strongly dependant on the natural setting, and problems occurring during the implementation of the projects were generally site specific. Therefore, the natural setting of each stream must be considered and schematic project designs, named "cookbook approaches" by Kondolf (1998), are not applicable to most specific restoration sites. For example, only minor changes in channel morphology had occurred in a sand-bed stream section more than two years after wood placement (bankfull width 5-10 m, slope 0.01-0.1%). This is obviously due to a dense riparian vegetation consisting of reeds, which reinforces the stream banks, confines lateral channel migration and lowers flow velocity.

Third, the placement of wood structures is most successful, if the wood structures mimic natural wood with regard to the type and location, as it has been previously stated by several authors (Roni et al. 2002; Bisson et al. 2003). For example, one respondent reported some large cylindrical logs placed perpendicular to flow as grade controls were undermined (3 out of 14), although sandbags were placed upstream of the logs to prevent scour beneath them. This is consistent with the findings of Gallistel (1999), who observed bare cylindrical logs placed in streams to prevent channel incision to be prone to undermination. Cylindrical logs perpendicular to the flow are uncommon in low-gradient sand-bed streams. Natural wood structures, which trap large amounts of sediment in such streams, usually consist of several complex, natural shaped wood pieces (e.g., accumulations of trees with branches or branches with twigs). Monitoring results of another respondent indicate that channel incision can alternatively be decreased or even reversed by placing a large number of natural shaped logs randomly in the stream. Sediment balance of the stream section (length 60 m, bankfull width 3 m, slope 0.32%) changed from –0.95 m^3 $100m^{-2}$ before wood placement to –0.08 m^3 $100m^{-2}$ in the first and +0.08 m^3 $100m^{-2}$ in the second year after the placement of 86 wood pieces with a mean diameter and length of 6.7 cm and 1.7 m respectively (Launhardt and Mutz 2002). However, because the hydrological regime of streams in this lowland region is subdued due to the frequent interruption of the watercourses by lakes, wood stability is high.

Therefore, further monitoring results of restoration projects are necessary to assess, if the restoration method described by Launhardt and Mutz (2002) could be applied in streams with higher gradients or less subdued hydrological regimes.

Fourth, the potential effects of wood placement must be evaluated within a watershed and reach-scale context. Otherwise, the wood placement can have adverse effects on stream morphology and biota. For example, one respondent reported the excessive growth of macrophytes (watercress, *Nasturtium officinale*) in a unshaded restored reach, where wood placed in the stream created low-velocity zones.

Aside these specific aspects, there are some general conclusion, which can be drawn form the survey. Two reasons are listed in literature why restoration projects should be monitored: First, it is not possible to precisely predict the effect of restoration measures on stream morphology and biota and hence, restoration measures are not necessarily beneficial (Kondolf 1998). Therefore, it is necessary to monitor the response of stream morphology and biota to the restoration measures, to allow for corrections (Bryant 1995). Second, monitoring results may provide valuable information for the improvement of future project designs (Bryant 1995; Kondolf 1995, 1996, 1998; Roper et al. 1997; Bash and Ryan 2002; Downs and Kondolf 2002; Bisson et al. 2003; Reich et al. 2003).

Nevertheless, in 9 out of the 23 projects no suitable monitoring was carried out (using photographs to document changes in channel morphology, no monitoring), which is in accordance to the results of Bash and Ryan (2002), who reported the lack of a monitoring for 47% of the restoration projects investigated in Washington State, USA. There are several possible reasons for the high number of projects without a suitable monitoring program: First, the funds of project managers are limited and the restoration measures, which are well-intended, are assumed to be inherently beneficial. Therefore, there is no reason for the project managers to restrict the extent of the restoration measures in favour of a monitoring program. Second, funding sources of water boards and local authorities are restricted to the planning and implementation of projects. Detailed quantitative monitoring is considered as research. Third, many restoration projects are planned and implemented by engineering consultants. Consultants who acknowledge the effects of the restoration measures planned as uncertain, thus requiring a detailed monitoring, probably do not receive the order.

Downs and Kondolf (2002) recommended to define learning objectives in addition to performance objectives and to measure the success of a restoration project in terms of achieving performance and learning goals. Therefore, restoration projects can be successful in providing valuable information for the design of future projects, even if the projects fail to achieve some of the performance objectives (Kondolf 1995).

The concept of "post-project appraisals" (Downs and Kondolf 2002) allows for the evaluation of the performance of restoration projects and the derivation of management guidelines for future projects on different levels of detail. According to this concept, the indication of the short-term performance of restoration measures is only possible if (a) the objectives are explicitly stated and described precisely to allow for the selection of quantifiable variables, which can be measured in the monitoring phase, (b) baseline data are collected to describe the pre-project state with regard to the project objectives, (c) the reasons for the specific project design are documented and comprehensible, (d) a baseline survey is conducted immediately after project implementation, (e) post-project monitoring surveys are conducted over at least a 5-year period. Data on the restoration projects investigated indicate that several monitoring programs are not suitable to assess the success of the projects with regard to specific objectives (e.g., creation of fish habitat). Therefore, there is an urgent need to improve the monitoring programs of future restoration projects in Central Europe.

The results of the survey reveal the successful use of large wood in several restoration projects, mainly to increase structural complexity with fixed wood structures. To benefit from all positive side effects and the low costs, future projects should use soft engineering techniques (large natural shaped wood structures without additional anchoring, which mimic natural wood) whenever possible. Moreover, suitable post-project appraisals should be implemented, because there is a lack of knowledge and information on the use of wood in stream restoration and a strong need to communicate the monitoring results of restoration projects. Finally, local restoration projects must be seen in a watershed context and considered as interim measures until processes are restored on a landscape scale.

6 Conclusions and prospects

6.1 Integrating large wood in general concepts of fluvial morphology

The significance of large wood to channel morphology not only depends on the influence of large wood on erosion and deposition, but also on the amount of large wood present in the channel. One of the studies compiled in this thesis showed that single large fallen trees markedly increase structural diversity on the mesoscale, particularly in terms of pool volume and cross-section complexity (see section 3). The number of fallen trees in some of the most natural Central European stream sections is 21 small fallen trees km^{-1} and the amount of large wood in the river Oder in historical times was 16 large fallen trees km^{-1}. However, the amount of wood in some of the most natural streams flowing through deciduous forest in other temperate forested ecoregions is about 3 times the volume found in the Central European stream sections mentioned above, and even these streams have been altered in respect to the volume of large wood due to historic or current forest practices and the removal of large wood (see section 2). Therefore, it can be deduced that the large wood standing stock is probably considerably less than the potential amount of large wood.

Assuming that the number of large fallen trees in the potential natural state is considerably higher compared to the numbers given above, and considering the fact that the single large fallen trees investigated in section 3 markedly altered channel morphology along a stretch of several tens of meters, it is concluded that channel morphology is strongly influenced by large wood along the whole length of such Central European medium-sized streams in the potential natural state. These findings indicate that large wood is one of the key controls on channel morphology in Central European streams, as it has been shown for streams in other temperate forested ecoregions around the world (see section 1.2).

Therefore, the influence of large wood on channel morphology should be integrated in the general concepts of fluvial morphology, as it has been already suggested in literature: *"The time has arrived for wood, and vegetation in general, to assume a place beside the sediment regime…and the discharge regime as a primary control on the morphology and dynamics of river systems."* (Montgomery and Piégay (2003), p. 4). In general concepts of fluvial morphology, the significance of vegetation to fluvial forms and processes is presently mainly discussed in respect to the influence of vegetation cover on surface runoff and hydrology and the influence of bank vegetation on bank stability and channel width, whereas wood that enters the channel is not considered to be an important factor (Knighton 1998; Bridge 2003; Vandenberghe 2003).

In developing a general concept of fluvial morphology in which large wood is integrated as a key control, one must consider the fact that the average amount of large wood is probably constant over long time-periods and wide geographic areas (Murphy and Koski 1989), but variability on a reach scale is very high due to periodic changes like long-term forest cycles and stochastic disturbance events like wildfires, windthrow, floods, and insect outbreaks (Harmon et al. 1986; Gurnell et al. 1995; Nakamura and Swanson 2003). Therefore, present channel morphology and future morphological changes can vary locally and are strongly dependant on the disturbance history of the area in respect to large wood.

These considerations support the concept of Lane and Richards (1997). They stated that *"The channel can thus be envisaged as being on a kind of trajectory, where what goes on in the future is critically dependant upon what happens in the present, what went on in the past, and what is taking place in reaches upstream and downstream of the reach in question."* (Lane and Richards (1997), p. 254). As Schumm (1991) argues, the history of the system matters and determines the state of the system. This state, which is called "internal morphological configuration" according to Houben (2003), in turn controls the future response of the system to external driving forces (e.g., discharge). By contrast, equilibrium concepts imply that channel morphology at a reach scale reaches a steady state in the long-term that is dependant upon the physiographical setting (e.g., climate, geology, vegetation).

These considerations in turn have implications for the definition of the potential natural state and measures in stream restoration. It has been already mentioned that the potential natural state is the one which would develop from the present state under the present conditions without further human influence (see section 1.4). If equilibrium concepts are applied, the potential natural state can be clearly defined as one single specific state and active restoration measures can be used to reach this objective. By contrast, according to the concept of "internal morphological configuration" the future state of a stream is strongly dependant on the internal system state and the "conditioning" effect of previous events. Bearing in mind that future events, like the ones which deliver large amounts of large wood to streams (e.g., wildfire, windthrow, insect outbreaks), often are stochastic in nature, it seems impossible to define one single specific potential natural state, even if the initial system state is known. There are rather a large number of different possible potential natural states and the future disturbance history determines which of these states gets real. Therefore, active restoration measures are only appropriate, if the stream or river is far from these possible potential natural states. Only if passive restoration (restoration of processes) is applied in long stream reaches or whole catchments, the large variety of potential natural states will develop in dependence on the disturbance history which differs locally.

6.2 The use of large wood in stream restoration – substituting costs by time

The results presented in section 4 on the use of large wood in stream restoration showed that soft engineering, active restoration methods (placement of large wood without additional anchoring) can potentially be used to restore a larger part of the streams in Central Europe, and even passive restoration techniques (restoring the process of wood recruitment) can potentially be applied in Central European streams. However, most of the restoration projects in which large wood has been used so far did apply conventional bio-engineering techniques (placement of fixed large wood structures), so called hard engineering (see section 5). The fixation represents a large portion of the costs, and restoration projects in which soft engineering methods are used cause less costs (see section 5.4.3). The restoration projects investigated in section 5 show that large wood can be successfully used even in areas where adjacent land uses rather tightly constrain the options for stream restoration and thus, the large wood structures placed in the channel must be fixed. But one of the essential advantages of large wood – its low costs - gets partly lost, if the wood structures have to be fixed.

Given these results and following Kauffman et al. (1997) and Bisson et al. (2003), it is suggested to classify restoration measures between the extremes of pure active and pure passive restoration (Table 6.1). It is assumed that costs decrease and the time necessary to reach the desired state of the stream increases from pure active to pure passive restoration. In this concept of "substitution of active measures / costs by time", the placement of fixed wood structures can be classified as "pure active restoration", if the wood is placed in the stream solely to serve as habitat. If the wood structures are fixed in the stream to initiate natural channel dynamics, this can be considered to be a less stringent active restoration measure. The placement of wood structures without additional anchoring can be classified as an intermediate restoration measure, and the recruitment of large wood (restoring the process of wood recruitment) can be considered to rather be a passive restoration measure.

It is further hypothesized that cost-effectiveness of pure active and pure passive restoration measures differ and change with time (Fig. 6.1). Active restoration measures cause high costs at the beginning, but they also markedly improve the state of the channel in the short-term. Therefore, these measures have an intermediate cost-effectiveness at that time. If no further measures are undertaken, cost-effectiveness is only dependant on the future effect of the restoration measures. Cost-effectiveness probably increases in the medium-term, because it takes some time for the disturbances caused by the building operations to vanish (e.g., coarse substrate filled with interstitial fines) and because of the time-lag until certain measures show an effect (e.g., formation of pools caused by log weirs). But in the long-term, cost-effectiveness probably sharply decreases, because the positive effects decrease or vanish (e.g., decay or failure of large wood structures).

The costs caused by passive restoration measures are probably constant over time for most measures (e.g., restricting land use in riparian buffer strips). They cause low to median costs related to the length of the restored channel section, but they do have no or little effect in the

Table 6.1
Description of the two general methods of stream restoration (pure active and passive restoration). In passive restoration active measures and costs are substituted by time.

substitution of active measures / costs by time	
active restoration	passive restoration
- desired state is built (often by using heavy machinery)	- desired state develops through natural channel dynamics
- restoration of states	- restoration of processes
- knowledge on desired state is necessary (e.g., planform, sinuosity, channel features)	- knowledge on natural channel dynamics is necessary to decide which processes have to be restored
- particularly suited to restore streams on a reach scale	- particularly suited to restore streams on a catchment scale
(a) to create habitat for endangered species until processes can be restored, which provide these habitats	(a) because many processes act on large spatial scales
(b) if land use rather tightly constrains the options of stream restoration	
- short time-span necessary to reach the desired state of the stream (desired state is built)	- long time-span necessary to reach the desired state of the stream (stream has to adjust to the restored processes, especially long in streams with cohesive sediments)
- high costs for implementation of measures*	- low costs for implementation of measures*

*it is assumed that the purchase of adjacent land to allow for lateral channel migration is necessary for both restoration methods

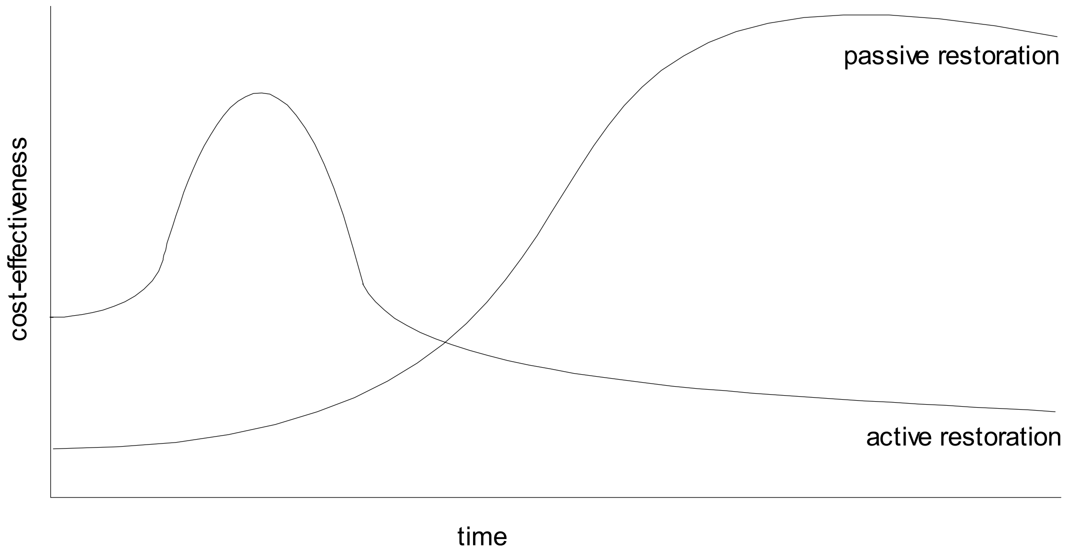

Figure 6.1: Cost-effectiveness of pure passive and active stream restoration in dependence on time.

short-term. Therefore, these measures have a low cost-effectiveness at that time. In the medium-term, the restored processes increasingly improve the state of the channel and cost-effectiveness increases (e.g., input of large wood from riparian buffer strips). In the long-term, processes are restored, the channel has adjusted to these processes and no further improvement is to be expected. Because costs are low, the cost-effectiveness only slightly decreases in the future.

6.3 Prospects of future research

The main objective of this thesis was to help develop a Central European perspective on the significance of large wood in streams and rivers (see section 2, 3 and 6.1) and its use in stream restoration (see section 4, 5, and 6.2). Because stream restoration projects primarily try to improve habitat quality by increasing structural diversity, the studies focused on the significance of large wood to channel morphology. As it has been mentioned in the previous sections (see 1.2 and 1.3), the relevance of large wood for channel morphology and its potential use in stream restoration has long been overlooked in Central Europe, and only few studies have focused on large wood so far. Of course, within the scope of a single thesis, only few of the important issues concerning large wood in Central European streams can be addressed. The results of the studies compiled in this thesis show that there are some key research need areas for future investigations:

First, the minimum amount of large wood that should be present in restored streams was derived from some of the most natural Central European stream sections (see section 2), but these streams are still far from the potential natural state. Models of wood dynamics can potentially be used to simulate the number and volume of large wood pieces present in the potential natural state of different stream and river types. However, there is a lack of knowledge on the decay rate of logs in the aquatic environment, which is known to strongly influence the outcome of the models. Therefore, future research should focus on decay rates in a first step, to allow for a precise modelling of the large wood standing stock present in the potential natural state.

Second, the investigation on the influence of single large fallen trees on channel morphology indicates a strong morphologic control of large wood on a reach scale (see section 3). These are valuable results for active stream restoration on a reach scale, where such single large fallen trees are increasingly used. However, long stream reaches and a even whole catchments have to be restored in the forthcoming years to fulfil the requirements of the EU Water Framework Directive. Therefore, future research on the influence of large wood on channel morphology should focus on the catchment scale.

Third, the results presented in section 4 show that the recruitment and placement of large wood are appropriate measures to restore a larger part of the streams in the study area and probably in Germany and the neighbouring countries. It would be of great interest to conduct comparable studies in other countries with large data sets on stream hydromorphology (e.g., River Habitat Survey – UK, Système d'Evaluation de la Qualité du Milieu Physique – France) in order to develop a European perspective on the use of large wood in stream restoration projects.

Fourth, the mail survey on restoration projects in which large wood has already been used revealed that the vast majority of the wood structures were fixed to prevent downstream transport. Therefore, there is a strong need for future research on the stability of logs and on soft engineering techniques (mimic natural stable wood structures), which will drastically reduce costs and which are more favourable restoration methods from an ecological point of view. Furthermore, there is a strong need for studies concerning the influence of wood on water level. Some studies focused on the influence of large wood on channel hydraulics (Gippel 1995; Shields and Gippel 1995; Gippel et al. 1996a, 1996b; Mutz 2000, 2003; Shields et al. 2001; Daniels and Rhoads 2003; Hygelund and Manga 2003), but there is still a lack of knowledge on the influence of large wood on water level in different hydraulic environments (e.g., for different flow depths, Froude Number).

Fifth, the mail survey indicated that the placement of large wood without additional anchoring causes low costs compared to more active restoration measures. More detailed studies are necessary to evaluate the exact cost-effectiveness of different active and passive restoration measures using large wood. Theses studies should also consider positive side effects and non-ecological values (e.g., flood protection caused by the increase of travel time of flood waves, increase of the self purification ability of the stream, recreation value).

The key research need areas listed above show that interdisciplinary research is necessary to get a better understanding of how large wood influences fluvial systems and how this knowledge can be used in stream restoration.

7 Summary

Central European streams and rivers have been altered by man since deforestation and land-use change began to significantly influence erosion and alluvial deposition in the Mesolithic Age. The most severe alterations occurred in the 19^{th} and 20^{th} century, when virtually all rivers and most streams were cleared, straightened, and bank- / bed-revetments and embankments were built. These human alterations led to a severe degradation of stream and river ecosystems, both, in respect to hydromorphology and water quality. Water quality markedly improved, which is largely due to improved waste water treatment and decreased noxious emissions, but most Central European streams and rivers still are in a poor hydromorphological state. As a consequence, the restoration of streams and rivers has become a widely accepted social objective in developed nations, which increasingly becomes established in law like in the “European Water Framework Directive”, recently enacted by the European Union. Because the European Water Framework Directive requires a good ecological status of all European rivers to be achieved by 2015, there is presently a strong demand for cost-effective stream restoration.

In the beginning, stream restoration projects focused on the design of new channels and channel features to improve the hydromorphological state using heavy machinery. It has been widely stated and it can be considered to be “state of the art” that streams and rivers should alternatively be restored by initiating natural channel dynamics, which causes the formation of a natural channel pattern and channel features, whenever possible. Such approaches, which focus on the restoration of natural processes, are thought to cause less costs and hence, are of special interest, because long stream reaches and even whole catchments have to be restored to fulfil the demands of the Water Framework Directive.

One out of several possible measures to initiate natural channel dynamics by altering local channel hydraulics is the placement of cylindrical tree boles, rootwads or whole trees, called large wood. Large wood is a natural component of all aquatic ecosystems in temperate forested ecoregions and therefore, can be considered to be the most natural way to initiate natural channel dynamics compared to boulders or groins.

The role of large wood in stream ecosystems and its use in stream restoration has been a key research area in North America, where the impact of large wood on stream ecosystems is much more apparent, because historical descriptions of pristine stream ecosystems with a high wood standing stock exist due to the short European settlement history. These studies

indicate that large wood is one of the key factors of pristine ecosystems in temperate forested ecoregions, which influences not only stream hydraulics and morphology, but also hydrology, sediment budget, and biota across a wide range of spatial and temporal scales. Furthermore, these studies show that large wood can be successfully used in stream restoration, not only for initiating natural channel dynamics, but also for many other objectives.

In contrast to North America, the relevance of large wood for stream ecosystems has long been overlooked in Central Europe, presumably because it is rarely found in Central European streams due to the long term human impact on streams and the extensive management of virtually all forests over many centuries. Transferability of the results of North American studies is limited, because land-use pressure is especially high in Central Europe and the natural setting (e.g., discharge, geology, vegetation) and restoration objectives differ from North America, although the fundamental principles of how large wood influences stream and river ecosystems are probably the same in all temperate forested ecoregions.

The main objective of the thesis is to help develop a Central European perspective on the significance of large wood in streams and rivers and its use in stream restoration. Four studies are compiled in this thesis, which focus on (a) the potential natural state of Central European streams in respect to the amount and distribution of large wood, (b) the influence of large wood (single large fallen trees) on channel morphology, (c) the quantification of the potential use and the simulation of the effects of large wood in restoration projects, and (d) the review of restoration projects in which large wood has been used so far.

Potential natural state of Central European streams in respect to the amount and distribution of large wood: As restoration should approach to develop a degraded ecosystem towards its potential natural state, called “Leitbild” in German, stream restoration projects in which large wood is used should be geared to the potential natural amount and distribution of large wood. The potential natural state can be deduced from reference sections, historical records, and modelling.

As a first step to describe the potential natural state of streams in respect to large wood, the results of nine investigations were summarized, in which the amount of large wood present in Central European reference sections was quantified (n = 34). Although these reference sections are among the most natural stream sections and in a “near-natural” condition according to Central European standards, the volume of large wood is low compared to other temperate forested ecoregions (factor 3). Furthermore, large fallen trees, which can act as key-pieces in the formation of wood accumulations, are missing completely. Regarding the three main ecoregions, large wood volume is significantly lower in the wide alpine floodplains compared to the lower mountain and lowland stream sections. The latter have a median wood volume of 41.4 m^3 ha^{-1} related to stream bottom area.

The range of volumes found in the study streams can be regarded as the minimum volume of large wood that should be present in a "near-natural" Central European stream. From the distribution of size classes, comparison with the amount of wood in some of the most natural streams flowing through deciduous forest in other temperate forested ecoregions, and the historical description of the river Oder, it is deduced that the current large wood standing stock is considerably less than the potential amount of large wood. For centuries, all of the streams have been anthropogenically influenced. Historic alterations of the stream, its floodplain, and the riparian vegetation may still affect large wood supply and standing stock. It is concluded that virtually all streams in Central Europe are highly altered with respect to the loading of large wood, and stream restoration projects should aim to increase the input of large wood even in the most natural stream sections.

Influence of large wood (single large fallen trees) on channel morphology: The main objective of stream and river restoration projects that try to initiate natural channel dynamics is to create natural channel features like pools, bars, and cut banks, which in turn are important habitats, e.g. for fish. That is, stream and river restoration primarily tries to change channel morphology by modifying channel hydraulics. To markedly alter channel hydraulics and morphology, the wood pieces placed in the streams and rivers must be sufficiently large. In many streams and rivers this holds true only for large fallen trees, which are increasingly used in restoration projects. But few is known about the exact effect of such single large fallen trees on channel morphology; about the type and size of the channel features, which are caused by such large wood pieces, and the time and discharge necessary for such channel features to develop. Therefore, the impact of single large fallen trees on mesoscale channel morphology was investigated in six short channel sections in Central Europe.

The results show that the single large fallen trees significantly increased structural diversity at almost all spatial scales, particularly in terms of pool volume and cross-section complexity. Pool volume of the sections investigated is well within the upper range of pool volume found in high-gradient streams in northwestern America. 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. Furthermore, large wood increased variability of some cross-section parameters, which is of special importance, because habitat diversity is assumed to increase with cross-section variability. Moreover, some rare habitat types are clearly associated with the large fallen trees. These results indicate that single large fallen trees significantly enhance channel morphology within one to several years along a stretch of several tens of meters.

Quantification of the potential use and the simulation of the effects of large wood in restoration projects: Despite the beneficial role of large wood for channel morphology and stream ecosystems in general, it must be considered to be a potential threat to land uses and works in the channel and on the adjacent floodplain. Large wood can be transported downstream, damaging bridges and other works and rises the water level, thus increasing flood probability upstream. Fixation of the large wood pieces can prevent downstream transport, but probably markedly increases the costs and is less preferable from an ecological point of view, because many channel features can only be created and maintained, if natural wood transport and dynamics are restored. Therefore, in a densely populated area like Central Europe, adjacent land uses rather tightly constrain the options for stream restoration projects in which large wood is used without additional anchoring. The potential use and effects of large wood in Central European streams was quantified to assess, if large wood recruitment (passive restoration) and placement (active restoration) are suitable methods to restore a considerable part of the streams and rivers.

Hydromorphological data, called "Gewässerstrukturgütedaten", of three federal states in Germany were used to identify stream sections, which can be restored by the placement (anthropogenic input of large fallen trees) or recruitment (restoring the natural recruitment of large fallen trees) of large wood, so called "active" and "passive" restoration. Furthermore, the potential enhancement due to these restoration measures was assessed. Passive restoration (large wood recruitment) is suited for only a small percentage of the streams and rivers, but total length of these channel reaches is high compared to the length of the reaches restored so far. The potential use of active restoration (placement of large wood) is much higher. About one fifth of the streams and rivers can be restored by the placement of large wood, if the land uses pasture and grassland are restricted.

There are differences between (a) the lower mountain area, where a large number of channel segments can be restored, yielding an improvement from a moderate/good to a good/excellent morphological status and (b) the lowlands, where only a small number of channel segments can be restored, yielding an improvement from a bad to a moderate morphological state. The latter upgrading might be sufficient to reach a "good ecological status" as defined by the EU Water Framework Directive. The results of this study show the suitability of the recruitment and placement of large wood as appropriate measures to restore a large proportion of the streams in the study area.

Review of restoration projects in which large wood has been used so far: Despite the fact that even single large fallen trees can act as a strong morphologic control in Central European streams and large wood can potentially be used to restore a larger part of the streams and rivers in Central Europe, it is rarely used in stream restoration projects so far. Only few of these projects have been described in open literature and hence, information from which restoration guidelines can be derived are missing. Therefore, a mail survey was started to summarize the experiences that have been gained so far, which may provide valuable information for the improvement of future project designs.

Although the number of restoration projects, which could be investigated is limited (n = 23), the survey revealed the following aspects: The objective of stream managers mainly is to increase structural complexity by initiating natural channel dynamics with fixed wood structures (active restoration with hard engineering methods). In some projects, wood structures without additional anchoring (active restoration with soft engineering methods) were used. Failure rate of these structures is low, and preliminary monitoring results indicate that the hydromorphological status improved rapidly in most projects. However, there is potential for improvement from an ecological and economical point of view. The size and the potential effect of some wood structures on stream hydraulics and morphology is low and can be increased without inferring with local restrictions. Furthermore, in most of the cases, complex natural shaped wood structures could have been used instead of bare cylindrical logs to benefit from positive side effects.

The data on the restoration projects investigated indicate that costs can be markedly reduced and positive side effects are to be expected, if wood structures without additional anchoring are used. Statistical analysis indicate that stability of the wood structures is dependant on the size of the structures, time since wood placement, and specific stream power but not on the fixation of the wood structures, which shows that soft engineering methods can be used without increasing the risk of downstream transport. Therefore, it is highly recommended to use such soft engineering methods in future projects whenever possible.

The results of the survey further reveal that the effect of wood structures on stream morphology is strongly dependant on the natural setting, and therefore, schematic project designs are not applicable to most specific restoration sites. The potential effects of wood placement must be evaluated within a watershed and reach-scale context. Otherwise, the wood placement can have adverse effects on stream morphology and biota. Furthermore, there is a lack of knowledge on the use of wood in stream restoration, an urgent need to improve the monitoring programmes of future restoration project and a strong need to communicate the monitoring results.

Two major conclusions can be drawn from the results of the four studies described above:

First, the results on the potential use of large wood and the case studies investigated show that various restoration methods exist, which differ in respect to their potential use, costs, and the field of application. A conceptional framework is introduced to classify these restoration methods between the extremes of pure active and pure passive restoration and to assess their cost-effectiveness in dependence on time. Costs are assumed to decrease and the time necessary to reach the desired state of the stream to increases from pure active to pure passive restoration. In this concept of "substitution of active measures / costs by time", the placement of fixed wood structures can be classified as "pure active restoration", if the wood is placed in the stream solely to serve as habitat. If the wood structures are fixed in the stream to initiate natural channel dynamics, this can be considered to be a less stringent active restoration measure. The placement of wood structures without additional anchoring can be classified as an intermediate restoration measure, and the recruitment of large wood (restoring the process of wood recruitment) can be considered to rather be a passive restoration measure.

Second, the results on the amount of large wood present in the potential natural state and on the influence of large wood in channel morphology presented above indicate that large wood is one of the key controls on channel morphology in Central European streams, as it has been shown for streams in other temperate forested ecoregions.

Therefore, the influence of large wood on channel morphology should be integrated in the general concepts of fluvial morphology as a key control. Because the wood standing stock of a channel reach is strongly dependant on stochastic disturbance events like wildfires, windthrow, floods, and insect outbreaks, such concepts should consider the local disturbance history. This consideration supports a concept, which is recently discussed in fluvial morphology. According to that concept, the history of the system determines the present state of the system, which represents the "internal morphological configuration" and in turn controls the future response of the system to external driving forces (e.g., discharge).

Therefore, it seems impossible to define one single potential natural state, because the system does not reach a steady state in the long-term as it is implied by equilibrium concepts. There are rather a large number of different possible potential natural states and the future disturbance history determines which of these states gets real. Only if passive restoration methods (restoration of processes) are applied in long stream reaches or whole catchments, the large variety of potential natural states will develop in dependence on the disturbance history, which differs locally.

The studies compiled in this thesis can be considered to be some of the first steps to develop a Central European perspective on wood in streams and rivers, but there is a strong need for future research on large wood in fluvial morphology. This surely holds true for other disciplines like hydraulic engineering, biology, ecology, and even social-sciences, which also work on fluvial systems. Hopefully, the results presented in this thesis stimulate future research on wood in Central European streams and rivers, which is essential to successfully restore these systems.

Zusammenfassung

Einleitung

Seit Beginn der Rodungen im Mesolithikum und der damit verbundenen Bodenerosion und Akkumulation von Auelehmen beeinflusst der Mensch das Erscheinungsbild der Fließgewässer in Mitteleuropa. Aber erst durch die wasserbaulichen Eingriffe im neunzehnten und zwanzigsten Jahrhundert hat der Mensch massiv in das Ökosystem Fließgewässer eingegriffen. Die Begradigung und der Verbau von Bächen und Flüssen führte zu einer strukturellen Verarmung und damit zum Verlust einer Vielzahl von Lebensräumen und zur Beeinträchtigung wichtiger Funktionen der Fließgewässer wie der Hochwasserretention und des Selbstreinigungsvermögens. Darüber hinaus wurde die Wasserqualität durch die Einleitung von Abwässern und die Belastung aus diffusen Quellen stark beeinträchtigt. Die Renaturierung von Fließgewässern wurde daher zu einem wichtigen umweltpolitischen Ziel und hat Eingang in die nationale und europäische Gesetzgebung gefunden wie etwa in das Wasserhaushaltsgesetz und die EU-Gewässerrahmenrichtlinie. Es besteht jedoch eine deutliche Diskrepanz zwischen diesen umweltpolitischen Forderungen und den zur Verfügung stehenden finanziellen Mitteln. Insbesondere die Umsetzung der oben genannten EU-Gewässerrahmenrichtlinie erfordert die Entwicklung und den Einsatz möglichst kosteneffizienter Renaturierungsmethoden.

Im Rahmen der ersten Renaturierungsprojekte zu Beginn der 1980iger Jahre wurden vor allem baulich-gestalterische Maßnahmen durchgeführt, die i.d.R. mit hohen Kosten verbunden waren. Seit einigen Jahren werden vermehrt Renaturierungskonzepte erstellt, bei denen die Initiierung einer eigendynamischen Gewässerentwicklung im Mittelpunkt steht. Da die gewünschten morphologischen Strukturen wie Kolke, Uferabbrüche und Inseln auf natürliche Weise durch die Kraft des Wassers geschaffen werden, gelten diese Methoden als besonders kosteneffizient. Die Einbringung von Totholz ist eine von mehreren Möglichkeiten, durch die Veränderung der hydraulischen Bedingungen eine eigendynamische Gewässerentwicklung zu initiieren oder zu fördern. Totholz in Form von Ästen, Wurzelballen oder ganzen Stämmen kommt natürlicherweise in allen Gewässern vor, deren Auen im potenziell natürlichen Zustand von Wäldern dominiert werden. Im Gegensatz dazu müssen andere Materialien, wie beispielsweise Wasserbausteine, in vielen Gewässertypen als unnatürliches Substrat angesehen werden und Buhnen stellen in jedem Fall künstliche Strukturen dar. Daher erscheint der Einsatz von Totholz bei der Renaturierung von Fließgewässern aus ökologischer Sicht besonders sinnvoll.

Die Bedeutung von Totholz in Fließgewässern und dessen Einsatzmöglichkeiten bei Renaturierungsvorhaben ist in Nordamerika seit Beginn der 1980iger Jahre ein Forschungsschwerpunkt. Die Forschungsergebnisse lassen vermuten, dass Totholz natürlicherweise in allen Fließgewässerökosystemen der gemäßigten Breiten eine wichtige Steuergröße ist, die nicht nur die Hydraulik und Morphologie, sondern auch den Sedimenthaushalt, die Hydrologie und die Besiedlung der Gewässer maßgeblich bestimmt. Darüber hinaus zeigen diese Arbeiten, dass Totholz nicht nur zur Initiierung einer eigendynamischen Entwicklung, sondern auch zur Umsetzung vieler weiterer Renaturierungsziele eingesetzt werden kann.

Im Gegensatz dazu beschäftigen sich bisher nur wenige Arbeiten mit der Bedeutung von Totholz und den Einsatzmöglichkeiten bei Renaturierungsvorhaben in mitteleuropäischen Fließgewässern. Die Bedeutung von Totholz ist hier weniger offensichtlich, da größere Mengen an Totholz heute nur noch in wenigen, meist kleinen Fließgewässern vorkommen. Dies ist Folge der seit Jahrhunderten andauernden forstlichen Nutzung der Wälder und der Räumung der Gewässer. Es ist anzunehmen, dass sich die Wirkung von Totholz in mitteleuropäischen Fließgewässern nicht grundlegend von der in anderen bewaldeten Regionen der gemäßigten Breiten unterscheidet. Dennoch sind die Ergebnisse der oben erwähnten nordamerikanischen Arbeiten nur eingeschränkt auf mitteleuropäische Verhältnisse übertragbar. Dies liegt zum einen darin begründet, dass die Bedeutung von Totholz und dessen Wirkung in Fließgewässern sowohl von naturraumtypischen und gewässertypspezifischen Kenngrößen (z.B. Abfluss, Sohlmaterial, Gefälle) als auch von totholzspezifischen Parametern (z.B. Menge, Größe, Lage, Verteilung) abhängt. Des Weiteren weichen die Renaturierungsziele in Mitteleuropa von denen in Nordamerika ab. Zudem unterliegen die Renaturierungsprojekte aufgrund des höheren Nutzungsdrucks sehr viel größeren Restriktionen.

Vorrangiges Ziel der vorliegenden Dissertation ist es daher, einen Beitrag zum besseren Verständnis der Bedeutung und morphologischen Wirkung von Totholz in mitteleuropäischen Fließgewässern zu leisten sowie die Einsatzmöglichkeiten von Totholz bei der Renaturierung von Gewässern in quantitativer und qualitativer Hinsicht zu untersuchen. Die Dissertation umfasst vier Untersuchungen, die sich schwerpunktmäßig mit den folgenden Themen beschäftigen:

1.) Die Totholzmengen mitteleuropäischer Fließgewässer im potenziell natürlichen Gewässerzustand, welche als Leitbilder für die Renaturierung von Fließgewässern herangezogen werden können.

2.) Die morphologische Wirkung von Totholz in Form einzelner Sturzbäume, die im Rahmen von Renaturierungsprojekten in Gewässer eingebracht werden können.

3.) Die Bestimmung des Potenzials der Renaturierung von Fließgewässern durch das Belassen oder die Einbringen von Totholz und die Quantifizierung der damit verbundenen, potenziellen strukturellen Aufwertung.

4.) Die Auswertung von Renaturierungsprojekten in Mitteleuropa, bei denen Totholz bereits eingesetzt worden ist.

Totholzmenge mitteleuropäischer Fließgewässer im potenziell natürlichen Gewässerzustand

Das Ziel einer Fließgewässerrenaturierung ist i.d.R. die Verbesserung hin zum potenziell natürlichen Gewässerzustand, dem Leitbild. Es erscheint daher sinnvoll, dass sich bei der Renaturierung von Fließgewässern die Größe, Form und Menge des eingebrachten Totholzes am potenziell natürlichen Zustand orientiert bzw. diesem entspricht. Darüber hinaus lässt sich anhand der Totholzmenge im potenziell natürlichen Gewässerzustand abschätzen, welche Bedeutung Totholz im leitbildgemäßen Zustand hat. Bei der Erstellung von Leitbildern werden i.d.R. drei sich ergänzende Informationsquellen genutzt: der Zustand von naturnahen Referenzgewässern, die Beschreibung historischer Zustände und Ergebnisse von Modellierungen.

Um eine erste Vorstellung von der Totholzmenge im potenziell natürlichen Gewässerzustand zu entwickeln, wurden im Rahmen der vorliegenden Arbeit die Daten von neun, zum Teil bisher unveröffentlichten Untersuchungen ausgewertet, in denen die Totholzmenge und Größenverteilung in naturnahen mitteleuropäischen Fließgewässern quantifiziert wurde. Es handelt sich um insgesamt 34 Gewässerabschnitte, die gemessen an mitteleuropäischen Verhältnissen als Referenzgewässer bezeichnet werden können (keine forstliche Nutzung, keine Räumung von Totholz seit mindestens 10 Jahren, standortgerechte Vegetation). Bei der Berechnung der Totholzmenge wurde das Volumen von grobem Totholz (Durchmesser > 0,1 m) und Totholz-Akkumulationen berücksichtigt und sowohl auf die Länge des Gewässerabschnitts als auch auf die Sohlfläche bezogen.

Die Totholzmenge und -anzahl beträgt im Mittel 17,2 m^3 km^{-1} und 37,8 m^3 ha^{-1} bzw. 200 Elemente km^{-1} und 300 Elemente ha^{-1} (Median der 34 Referenzgewässer). Die Anzahl größerer Totholz-Elemente (Durchmesser > 0,2 m, Länge > 3 m), die als Sturzbäume bezeichnet werden können, ist mit 21 Sturzbäumen pro Fließkilometer gering. Größere, lagestabile Sturzbäume (Durchmesser > 0,5 m, Länge > 10 m), die als Fänger fungieren und potenziell zur Bildung großer Akkumulationen führen können, kommen in den untersuchten Gewässerabschnitten nicht vor. Nach Ökoregionen differenziert ergeben sich signifikante Unterschiede zwischen der geringen Totholzmenge in alpinen Gewässern (2 m^3 ha^{-1}) sowie der Totholzmenge in den Gewässerabschnitten im Mittelgebirge (36,9 m^3 ha^{-1}) und im Norddeutschen Tiefland (41,8 m^3 ha^{-1}). Die durchschnittliche Totholzmenge in den zwei letztgenannten Ökoregionen beträgt 41,4 m^3 ha^{-1}.

Die oben genannten Totholzmengen können als Mindestmengen betrachtet werden, die in naturnahen Fließgewässern vorkommen. Aus den folgenden Gründen ist anzunehmen, dass selbst diese, für mitteleuropäischen Verhältnisse naturnahen Gewässerabschnitte, in Hinblick auf die Totholz-Ausstattung noch stark vom potenziell natürlichen Gewässerzustand abweichen. Erstens fehlen größere Sturzbäume, die in natürlichen mitteleuropäischen Wäldern in größerer Zahl vorkommen können und aufgrund ihrer Größe einen erheblichen Teil der Totholzmenge in Fließgewässern bilden. Zweitens zeigen sich keine Unterschiede zwischen den Totholzmengen in den untersuchten Gewässerabschnitten des Norddeutschen Tieflandes und der Mittelgebirge. Da sich diese Ökoregionen in Hinblick auf einige wichtige Parameter unterscheiden, welche die Totholzmenge maßgeblich beeinflussen (z.B. Baumartenspektrum und Produktivität der Uferwälder, Eintrags-Ursachen für Totholz), ist anzunehmen, dass die Gewässer dieser Ökoregionen im potenziell natürlichen Zustand unterschiedliche durchschnittliche Totholzmengen aufweisen müssten. Drittens zeigt der Vergleich mit Angaben aus der Literatur, dass die unter Laubwald verlaufenden naturnahen Gewässer in anderen bewaldeten Regionen der gemäßigten Breiten deutlich größere Totholzmengen besitzen (Faktor 3, $n = 26$). Hierbei ist zu bedenken, dass auch die Totholzmenge dieser naturnahen Gewässerabschnitte nach Aussage der Autoren nicht dem potenziell natürlichen Zustand entspricht. Dies lässt den Schluss zu, dass nahezu alle Fließgewässer in Mitteleuropa in Hinblick auf ihre Totholz-Ausstattung als extrem degradiert eingestuft werden müssen und selbst in scheinbar naturnahen Gewässern ein Totholz-Defizit besteht.

Morphologische Wirkung von Sturzbäumen

Das vorrangige Ziel heutiger Renaturierungsprojekte ist es, durch das Zulassen oder die Förderung einer eigendynamischen Entwicklung eine naturnahe Gewässermorphologie herzustellen, d.h. natürliche Strukturen wie Kolke, Bänke, Uferabbrüche und Inseln zu schaffen, welche wiederum wichtige Habitate für eine Vielzahl von Arten darstellen. Die Renaturierung von Fließgewässern zielt also primär darauf ab, durch die Veränderung der hydraulischen Verhältnisse die Gewässermorphologie zu modifizieren. Um die Hydraulik und damit die Gewässermorphologie wesentlich zu beeinflussen, müssen die eingebrachten Totholz-Strukturen eine ausreichende Größe besitzen. In vielen Fließgewässern ist dazu der Eintrag großer Totholz-Elemente in Form von ganzen Sturzbäumen notwendig. Bisher ist jedoch wenig über die genaue morphologische Wirkung solcher Sturzbäume bekannt, über die Art und Größe der Gewässerstrukturen die durch Sturzbäume gebildet werden und den Entwicklungszeitraum, der zur Ausbildung dieser Strukturen notwendig ist. Daher wurde die Wirkung einzelner Sturzbäume auf die mesoskalige Gewässermorphologie beispielhaft an sechs Gewässerabschnitten untersucht.

Auf Grundlage einer detaillierten Vermessung wurden für sechs Gewässerabschnitte und fünf totholzfreie Vergleichsabschnitte digitale Geländemodelle erstellt. Folgende Größen wurden mit Hilfe der Geländemodelle bestimmt: Fläche und Volumen der Gewässerstrukturen (Kolke, Bänke, Uferabbrüche), Sohl- und Ufer-Komplexität, gängige Querprofilparameter (Querprofil-Fläche, -Tiefe, -Breite) und die Querprofil-Komplexität, welche mit Hilfe der „AMT-Analyse“ bestimmt wurde. Hierbei handelt es sich um ein Maß, dass die Abweichung des Verlaufs des Querprofils von einer geraden Linie auf unterschiedlichen räumlichen Skalen beschreibt.

Die Ergebnisse der Untersuchung zeigen, dass die morphologisch-strukturelle Diversität an den durch Sturzbäume beeinflussten Gewässerabschnitten gegenüber den Vergleichsabschnitten signifikant erhöht ist. Dies trifft insbesondere auf das Kolk-Volumen und die Querprofil-Komplexität auf unterschiedlichen räumlichen Skalen zu. Die Erhöhung der Variabilität einiger Querprofil-Parameter ist als deutlicher Hinweis auf eine Erhöhung der Habitatdiversität zu werten. Darüber hinaus sind einige Gewässerstrukturen an das Vorkommen der Sturzbäume gebunden. Die Kolke in den untersuchten Totholz-Abschnitten erreichen Volumina von bis zu 36 m^3 und ihre Größe liegt mit 424 - 693 $m^3\ ha^{-1}$ im oberen Bereich der Werte, die in der Literatur für Fließgewässer in den Küstengebirgen Nordwest-Amerikas angegeben werden (229 - 755 $m^3\ ha^{-1}$). Dabei scheint das Kolk-Volumen maßgeblich vom Anteil der Querschnittsfläche abzuhängen, die von den Sturzbäumen eingenommen wird. Dieser sogenannte „Verdeckungsgrad“ ist ein Maß für die Einschränkung der hydraulischen Leistungsfähigkeit des Profils.

Die Unterschiede zwischen den durch die Sturzbäume beeinflussten Gewässerabschnitten und den Vergleichsabschnitten zeigt, dass der Eintrag von einzelnen Sturzbäumen bei durchschnittlichen Abflussereignissen innerhalb weniger Jahre zu einer signifikanten morphologisch-strukturellen Aufwertung des Gewässerabschnitts führen kann. Dabei wird die

Gewässermorphologie auf einer Strecke von mehreren zehner Metern signifikant verändert.

Bestimmung des Potenzials der Renaturierung von Fließgewässern mit Totholz und Quantifizierung der damit verbundenen, potenziellen strukturellen Aufwertung

Da Totholz im potenziell natürlichen Gewässerzustand in großen Mengen vorkommen würde und eine hohe morphologische Wirksamkeit besitzt, erscheint der Einsatz von Totholz bei der Renaturierung von Fließgewässern aus ökologischer Sicht sinnvoll. Jedoch kann Totholz gerade aufgrund der hohen morphologisch-hydraulischen Wirksamkeit eine Gefahr für Bauwerke an und im Gewässer sowie für angrenzende Nutzungen darstellen. Treibholz kann Brücken und andere Bauwerke beschädigen und größere Totholz-Elemente oder Akkumulationen können zu einer deutlichen Anhebung der Wasserspiegellagen oberstrom und damit zu einer erhöhten Überflutungswahrscheinlichkeit führen. Daher wird Totholz, welches im Rahmen von Renaturierungsprojekten in Gewässer eingebracht wird, i.d.R. durch Erdanker oder Wasserbausteine im Gewässer fixiert. Diese Verankerung ist häufig mit hohen Kosten verbunden und schränkt die ökologische Wirksamkeit der Renaturierung mit Totholz stark ein, da die Entstehung und der Erhalt einer natürlichen Strukturvielfalt an eine natürliche Dynamik, d.h. die Verlagerung des Totholzes gebunden ist. In der neueren Literatur wird daher die Einrichtung von Übergangsstrecken empfohlen. Hierbei schließt sich an einen totholzreichen Gewässerabschnitt, in dem eine natürliche Totholz-Dynamik zugelassen wird, eine Übergangsstrecke an, in der Totholz fixiert wird und an deren Ende gegebenenfalls ein Treibholzfänger installiert werden kann, um Bauwerke im Unterlauf zu schützen. Es stellt sich die Frage, ob diese Renaturierungsmethode des Belassens oder der Einbringung von Totholz ohne zusätzliche Verankerung in einer dicht besiedelten Region wie Mitteleuropa auf längeren Strecken angewandt werden kann.

Die Anwendbarkeit dieser Renaturierungsmethode wurde im Rahmen der Dissertation in einer Potenzialstudie überprüft. Als Datengrundlage dienten die Ergebnisse der Gewässerstrukturkartierung, welche für die drei Bundesländer Nordrhein-Westfalen, Hessen und Rheinland-Pfalz flächendeckend vorliegen und insgesamt ca. 44.880 Fließkilometer umfassen. Es wurde zwischen zwei Renaturierungsmethoden unterschieden, dem Belassen und der Einbringung von Totholz. Das Belassen ist im Gegensatz zu der aktiven Einbringung von Totholz eine passive Renaturierungsmethode. Bei dieser passiven Renaturierungsmethode wird der Prozess des Totholz-Eintrags aus standortgerechten Uferwäldern zugelassen. Voraussetzung für die Renaturierung eines Gewässers durch das Belassen von Totholz innerhalb eines realistischen Planungszeitraums ist daher das Vorhandensein eines solchen standortgerechten Uferwaldes. Es wurden für beide Renaturierungsmethoden jeweils drei Szenarien untersucht, die sich hinsichtlich der Nutzungen im Gewässerumfeld unterscheiden, welche durch die Initiierung einer eigendynamischen, lateralen Gewässerentwicklung eingeschränkt werden. In allen sechs Szenarien wurde vorausgesetzt, dass keine Bauwerke gefährdet werden und die Gewässerabschnitte Teil einer potenziell renaturierbaren Gewässerstrecke mit einer Mindestlänge von 300 m sind. Für die so identifizierten potenziell renaturierbaren Gewässerabschnitte wurde bestimmt, mit welcher strukturellen Verbesserung durch das Belassen oder die Einbringung von Totholz (zwei Sturzbäume pro 100 m Lauflänge) mittelfristig zu rechnen ist.

Die Methode der passiven Renaturierung ist aufgrund der geringen Ausdehnung standortgerechter Wälder und deren starker Fragmentierung nur in einem kleinen Teil der untersuchten Gewässerabschnitte anwendbar (~1%), deren absolute Länge mit ca. 500 km jedoch sicherlich weit über der Gesamtlänge der bisher renaturierten Gewässerstrecken im Untersuchungsraum liegt. Die aktive Renaturierung durch die Einbringung von Totholz ist hingegen in einem größeren Teil der untersuchten Gewässer potenziell möglich. Durch die sukzessive Berücksichtigung von Gewässerabschnitten mit angrenzenden forstwirtschaftlich genutzten Flächen, Grünlandbereichen und Ackerflächen steigt der Anteil der potenziell renaturierbaren Gewässerabschnitte von 6,5% auf 20,2% und 32%.

Es zeigen sich signifikante Unterschiede zwischen (a) dem Bereich der Mittelgebirge, in dem ein großer Teil der Gewässer potenziell mit Hilfe von Totholz renaturiert werden kann und eine strukturelle Verbesserung von einem mäßig-gutem zu einem guten bis sehr guten Zustand zu erwarten ist sowie (b) den Tieflandbereichen, in denen aufgrund der höheren Restriktionen nur ein geringerer Teil der Gewässer potenziell mit Hilfe von Totholz renaturiert werden kann und eine strukturelle Verbesserung von einem unbefriedigenden zu einem mäßigen Zustand zu erwarten ist. Diese Verbesserung des morphologischen Zustands im Tiefland führt sehr wahrscheinlich dazu, dass ein großer Teil dieser Gewässerabschnitte den „guten ökologischen Zustand“ erreicht und damit die Anforderungen der EU-Gewässerrahmenrichtlinie erfüllt.

Die Ergebnisse dieser Untersuchung zeigen, dass auch in einem dicht besiedelten Gebiet wie Mitteleuropa die Renaturierung von Fließgewässern durch das Belassen oder die Einbringung von Totholz ohne Verankerung auf längeren Gewässerstrecken möglich ist.

Auswertung von Renaturierungsprojekten mit Totholz

Obwohl Totholz in naturnahen Gewässern in großen Mengen vorkommt, bereits einzelne Sturzbäume eine hohe morphologische Wirksamkeit besitzen und die Renaturierung mit Totholz potenziell auf längeren Gewässerstrecken möglich ist, wurde Totholz bisher nur in wenigen Renaturierungsprojekten eingesetzt. Nur in einzelnen Fällen erfolgte dabei ein umfangreiches Monitoring, dessen Ergebnisse veröffentlicht wurden und zur Ableitung von Empfehlungen zur Renaturierung von Fließgewässern mit Totholz herangezogen werden können. Um die gesammelten Erfahrungen auszuwerten und daraus Empfehlungen für zukünftige Projekte abzuleiten, wurde eine Befragung von Projektträgern durchgeführt, die bereits Totholz bei der Renaturierung von Gewässern eingesetzt haben.

Durch Anfragen bei Behörden, Naturschutzverbände, Universitäten und anderen Forschungseinrichtungen in Mitteleuropa (n = 112) konnten 53 Renaturierungsprojekte ausfindig gemacht werden, in denen Totholz eingesetzt wurde. Achtundzwanzig Projektträger, die 41 der 53 Renaturierungsprojekte durchgeführt hatten, erklärten sich bereit an der Untersuchung teilzunehmen. Von diesen haben sich letztendlich 22 Projektträger an der Befragung beteiligt. Aufgrund des großen Aufwands zur Beantwortung des umfangreichen Fragebogens war es den meisten Projektträger nur möglich Daten zu einem ihrer Projekte zur Verfügung zu stellen, sodass insgesamt 23 Datensätze ausgewertet werden konnten. Die Ergebnisse der Befragung lässt folgende Schlussfolgerungen zu:

Vorrangiges Ziel der Projektträger ist die allgemeine Verbesserung der Gewässerstruktur durch die Initiierung einer eigendynamischen Entwicklung mit Hilfe von verankerten Totholz-Einbauten, d.h. es werden aktive Renaturierungsmethoden angewandt, die dem klassischen ingenieurbiologischen Wasserbau zuzurechnen sind. In einigen Projekten wurden Totholz-Elemente in die Gewässer eingebracht, ohne diese zu verankern. Hierbei handelt es sich um aktive Renaturierungsmethoden, die als naturnaher Wasserbau im engeren Sinne bezeichnet werden können. Nur ein geringer Teil der Totholz-Einbauten (8%) wurde seit dem Einbau verdriftet, obwohl in den untersuchten Gewässern bereits Hochwasserereignisse mit einer Jährlichkeit von durchschnittlich 5 Jahren aufgetreten sind. Die Verdriftungsgefahr ist in solchen Fällen signifikant erhöht, in denen besonders kleine Totholz-Elemente eingebaut wurden, der Einbau bereits längere Zeit zurückliegt oder bei besonders hoher spezifischer Flussleistung. Sie korreliert jedoch nicht mit der Art oder dem Umfang der Fixierung der Totholz-Einbauten. Da die Ergebnisse zeigen, dass die Einbringung von nicht fixierten Totholz-Elementen möglich ist, ohne dabei die Gefahr der Verdriftung zu erhöhen, sollte diese Renaturierungsmethode in Zukunft vermehrt Berücksichtigung finden. Zudem sind die Kosten für die Einbringung von nicht fixierten Totholz-Elementen im Vergleich zu fixierten Totholz-Einbauten signifikant niedriger.

Die Monitoring-Ergebnisse der Projekte zeigen, dass die Einbringung der Totholz-Elemente bereits in den ersten Jahren zu einer deutlichen strukturellen Verbesserungen führen. Aus ökologischer Sicht ließe sich der Einsatz von Totholz bei der Renaturierung jedoch in vielen Fällen noch optimieren. So ist die Menge des eingebrachten Totholzes (Median 27,9 $m^3\ ha^{-1}$) gering im Vergleich zum Totholz-Vorkommen in naturnahen Gewässern vergleichbarer Ökoregionen Mitteleuropas (Median 41,4 $m^3\ ha^{-1}$) und anderen bewaldeten Regionen der gemäßigten Breiten (Median 126 $m^3\ ha^{-1}$). Sie liegt damit weit unterhalb der Totholzmenge, die im potenziell natürlichen Gewässerzustand zu erwarten wäre. In einigen Fällen ist die Größe der Totholz-Einbauten und damit ihre hydraulisch-morphologische Wirksamkeit gering, obwohl keine offensichtlichen Restriktionen vorhanden sind. Darüber hinaus könnten in vielen Fällen anstelle der zylindrischen Totholz-Einbauten strukturreichere Totholz-Elemente verwendet werden, wie ganze Sturzbäume mit Wurzelballen und Krone. Diese würden aufgrund ihrer komplexeren Form ein größere Habitatdiversität schaffen und somit positive Nebeneffekte erzielen.

Die Auswertung der Renaturierungsprojekte zeigt weiter, dass die morphologische Wirkung der Totholz-Einbauten stark von den lokalen naturräumlichen Gegebenheiten abhängt und bei der Umsetzung der Maßnahmen sehr spezifische Problem auftreten. Daher sollten allgemeine Renaturierungskonzepte eingehend auf ihre Anwendbarkeit geprüft und gegebenenfalls modifiziert werden. Ferner müssen die Auswirkungen der Einbringung von Totholz auf den Gewässerabschnitt und das gesamte Einzugsgebiet berücksichtigt werden, da die lokal durchgeführten Renaturierungsmaßnahmen unerwünschte Nebeneffekte auf höheren räumlichen Ebenen besitzen können. Darüber hinaus zeigt die Umfrage, dass ein Wissensdefizit bezüglich der konkreten Umsetzung der Maßnahmen besteht und es dringend erforderlich ist in zukünftigen Projekten ein geeignetes Monitoring durchzuführen und die Ergebnisse einem breiten Fachpublikum zugänglich zu machen.

Aus den Ergebnissen der vier, im Rahmen der Dissertation durchgeführten Untersuchungen lässt sich zum einen ein allgemeines Konzept zur Klassifikation von Renaturierungsmaßnahmen und der Betrachtung der Kosteneffizienz ableiten. Zum anderen können die Ergebnisse einen Beitrag zu der Diskussion über die morphologische Konfiguration und ihrer Bedeutung für allgemeine fluvialmorphologische Konzepte leisten.

Konzept der Substitution von Maßnahmen durch Zeit

Die Potenzialstudie zu den Einsatzmöglichkeiten der aktiven und passiven Renaturierung mit Totholz und die Auswertung der bisher durchgeführten Renaturierungsprojekte zeigt, dass es eine Vielzahl unterschiedlicher Renaturierungsmaßnahmen gibt, die sich vor allem hinsichtlich ihrer potenziellen Anwendbarkeit, Kosten und Einsatzmöglichkeiten unterscheiden. Um einen besseren Überblick über die möglichen Renaturierungsmaßnahmen geben zu können und um die Auswahl von Maßnahmen für konkrete Renaturierungsprojekte zu erleichtern, wurde ein konzeptioneller Rahmen zur Klassifikation von Renaturierungsmaßnahmen entwickelt, das sogenannte „Konzept der Substitution von Maßnahmen durch Zeit“.

Hierbei werden die rein aktive Renaturierung (rein bauliche Maßnahmen) und die rein passive Renaturierung (reiner Prozessschutz) als Extreme aufgefasst, zwischen denen sich die verschiedenen Renaturierungsmaßnahmen einordnen lassen. So gibt es Totholz-Einbauten, die keine weitere Funktion als Strömungslenker zur Initiierung einer eigendynamischen morphologischen Entwicklung besitzen und nur das Totholz selbst als Habitat dient. Beispiel hierfür sind Fischunterstände aus Rundhölzern, die auf Holzpflöcken über der Sohle eingebaut werden. Dies kann als rein aktive Renaturierungsmethode klassifiziert werden, da die erwünschten Habitate allein durch die bauliche Maßnahme des Einbaus der Fischunterstände geschaffen werden. Der Einbau von verankerten Strömungslenkern, die eine eigendynamische morphologische Entwicklung initiieren sollen, kann als weniger aktive Renaturierungsmethode bezeichnet werden. Die Einbringung von nicht verankerten Strömungslenkern kann als eine Übergangsform zur passiven Renaturierung aufgefasst werden und die Förderung des Totholz-Eintrags durch die Renaturierung naturnaher Uferwälder ist als Prozessschutz und damit als passive Renaturierungsmethode zu klassifizieren.

Bei der rein aktiven Renaturierung wird der Zielzustand i.d.R. kurz nach der Durchführung der baulichen Maßnahme erreicht, es entstehen jedoch vergleichsweise hohe Kosten. Werden die baulichen Maßnahmen in zunehmendem Maße durch eine eigendynamische morphologische Entwicklung, d.h. durch eher passive Renaturierungsmethoden ersetzt, verringern sich die Kosten. Jedoch wird auch ein längerer Entwicklungszeitraum bis zum Erreichen des Zielzustandes benötigt, dessen genaue Ausprägung sich nur eingeschränkt prognostizieren lässt. Daher kann von einer Substitution von Maßnahmen bzw. Kosten durch Zeit gesprochen werden. Aufgrund der gut planbaren Wirkungen und der hohen Kosten eignet sich der Einsatz aktiver Renaturierungsmethoden vor allem bei hohen Restriktionen im bebauten Bereich und auf kurzen Gewässerabschnitten. Demgegenüber erscheint der Einsatz von passiven Renaturierungsmethoden vor allem bei geringen Restriktionen in der freien Landschaft und auf langen Gewässerabschnitten sinnvoll.

Einbindung von Totholz in allgemeine fluvialmorphologische Konzepte

Die Ergebnisse der Untersuchung zur Totholzmenge in naturnahen Gewässern und der morphologischen Wirkung von Totholz legt die Schlussfolgerung nahe, dass Totholz neben anderen Steuergrößen, wie dem Abfluss, Geschiebetrieb oder Gefälle, die Ausprägung mitteleuropäischer Fließgewässer im potenziell natürlichen Gewässerzustand maßgeblich bestimmt. Da dies auch bereits für andere bewaldete Regionen der gemäßigten Breiten nachgewiesen wurde, erscheint es dringend erforderlich, die Steuergröße Totholz in allgemeine fluvialmorphologische Konzepte zu integrieren, worauf in der neueren Literatur auch verstärkt hingewiesen wird.

Bei der Erstellung eines solchen Konzepts muss berücksichtigt werden, dass zwar die durchschnittliche Totholzmenge über längere Zeiträume und größere räumliche Skalen konstant bleibt, die lokale Variabilität jedoch aufgrund periodischer Veränderungen (z.B. Waldzyklen) und stochastischer Katastrophenereignisse (z.B. Waldbrände, Stürme, Hochwässer, Insekten-Kalamitäten) sehr hoch ist. Daher hängt der Zustand eines bestimmten Gewässerabschnitts und dessen weitere morphologische Entwicklung im potenziell natürlichen Zustand wesentlich von solchen periodischen und stochastischen Ereignissen, d.h. der „Entwicklungsgeschichte“ des Gewässers ab.

Diese Überlegungen stützen ein Konzept, welches seit einigen Jahren diskutiert wird und in Anlehnung an neuere Arbeiten als „Konzept der morphologischen Konfiguration“ bezeichnet werden könnte. Danach bestimmt die Entwicklungsgeschichte des Gewässers wesentlich den rezenten Zustand des Systems. Die weitere Entwicklung ist abhängig von diesem rezenten Ausgangszustand, sodass die morphologische Konfiguration die zukünftige Reaktion des Systems auf Steuergrößen, wie z.B. den Abfluss, determiniert. Im Gegensatz dazu geht man bei den in der Fließgewässermorphologie und –ökologie noch weit verbreiteten Gleichgewichtskonzepten davon aus, dass das System langfristig einen Gleichgewichtszustand erreicht, der von den naturräumlichen Gegebenheiten abhängt (z.B. Klima, Geologie, Topographie, Vegetation).

Die Anwendung dieses Konzepts der morphologischen Konfiguration hat Auswirkungen auf die Definition des potenziell natürlichen Gewässerzustandes und die Renaturierung von Gewässern. Geht man davon aus, dass das Gewässer langfristig einen Gleichgewichtszustand erreicht, kann dieser als potenziell natürlicher Zustand dienen und aktive

Renaturierungsmaßnahmen zum Erreichen dieses Ziels durchgeführt werden. Im Gegensatz dazu ist gemäß des Konzepts der morphologischen Konfiguration der zukünftige Zustand eines Gewässers wesentlich von dem Ausgangszustand und damit von zurückliegenden, prägenden Ereignissen abhängig. Da viele dieser prägenden Ereignisse, wie z.B. der Eintrag von Totholz, stochastischer Natur sind, erscheint es nicht möglich einen einzelnen potenziell natürlichen Zustand zu definieren, selbst wenn der Ausgangszustand des Systems bekannt ist. Vielmehr ist eine Vielzahl unterschiedlicher potenziell natürlicher Zustände denkbar, wobei die zukünftige Entwicklungsgeschichte eines Gewässerabschnitts bestimmt, welcher dieser Zustände eintritt. Daher können aktive Renaturierungsmethoden nur dann eingesetzt werden, wenn das Gewässer noch weit von diesen potenziell natürlichen Zuständen entfernt ist. Nur durch die passive Renaturierung, d.h. den Prozessschutz auf längeren Gewässerstrecken kann sichergestellt werden, dass die Vielzahl möglicher potenziell natürlicher Zustände in dem Gewässer vorkommen werden.

Die in der vorliegenden Dissertation zusammengestellten Untersuchungen zeigen, dass Totholz auch in mitteleuropäischen Fließgewässern eine wichtige Steuergröße darstellt, welche die Gewässermorphologie im natürlichen Zustand wahrscheinlich maßgeblich bestimmt und ein großes Potenzial für die kosteneffiziente Renaturierung von Gewässern besitzt. Es erscheint dringend erforderlich, diese Größe in der zukünftigen gewässermorphologischen Forschung verstärkt zu berücksichtigen. Dies trifft nicht nur auf die Fluvialmorphologie zu, sondern auch auf andere Disziplinen, die sich mit Fließgewässerökosystemen und deren Renaturierung beschäftigen wie etwa die Biologie, Ökologie, den Wasserbau und die Sozialwissenschaften. In diesem Sinne ist die vorliegende Arbeit als einer der ersten Schritte zu einem besseren Verständnis über die Steuergröße Totholz zu verstehen, die notwendig sind um Fließgewässer erfolgreich zu renaturieren.

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