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The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria

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Summary

1. Wood is increasingly used in restoration projects to improve the hydromorphological and ecological status of streams and rivers. However, despite their growing importance, only a few of these projects are described in the open literature. To aid practitioners, we conducted a postal mail survey to summarize the experiences gained in central Europe and compile data on 50 projects.

2. Our results indicated the potential for improvement from an ecological point of view, as the number and total wood volume, and the median volume of single wood structures placed in the streams per project, were low compared with the potential natural state. Moreover, many wood structures were placed nearly parallel to the water flow, reducing their beneficial effect on stream hydraulics and morphology.

3. Restoration success has been monitored in only 58% of the projects. General conclusions drawn include the following. (i) The potential effects of wood placement must be evaluated within a watershed and reach-scale context. (ii) Wood measures are most successful if they mimic natural wood. (iii) Effects of wood structures on stream morphology are strongly dependent on conditions such as stream size and hydrology. (iv) Wood placement has positive effects on several fish species. (v) Most projects revealed a rapid improvement of the hydromorphological status.

4. Most of the wood structures have been fixed, called 'hard engineering'. However, soft engineering methods (use of non-fixed wood structures) are known to result in more natural channel features for individual stream types, sizes and sites, and are significantly more cost-effective.

5. *Synthesis and applications.* Large wood has been used successfully in several projects in central Europe, predominantly to increase the general structural complexity using fixed wood structures. Our results recommend the use of less costly soft engineering techniques (non-fixed wood structures), higher amounts of wood, larger wood structures and improved monitoring programmes for future restoration projects comparable with those in this study. We recommend the use of 'passive restoration' methods (restoring the process of wood recruitment on large scales) rather than 'active restoration' (placement of wood structures on a reach scale), as passive restoration avoids the risk of non-natural amounts or diversity of wood loading developing within streams. Local, active placement of wood structures must be considered as an interim measure until passive restoration methods have increased recruitment sufficiently.

Key-words: alpine streams, lowland streams, monitoring, mountain streams, passive restoration, restoration success, soft-engineering, woody debris

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Introduction

Over the last two decades, restoration of hydromorphologically degraded rivers has become a widely accepted social objective in developed nations with an associated increase in scientific interest in stream restoration (Shields *et al.* 2003; Bernhardt *et al.* 2005). In densely populated areas such as central Europe, a large proportion of rivers is heavily degraded, leading to a strong demand for simple and cost-effective restoration measures. Large wood (defined as logs with a diameter > 0·1 m and a length > 1 m, according to Gregory, Boyer & Gurnell 2003) is an important component 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 (Harmon *et al.* 1986; Gurnell, Gregory & Petts 1995; Gregory, Boyer & Gurnell 2003). Considering these beneficial effects, the addition of large wood can be used not only for initiating natural channel dynamics but also for local bank protection (Shields, Morin & Cooper 2004), to enhance spawning and rearing habitat for fish (Cederholm *et al.* 1997; De Jong, Cowx & Scruton 1997), to create cover for fish (De Jong, Cowx & Scruton 1997; Lehane *et al.* 2002) and to enhance habitat for benthic macroinvertebrates (Hilderbrand *et al.* 1997). Even in a densely populated region like central Europe, up to one-third of the streams could potentially be improved by restoration with wood (Kail & Hering 2005).

Despite the beneficial effects of large wood and its potential application in many stream reaches, it has rarely been utilized in European stream restoration projects, in contrast with North America, where wood placement is a common restoration method (Roper *et al.* 1998; Roni *et al.* 2002). Only a few of the projects in central Europe have been described in more detail within the literature: Gerhard & Reich (2000), Zika & Peter (2002), Becker, Rey & Willi (2003), Semrau, Sommerhäuser & Hurck (2003) and Siemens (2005) describe single projects; Reich, Kershner & Wildman (2003) and Kail (2005) describe 11 and 23 projects, respectively. Transferability of North American studies is limited, as land-use pressure is particularly high in central Europe, potentially constraining the use of restoration methods developed in less densely populated regions. Discharge, geology, vegetation and restoration objectives in central Europe also differ from those in the north-western USA, where many of the published restoration projects were implemented. Discharge in the Pacific North-West is more flashy and slope generally higher, resulting in increased stream power at high flows, with an associated increase in the risk of wood being transported downstream. Moreover, tree species have lower decay rates and are greater in size, resulting in larger natural wood loadings. Many projects in the Pacific North-West aim to enhance fish habitat, whereas the overall objective of most projects in central Europe is to enhance the structural complexity of the streams.

Based on a comprehensive overview of central European stream restoration projects in which large wood had been used, we aimed to provide guidance for future projects by evaluating the experiences gained in the restoration projects. We detail problems that have occurred during planning and implementation, the wood structures and wood volume used, and the costs, monitoring techniques and risks.

Materials and methods

TERMS AND DEFINITIONS

The term ‘stream restoration’ is used for a wide variety of project objectives, ranging from conventional bio-engineering to the restoration of natural processes (Kondolf 1996). In the USA, stream restoration is defined as ‘the return of an ecosystem to a close approximation of its condition prior to disturbance’ (National Research Council USA 1992) or as ‘the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed’ (http://www.ser.org/content/ecological_restoration_primer.asp, accessed August 2007). In densely populated areas such as central Europe, river and floodplain morphology and hydrology have been significantly altered by humans. Some of these alterations can be reversed by natural channel dynamics (e.g. channel straightening) while others are irreversible (e.g. changes of valley slope caused by mining). Where irreversible change has occurred, the recovery to a previous pre-historical natural state is impossible (Kauffman *et al.* 1997; Brown 2002). To overcome this problem, the objective of stream restoration projects in central Europe is to allow the stream to develop towards a potential natural state, defined as the equilibrium state that would emerge under the present hydrological and morphological conditions, including the irreversible changes, without any further human intrusion (Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK) 1996). This ‘guiding image’ (Palmer *et al.* 2005) is comparable to the concept of the potential natural vegetation of Tüxen (1956). Within the scope of this study ‘restoration’ is defined as any approach to develop a degraded ecosystem towards its potential natural state.

QUESTIONNAIRE AND DATA COLLECTION

We consulted 165 local and regional authorities, stream managers and stream ecologists in central Europe to identify restoration projects in which wood had been used. Seventy-two project managers, who planned and implemented a total of 83 restoration projects, agreed to participate in the survey and provided data on 50 restoration projects.

A postal mail survey containing 33 questions (Table 1) was developed and pre-tested according to standard survey techniques (Noelle-Neumann & Petersen 2000). Almost all restoration projects were located in Germany

Table 1. Structure and content of the questionnaire

- General description of restoration project
  - State of knowledge about the stream (judgement of project manager)
  - General project objectives
  - Restrictions/planning conditions
  - Extent of project (lateral extent and length of restored reach)
  - Physical measures other than wood placement
  - Total cost of planning and implementation
  - Description of monitoring (type and interval of monitoring)
- General description of wood measures
  - Length of restored reach
  - Date of restoration
  - Cost of planning 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 (judgement of project manager)
  - Modification of future project designs as a result of 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 wood structures (given for different sets of wood structures if they markedly differ)
  - Objectives of wood placement
  - Type and number of wood structures
  - Average size of wood structures (diameter and length or length, width, and depth)
  - Orientation to flow
  - Fixation of wood structures
  - Blockage ratio according to Gippel *et al.* (1996)
  - Failure of wood structures (damage, rotation, downstream transport)
- Description of stream reach after stream restoration (at the time of the survey)
  - Discharge since wood placement
  - (Preliminary) Results of monitoring
- General description of stream reach
  - Location
  - Channel pattern (present and natural state)
  - Channel planform/sinuosity (present and natural state)
  - Channel slope
  - Channel width (bankfull width and wetted width at mean flow)
  - Width/depth ratio
  - Discharge (long time mean)
  - Water quality
  - Stream bed and bank material
  - Adjacent land uses

and Austria, with the exception of one project implemented in Liechtenstein (Fig. 1). The main characteristics of the restored streams are described in Appendix S1 in the supplementary material.

Closed questions (single or multiple choice) were used in most cases. Open questions were used in two key areas, where we expected a wide range of responses at different levels of detail: (i) questions on monitoring results and (ii) problems that occurred during planning, approval and implementation of the projects.

Each respondent rated the general project objectives and the objectives of wood placement on a Likert scale ranging from 1 (unimportant) to 5 (very important). A mean score was calculated for each Likert-scaled project objective using the ratings given for the 50 projects. Restoration projects were classified as having an 'ecological', 'dual' or a 'non-ecological focus' based on the Likert scores for the general project objectives. Projects were classified as having an ecological, dual or non-ecological focus if the respective objectives were rated high (Likert score 4–5) (Fig. 1).

For each restoration project, land-use intensity was assessed by calculating a score based on the percentage of floodplain area covered by different land uses as detailed by the respondents. Land uses were roughly grouped as follows: (i) forest and natural non-woody vegetation; (ii) grassland, pasture and fallow land; (iii) cropland and (iv) urban areas. The percentage of floodplain area covered by these four categories was multiplied by four different factors (0, 0·3, 0·6 and 1, respectively). The score was calculated by summing these four values and generating ranges from 0 (low land-use pressure, 100% of floodplain covered by natural vegetation) to 100 (high land-use pressure, 100% of floodplain covered by urban areas).

The volume of single logs and single trees was calculated using the diameter and length given by the respondents assuming a cylindrical shape; the volume of wood accumulations was calculated using the length, width

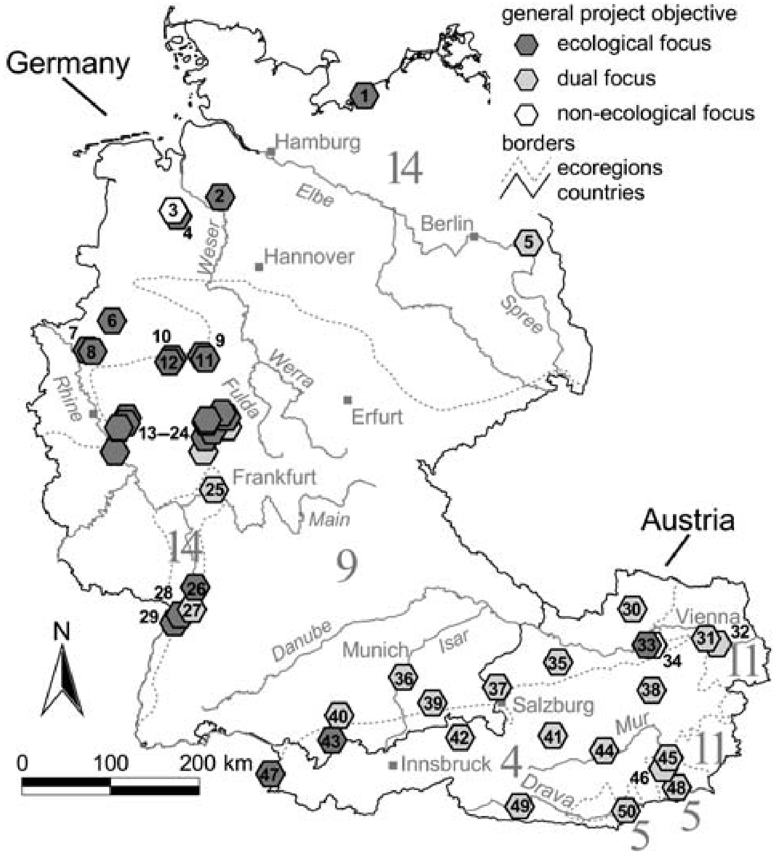

Fig. 1. Location of restoration projects in Germany, Austria and, Liechtenstein. Projects are classified as having an ecological, a dual or a non-ecological focus based on the Likert scores for the projects' objectives given by the respondents. Borders of ecoregions are outlined schematically by dotted lines [according to Illies (1978), modified according to Briem (2003) in Germany and Moog *et al.* (2001) in Austria]: 4, Alps; 5, Dinaric western Balkan; 9, central highlands; 11, Hungarian lowlands; 14, central plains.

and depth given. To assess the wood volume of the accumulations without hollow spaces, a wood/air ratio of 0·5 was used for accumulations of fine wood (following Eckert *et al.* 1996), a ratio of 0·7 for accumulations of logs and trees (wood/air ratio for 'trunks' given in Thévenet, Citterio & Piégay 1998) and an intermediate ratio of 0·6 for accumulations of large wood.

DATA ANALYSIS

Principle component analysis (PCA) was used to investigate differences in restoration projects and to delineate 'types' of restoration projects. Only variables that were provided by most of the respondents were considered; the analysis was limited to 37 projects for which sufficient data were available. Data on continuous variables were log-transformed, centred to mean zero and standardized to variance 1. Binary dummy variables were used for the categorical parameters. To characterize the location of the restoration projects, the variable 'located in lowland/lower mountain region' (project numbers 1–29 compared with project numbers 30–50 in alpine regions) was used (Fig. 1).

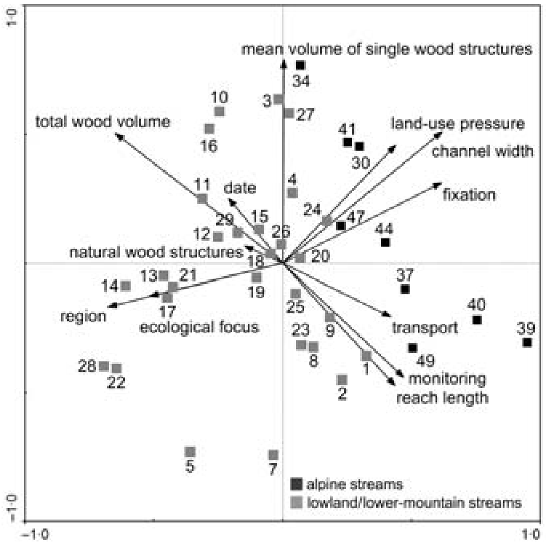

Fig. 2. PCA on 37 restoration projects. Numbering corresponds to numbers in Fig. 1.

Results

DIFFERENCES BETWEEN RESTORATION PROJECTS

The 37 restoration projects considered in the PCA biplot were characterized by a distinct gradient (Fig. 2). Restoration projects in the lowland/lower mountain region differed markedly from projects in the alpine region. In the latter, mainly fixed wood structures had been placed in larger streams where land-use pressure was particularly high. Most of these projects did not have a pure ecological focus and large wood was also used, for example for bank protection. Bivariate statistics revealed that channel width and land-use pressure were higher (Mann–Whitney *U*-test, $P < 0{\cdot}001$, $n = 48$, and $P < 0{\cdot}01$, $n = 46$, respectively) and number of projects with an ecological focus was lower (chi-squared cross-tabulation, $P < 0{\cdot}001$, $n = 50$) in the alpine region.

PROJECT OBJECTIVES

The overall objective of the stream restoration projects was to enhance the general hydromorphological status of a site and was typically less focused on single species or channel features (Fig. 3). All non-ecological objectives were rated low, particularly the objective 'conventional engineering' (mean score 1·7). The general ecological objectives 'initiate lateral channel migration' (re-meandering) and 'increase general structural complexity' were rated high (mean scores of 3·4 and 3·9, respectively). The selective ecological objectives had medium and low mean scores, respectively ('creation of specific channel features' mean score 2·4, 'protect specific species' mean score 1·8). However, the most important objective for the specific use of wood was 'creation of fish habitat' (mean score 3·5).

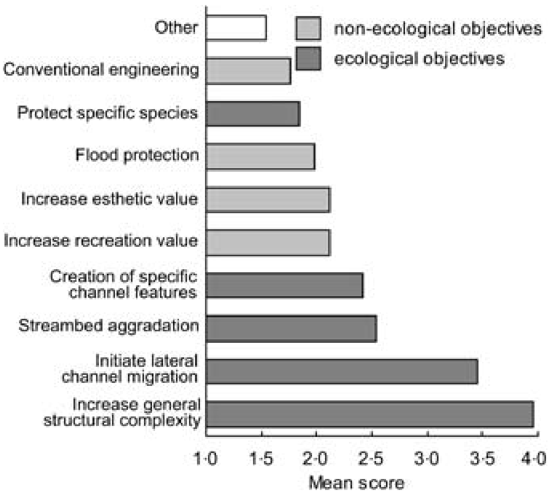

Fig. 3. Mean scores for the general projects' objectives, calculated from the scores given by the respondents for each of the objectives on a five-point Likert scale.

NATURE AND EXTENT OF WOOD MEASURES

Length of the restored reaches and amount of wood placed in the streams were low and differed markedly between projects (Fig. 4). Most reaches were short (median length 0·3 km, 36 times bankfull channel width) and both the number and size of the wood structures in the single projects were small compared with North American projects (median number of wood structures $n = 10$, median total volume 7·6 m^3). Related to stream bottom area, the median number of wood structures was 25 ha^{-1} and the median total volume was 34·0 m^3 ha^{-1}.

The majority of the wood structures were natural-shaped (e.g. root-wads and trees with branches) when related to both the number (61%) and volume (72%) of wood structures (Fig. 5). The percentage of single trees was 37% by number and 29% by volume, respectively. However, mean diameter and length of the single trees were small (0·38 m and 7·3 m, respectively), leading to a low blockage ratio (≤ 0·3 for 75% of the trees). For the majority of trees it was unlikely that other wood pieces could be trapped and wood accumulations form. Moreover, tree length was less than bankfull channel width for 55% of the trees, which markedly increased the risk of downstream transport (Bryant 1983; Nakamura & Swanson 1994).

Mean diameter, length and volume of single wood structures were 0·37 m, 3·7 m and 0·79 m^3, respectively ($n = 73$ groups of wood structures, for which diameter and length were given separately by the respondents, representing a total of 1351 wood structures). To assess the potential impact of wood structures on stream hydraulics and morphology, the size of the structures must be related to stream size, based on the proportion of the cross-section area blocked by the wood structures (blockage ratio B according to Gippel *et al.* 1996). The blockage ratio was ≤ 0·3 for 82% of the structures (Fig. 6), although mainly small streams had been restored (73% of the structures were placed in streams with a bankfull width less than 10 m).

In general terms, blockage ratios ≤ 0·1 are too low to affect stream hydraulics significantly or to cause a detectable upstream afflux (Gippel 1995; Gippel *et al.* 1996), and the drag coefficient of cylindrical logs, which also determines the hydraulic effect, sharply decreases for angles < 60° and is low for angles < 30° (Gippel *et al.* 1996). About one-third of the wood structures (34%) had blockage ratios ≤ 0·1 and a significant proportion of the wood structures, for which the orientation to flow was given ($n = 503$), were placed nearly parallel to the flow (0°–< 30°; 33%) or had an angle to flow from 30° to < 60° (16%). However, more than half of the wood structures (64%) with $B \leq 0·1$ and about half of the wood structures (54%) with angles < 60° were used

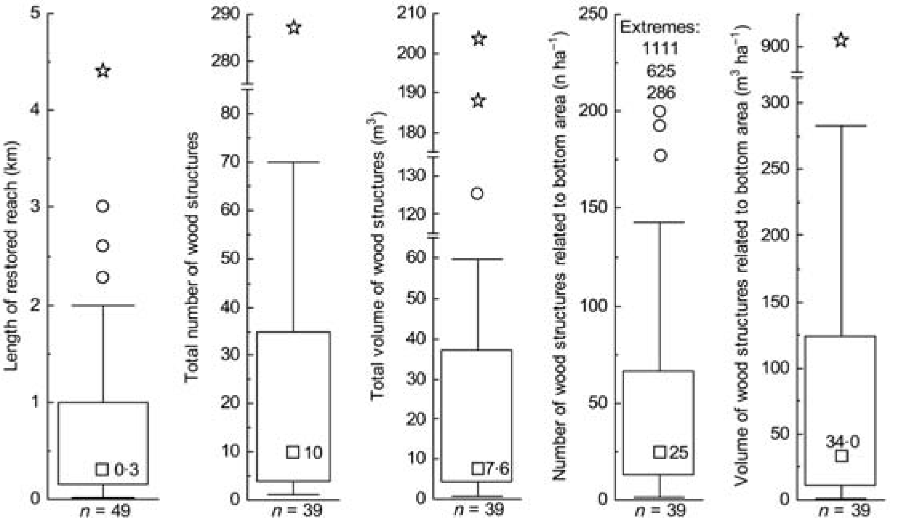

Fig. 4. Box-whisker plots of restoration projects and wood characteristics. Non-outlier maximum and minimum, 25–75%, median, outliers (outlier coefficient = 1·5), and extremes (extreme coefficient = 3) are given.

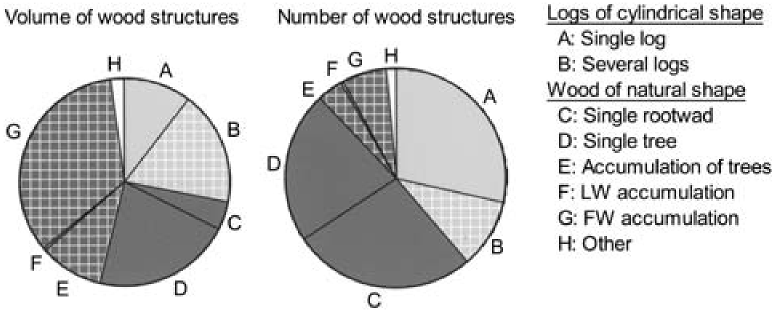

Fig. 5. Types of wood structures used in the restoration projects related to number and wood volume. FW, fine wood (diameter approximately < 0·1 m); LW, large wood (diameter approximately > 0·1 m). The same pattern is used for wood structures consisting of a single piece and several pieces, respectively, to give a visual impression of the share of these two gross categories (single pieces and accumulations).

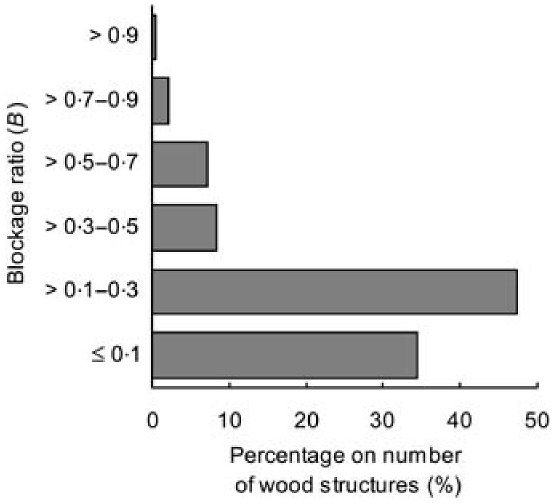

Fig. 6. Blockage ratio (*B*) of the wood structures, according to Gippel *et al.* (1996) ($n = 516$ wood structures for which a blockage ratio was given, representing 32 restoration projects).

in restoration projects, which are under no restrictions (rise in water level was not named as a restriction for stream restoration).

The vast majority of the wood structures (72%) were fixed using methods described by Gerhard & Reich (2001) or on the web sites http://wdfw.wa.gov/hab/ahg/shrg/ and http://Totholz.de (both accessed in August 2007). Most of the structures were either fixed with boulders (15%) or in the stream bed with wooden piles (22%). Some structures were buried in the bank (9%) or cabled to bank anchors (5%) (e.g. trees on banks). Few of the structures mimicked natural stable wood (5%) (e.g. wood structures partially placed on a stream bank or wedged between trees on the banks) or were not fixed at all and potentially moving freely at high flows (29%). Sand/loamy and gravel/cobble bed streams differed in the methods used for wood fixation; the most common fixation method in sand bed and loamy streams was wooden piles (41%) whereas boulders were most commonly used in gravel or cobble bed streams (29%) (Fig. 7).

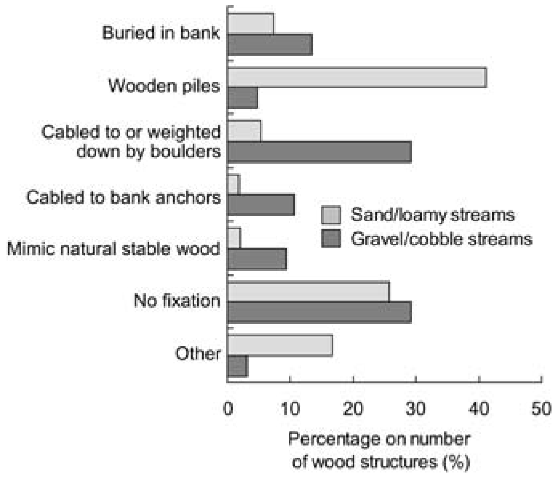

Fig. 7. Methods used for the fixation of the wood structures in gravel/cobble bed and sand bed/loamy streams.

COSTS OF STREAM RESTORATION WITH WOOD

Costs for wood placement were related to wood volume, as they are considered to be dependent on the amount of wood placed in the stream. Costs for implementation (placement and fixation of 1 m^3 of wood volume) differed between projects ($n = 28$), with an interquartile range of about 993 euros m^{-3} and median costs of 396 euros m^{-3}. Costs for implementation were significantly lower in projects where wood structures were 'not heavily fixed' (median = 93 euros m^{-3}) and about seven times lower compared with 'heavily fixed' wood structures, for which median costs were 664 euros m^{-3} (Mann–Whitney *U*-test, $P < 0{\cdot}01$, $n = 28$). However, these costs excluded maintenance that may, for example, occur after the decaying of wood that has not been kept continuously wet.

MONITORING EFFORT AND RESULTS

Monitoring was carried out in 58% of the projects, although methods and intensity differed. Excluding photographs and visual inspection, the proportion of projects monitored dropped to 44%. Cross-profiles or a detailed hydromorphological survey were used to monitor changes in channel morphology, and macroinvertebrates or fish as biological quality measures were used in 36% and 34% of the projects, respectively. However, in only 26% of the projects were both monitored. A discrepancy existed between the frequently stated objective of the 'creation of fish habitat' and the monitoring measures. Thirty-eight per cent of the monitored projects rated high for the objective 'creation of fish habitat' did not monitor the fish fauna or morphological changes to an extent that allowed the generation of fish habitat (e.g. cover, pools or spawning gravel) to be detected.

Downstream transport of wood structures was observed in 20% of the projects but the number of wood structures that moved was low (3% of total). In those projects characterized by downstream transport of wood, a median share of 25% of the wood structures moved. The return interval of the high flows since wood placement was known for 38% of the restoration projects, and ranged from 1 to 125 years, with a median return interval of 7·5 years. Projects where wood movement was observed did not differ significantly from projects with stable wood structures in terms of bankfull width, slope, mean annual discharge, mean high flow since wood placement, specific stream power at mean high flow, return interval of high flows since wood placement, bed material, fixation/volume/blockage ratio of wood structures and time since wood placement (Mann–Whitney *U*-test used for continuous variables, chi-squared cross-tabulation used for binary variables). Thus the risk of downstream transport was not significantly increased in projects where wood structures were not heavily fixed (chi-squared cross-tabulation, $P = 0{\cdot}84$, $n = 40$). However, this could be partly because non-fixed wood structures were predominantly used in small streams, where the length of the wood structures often exceeded bankfull channel width, which is known potentially to increase wood stability (channel width significantly lower, Mann–Whitney *U*-test, $P < 0{\cdot}05$, $n = 40$; share of wood structures for which length > bankfull channel width significantly higher, chi-squared cross-tabulation, $P < 0{\cdot}05$, $n = 40$).

As most projects had been implemented recently, only preliminary monitoring results were reported (lower and upper quartile of time since wood placement 10 and 50 months, respectively). Monitoring results differed in the level of detail and were predominantly qualitative in nature, preventing statistical analysis of the data. However, the following general conclusions could be drawn from the monitoring results and the experiences gained during planning, approval and implementation of the projects.

Local morphological changes (e.g. sorting of bed material, creation of pools, bars and cut-banks) generally started with the first high flows after wood placement. Twenty-four out of 30 respondents observed major morphological changes.

Monitoring results for fish fauna were available for five projects in lower mountain and alpine regions. Three of the respondents reported an increase in the number and biomass of brown trout *Salmo trutta fario* near the wood structures. Data from one respondent showed a significant increase in the number of brown trout in restored reaches compared with control reaches 2 years after wood placement (chi-squared cross-tabulation, $P < 0{\cdot}05$, $n = 28$) (Becker, Rey & Willi 2003). Another respondent reported a 15-fold increase in the number of brown trout 3·5 years after the addition of wood; however, data on control reaches were not available (Siemens 2005. Moreover, respondents reported positive effects on minnow *Phoxinus phoxinus*, bullhead *Cottus gobio*, chub *Leuciscus cephalus* and barbel *Barbus borbus* populations. Effect of wood on grayling *Thymallus thymallus* differed between projects.

The effect of wood structures on stream morphology was strongly dependent on river and floodplain morphology and hydrology. Problems occurring during the implementation of the projects were generally unique to the site, therefore the characteristics of each stream must be considered and schematic project designs, named 'cookbook approaches' by Kondolf (1998), are not generally applicable. For example, only minor changes in channel morphology had occurred in a sand-bed stream section more than 2 years after wood placement (bankfull width 5–10 m, slope 0·01–0·1%) related to dense riparian reed vegetation, which reinforces the stream banks, confines lateral channel migration and lowers flow velocity.

One respondent reported that some large cylindrical logs placed perpendicular to flow as grade controls were undermined (three out of 14), although sandbags were placed upstream of the logs to prevent scour beneath them ('underflow jam' according to Wallerstein, Thorne & Doyle 1997). Monitoring results of another respondent indicated that channel incision could alternatively be decreased or even reversed by placing a large number of naturally shaped logs randomly in the stream (detailed results published in Launhardt & Mutz 2002).

The potential effects of wood placement must be seen within a watershed and reach-scale context, otherwise wood placement can have adverse effects on stream morphology and biota. For example, one respondent reported the excessive growth of macrophytes in an unshaded restored reach where wood had created low-velocity zones. We assessed this as being an adverse effect, as the stream would be bordered and shaded by a riparian forest in the potential natural state, limiting the growth of macrophytes.

Discussion

DIFFERENCES BETWEEN GEOGRAPHICAL REGIONS

The results indicate differences between restoration projects in alpine regions compared with projects in lowland and lower mountain regions. In alpine regions a higher number of projects with non-ecological objectives using fixed wood structures was carried out. Despite higher land-use pressure and large stream size, the infrequent use of large wood for ecological stream restoration in alpine regions may be because of the higher channel slope and stream power, which leads to a higher risk of downstream transport of large wood pieces. Several methods have been developed to assess the risk of downstream transport (Braudrick & Grant 2000; Abbe, Brooks & Montgomery 2003), as well as the ecological benefit of large wood (Shields & Gippel 1995; Manga & Kirchner 2000). However, these methods have rarely yet been applied in stream restoration projects in central Europe. We recommend testing and further developing these methods to allow for reliable risk and benefit assessment in future restoration projects.

NATURE AND EXTENT OF WOOD MEASURES

From an ecological perspective, our results indicate a potential for improvement with regard to the amount of wood and the size of wood structures. The median wood volume placed in the restored streams (34·0 $m^3\ ha^{-1}$) was within the range found in some of the most 'natural' stream sections in central Europe (median volume 37·8 $m^3\ ha^{-1}$; Kail 2005). The wood volume in 'most natural streams' in other temperate forested ecoregions, in the USA, Australia, New Zealand, northern Spain and the UK, is about three times the volume placed in the restored streams in our study area (median volume 126·0 $m^3\ ha^{-1}$). Therefore, from an ecological point of view, the amount of wood placed in restored stream reaches should be increased in future projects.

Many of the wood structures investigated were small compared with stream size, with two implications. First, the blockage ratio is low. Almost no effect on the water level upstream of wood structures is detectable for $B < 0{\cdot}1$ (Gippel 1995; Gippel *et al.* 1996) and pool volume caused by single large fallen trees depends on the blockage ratio (Kail 2003). To ensure that a project's objectives ('increase general structural complexity' and 'initiate lateral channel migration') are reached, blockage ratio should be increased in future projects, for example by simply rotating the wood structures perpendicular to the flow or by placing single large wood structures. Secondly, large wood structures, such as whole large trees with root-wad and branches, are rarely used. Such large trees are important from an ecological point of view because they act as key pieces in the formation of wood accumulations in natural stream reaches (Abbe & Montgomery 2003; Abbe, Brooks & Montgomery 2003). 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 particularly high if the length of the wood pieces exceeds bankfull channel width (Bryant 1983; Nakamura & Swanson 1994) and the trees have root-wads (Abbe & Montgomery 2003; Abbe, Brooks & Montgomery 2003). Bankfull width was less than 20 m in the majority of the restored reaches. In such small- to medium-sized streams, tree height can easily exceed bankfull width and, hence, single trees are large enough to be stable without additional anchoring. Therefore, we recommend the use of key pieces of appropriate size/shape that are placed in areas where channel morphology and hydraulics favour stability.

MONITORING

Although most projects had been monitored for a short time, they all experienced moderate high flow events; the median maximum return interval for the restored streams was 7·5 years. The share of the wood structures transported downstream (3%) was in the lower range of the rates reported in the literature for artificial instream structures, ranging from 3% to 43% (reviewed by Roper *et al.* 1998). This may because of (i) different definitions of downstream transport (Roper *et al.* 1998; Roni *et al.* 2002), (ii) comparable high peak flows, gradients and sediment transport rates of the streams described in literature, most of which are located in the Pacific North-West (USA) or (iii) different periods of time since wood placement. The low failure rate indicates that the wood structures were sufficiently fixed but, to assess final stability, high flows occurring during the life span of wood structures should be considered.

The rationale for monitoring restoration projects can be classified as follows. First, it is not possible to predict precisely the effect of restoration measures, and hence restoration measures are not necessarily beneficial (Kondolf 1998). Therefore it is necessary to monitor the response of stream morphology and biota to allow for corrections (Bryant 1995). Secondly, monitoring results may provide valuable information for the improvement of future project designs (Bryant 1995; Kondolf 1995, 1996, 1998; Bash & Ryan 2002; Downs & Kondolf 2002; Bisson *et al.* 2003; Reich, Kershner & Wildman 2003). However, in 42% of the projects in this review no monitoring was carried out. This is in accordance with the results of Bash & Ryan (2002), who reported the lack of monitoring for 47% of the restoration projects investigated in Washington state, USA. Bernhardt *et al.* (2005) reported an even lower rate (10%) for the 37 099 projects they investigated in the USA. To increase awareness of the importance of monitoring, learning objectives should be defined in addition to performance objectives (Downs & Kondolf 2002). 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).

SOFT AND HARD ENGINEERING

The placement of wood structures that are able to move at high flows is preferable from an ecological viewpoint to the use of fixed wood structures (called soft vs. hard engineering according to Bisson *et al.* 2003). A soft engineering approach is preferable because (i) the morphological features caused by these wood structures are similar to those created by natural wood in respect to type and size, (ii) they occur where they would naturally form and (iii) wood dynamics are an important part of channel dynamics, influencing channel morphology and biota at different places as the wood moves through the system. This study proved that soft engineering is also preferable from an economical point of view because of its low cost. Kail & Hering (2005) showed that soft engineering methods can potentially be used to restore a large part of streams, even in a densely populated region such as central Europe. The present study reveals that soft engineering methods have already been applied successfully in several restoration projects. This study further indicates that soft engineering methods may not increase the risk of downstream transport of wood structures if applied properly. However, the experiences of this study are limited to small streams and to comparatively short time spans. Risks of floating wood may be greater following the decay of wood structures and in larger rivers. In contrast to the results of Reich, Kershner & Wildman (2003), the present study shows that most wood structures were heavily fixed and soft engineering methods were the exception rather than the rule. In small streams soft engineering methods could be used more often, although the final decision should be made on a case by case basis.

PASSIVE AND ACTIVE RESTORATION

The placement of wood structures that are not fixed (soft engineering) can be called active restoration, according to Bisson *et al.* (2003). Such wood placement can be considered as an interim measure to improve degraded stream reaches rapidly prior to the establishment of a riparian forest constantly ensuring wood input (Cederholm *et al.* 1997; Roper *et al.* 1998; Bisson *et al.* 2003). For three reasons, we consider the restoration of habitat-forming landscape processes, such as the establishment of a riparian forest (called passive restoration according to Kauffman *et al.* 1997), to be preferable to the ‘active’ creation of local instream habitats, as has been already proposed in literature (Kauffman *et al.* 1997; Roni *et al.* 2002; Bisson *et al.* 2003; Wohl *et al.* 2005).

First, local, active, restoration measures often treat the symptoms and not the causes of stream degradation, and risk neglecting catchment-scale, processes leading to further degradation (Frissell & Nawa 1992; Kauffman *et al.* 1997). It has been proposed that restoration projects are more likely to be successful if they are undertaken in the context of entire watersheds (Wohl *et al.* 2005).

Secondly, active restoration measures may create conditions that do not correspond to the potential natural state. For example, in some re-meandering projects new channels are built using heavy machinery despite the problems of predicting natural width, depth and sinuosity of a stream. It is doubtful that the target condition for stream restoration, the potential natural state, can be described accurately for stream reaches if important controls have been altered by humans (e.g. increased valley slope as a result of subsidence caused by mining) and, therefore, historic conditions can not be used as reference or target conditions. In contrast, the establishment of natural riparian vegetation and natural wood input will initiate natural channel dynamics that will result in a new equilibrium state, the potential natural state. However, passive restoration may not be applicable in heavily degraded streams that are far from the potential natural state. This applies particularly to deeply incised streams, which are very common in the lowland parts of the study area. Large wood structures in large, incised sand-bed rivers have a high risk of downstream transport (Shields, Morin & Cooper 2004). In these instances passive wood input may have only minor effects on channel morphology.

Thirdly, even in a densely populated region such as central Europe, the process of natural wood input can be restored. A conservative estimate of Kail & Hering (2005) showed that presently about 6·5% of the streams in central Europe can potentially be restored by large wood recruitment from native or non-native riparian forests. In many parts of central Europe, pressures caused by land use may decrease in the future because of decreasing population density and alternative agricultural techniques. However, potential hazards from downstream transport of wood following passive restoration have not been estimated. Quantitative studies in differing stream types and differing types of riparian vegetation are required to judge the applicability of passive restoration.

Restoring habitat-forming processes on a catchment-scale, passive restoration, is a new and challenging approach (Hillman & Brierley 2005). It is particularly crucial to consider the spatial and temporal scales over which processes act to assess whether restoration objectives can be achieved within a reasonable period of time (Brooks & Brierley 2004) and whether it will be possible to predict the system response to restoration actions (Wohl *et al.* 2005). The amount of large wood is probably constant over long time periods and wide geographical areas (Murphy & Koski 1989) but variability on a reach scale is very high because of periodic changes such as long-term forest cycles and stochastic events (Harmon *et al.* 1986; Gurnell, Gregory & Petts 1995). Therefore the exact system response to restoring the large wood input on a reach scale is strongly dependent on the local, stochastic disturbance history, making it difficult to predict the effect of passive restoration on specific reaches.

These considerations have important implications for the definition of the potential natural state of a stream reach that should be used as a long-term target condition for stream restoration (Palmer *et al.* 2005). Because of the high variability of large wood input on a reach scale, natural wood loadings differ by at least one order of magnitude (Gurnell 2003) and, hence, it is not possible to define the amount of large wood as a specific single target condition. Rather, there are a large number of possible potential natural states differing in the large wood standing stock. The future disturbance history determines which of these states will be realized in a specific reach. It is only possible to define a wide range for wood loadings or minimum amounts that should be added to a stream reach as an active restoration measure, for example the minimum values for central European streams given in Hering *et al.* (2000). If passive restoration is applied in long stream reaches or entire catchments, the natural diversity of locally differing wood loadings will develop based on the disturbance history without the necessity of defining natural wood loadings. Using passive restoration therefore removes the risk of creating non-natural amounts or a non-natural diversity of wood loadings within the stream.

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Supplementary material

The following supplementary material is available for this article.

Appendix S1. Main characteristics of the restored streams

This material is available as part of the online article from: http://www.blackwell-synergy.com/doi/full/10.1111/j.1365-2664.2007.01401.x.
(This link will take you to the article abstract.)