Article

Engineered Large Wood Structures in Stream Restoration Projects in Switzerland: Practice-Based Experiences

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Abstract: The effects of large wood (LW) presence in streams on river ecology and morphology are becoming widely researched and nowadays their ecological benefits are undisputed. Yet LW presence in most Swiss plateau streams is poor mainly due to anthropological pressure on river ecosystems. The use of anchored, engineered LW structures under various forms in stream restoration projects is now state of the art. However, binding benchmarks for the equivalent naturally occurring instream LW quantities and complex LW structures do not yet exist. Therefore, hydraulic engineers often find themselves in a conflict between acceptable instream LW quantities for flood protection, quantities desirable from an ecological point of view and, last but not least, quantities accepted by the public based on the current ideologies of landscape design. In the first section, this paper treats the complexity of defining benchmarks for LW quantities in restoration projects. In the second section, we provide a qualitative practical insight into relevant questions when planning engineered LW structures, such as placement, anchoring, naturalness, and effectiveness from a hydraulic engineer’s point of view. The third part presents three examples of restoration projects with different dimensions where various engineered LW structures with different outcomes were built and introduced into active streams. Finally, the conclusion provides further possible measures to retain LW in streams and to restore more natural LW dynamics in rivers.

Keywords: large wood; key log; log jam; anchoring; river restoration; practice-based experiences

1. Introduction

Between the 18th and mid-20th century, Swiss plateau streams were widely modified for agricultural land reclamation and to augment flood protection. As a result, in-channel discharge capacity was enhanced and bank protection reinforced. At the same time dead wood volume in Swiss forests (especially in silviculture areas) dropped far below the amounts seen in European primeval forests due to intensified forestry [1]. As an effect, the natural input of fresh or dead large wood (diameter ≥10 cm and length ≥1 m based on Wohl and Jaeger (2009) [2], further referred to as LW), decreased. Stationary LW logs in stream beds act as an important trap for smaller LW, forming complex and temporally variable structures affecting the nearby morphology. Instream LW is at the base of the aquatic food chain by offering nutrition and a habitat for various invertebrates, as well as cover for fish.

To meet modern objectives for flood protection, various Swiss stream segments need additional protection measures. Furthermore, based on the 2011 revised Federal Waters Protection Act, Swiss waters need to be protected more aptly against harmful anthropologic effects [3]. For obvious ecological reasons and to optimize funding by federal authorities, flood protection projects are usually combined with suitable ecological restoration measures. These circumstances lead to a large number of stream restoration projects being initiated and completed in Switzerland.
The effects of various large wood structures (LWS) on morphology and aquatic habitats are becoming broadly researched and a common understanding of the related ecological and morphological benefits is being established. Early publications such as Maser et al. (1988), [4] or Maser and Sedell (1994) [5] already stated the importance of large organic debris present in forest streams and estuaries for productive salmonid habitats in Oregon, and provided recommendations for forest management and further research. More recently, Degerman et al. (2004) [6] showed a positive correlation between the presence of LW and the abundance of brown trout in small forest streams in Sweden. Wohl and Scott (2016) [7] proved the positive effects of LW in streams on sediment and particulate organic matter storage. Our involvement in various restoration projects has shown that, because of the related ecological benefits, engineered LWS have become widely used in restoration projects since they present a low-budget measure and are often locally available (e.g., from riparian clearances) and thus ecofriendly. However, the presence of (engineered) LWS in streams can possibly increase flood risk. LWS can act as a driftwood trap and therefore locally increase flow resistance and water levels, especially during flood events or, if poorly anchored, can be mobilized at higher discharges and turn into detrimental driftwood. In practice, instream LW is therefore unfortunately often seen as detrimental, especially where sufficient flood protection remains the main concern: for example in spatially confined river stretches close to settlement areas, or where hydropower infrastructure is present. Therefore, the use of large quantities of LW in restoration projects is sometimes met with reservation. In addition, the harvest of LW from riparian forests and stream maintenance habits leads to the regular extraction of LW from stream beds and riparian zones.

The assumption remains that the presence of LW in streams combined with mobilized driftwood could possibly lead to disadvantageous log jams. Yet, based on field research after the 2005 historic flooding in Switzerland, Bezzola and Hegg (2007) [8] showed that, on average, no more than 33% of the total driftwood resulted from mobilized instream LW within the monitored streams. The larger part consisted of freshly recruited trees and branches due to erosion processes, construction timber and firewood. Part of the monitored LW showed signs of bark bugs, implying that this fraction was most probably not recruited in stream beds. This assumption was underlined by more recent empirical GIS-based research on driftwood recruitment conducted in various streams in Switzerland by the Federal Office for the Environment, stating that instream wood accounts for a fraction of less than 10% of total driftwood [9]. The above-mentioned assumption for a potentially increased risk from driftwood due to instream LWS therefore seems to be an overestimation. Our statement is further emphasized by the work of Kail et al. (2007) [10] showing that the use of LWS in 50 analyzed restoration projects in Germany and Austria mainly led to low blockage ratios (proportion of cross-section obstructed by LW according to Gippel et al. (1996) [11]) and therefore merely affects stream hydraulics at higher discharges. Under these circumstances, the definition of the ecologically appropriate but tolerable quantity of (engineered) LWS in a restoration project in terms of increased flood risk, is a sensitive yet ecologically crucial subject with various stakeholders to consider.

2. Estimation of Natural Large Wood Quantities

Swiss plateau streams and riparian zones are strongly affected by anthropological land use and hydropower. In addition to the above-mentioned maintenance and forestry habits, barely any unaffected natural stream habitats, nor virgin or floodplain forests, still exist in Switzerland. Consequently, up to this day the possible LW recruitment into stream beds is strongly diminished [1]. Ruiz-Villanueva et al. (2016) [12] showed that wood storage in Swiss and similar Central European streams was comparably lower than in less anthropologically affected areas such as North America, Chile, or New Zealand. They suggested a plausible relation between LW storage and the naturalness of the river systems. Natural storage of LW in rivers was also closely linked to the stream bed type. Wyzga and Zawiejska (2010) [13] showed that instream LW storage was increased by a
wider multi-thread morphology and gravel bars or low islands, whereas channelized segments with a high-unit stream power showed lower storage capacity. This finding coincided with the results of Gurnell et al. (2002) [14] who emphasized the importance of riparian structures and morphological complexity to retain LW in larger streams compared to smaller streams where wood length and channel width were the predominant factors. Today, Swiss plateau streams often lack the once naturally occurring multi-thread morphology or extended gravel bars with small islands and meandering stream beds because of the widely restrained available bed width resulting from anthropological pressure, flood protection and adjacent land use. Based on a recent field survey, Küng and Jenzer (2020) [15] showed that even in three rather undisturbed representative Swiss stream segments in the Canton of Berne (i.e., Zulg, Schwarzwasser, and Sense), no key logs ($D > 60$ cm and $L > 10$ m) were present and LW volumes were of poor quality in two of the three streams. Consequently, the authors called for the elaboration of a benchmark system adapted to Swiss streams based on further field research.

Since the naturally occurring input of LW (especially key logs) into stream beds is widely restricted and storage capacity in Swiss streams is limited due to the broad absence of structures facilitating LW storage, it makes sense to define equivalent naturally occurring or ecologically desired LW quantities as benchmarks in restoration projects. The definition of binding numbers at the beginning of a restoration project is thus a key element to reestablish or enhance the desired habitats and to achieve the defined ecological and morphological objectives.

Various literature based on field surveys providing numbers for LW quantities exists. Benda and Sias (2003) [16] and King et al. (2012) [17] proposed frameworks for wood budgets based on a balance between recruitment and output to define wood volume per unit stream bed length for the Pacific Northwest. Yet these approaches require elaborate field data inputs. Based on collected field data from different streams in all three Central European ecoregions (lowlands, lower mountain area, and alpine region) in Germany, Austria and France, Kail (2005) [18] found median quantities of LW volumes of 1.7 m$^3$ and median log numbers of 20 pieces per 100 m of stream length (diameter of $>0.1$ m). Only undisturbed catchments where logs have not been removed and the management of riparian forests was absent were monitored. These numbers could be adopted for Swiss streams. However, regarding possible LW recruitment and storage, these monitored streams can at best be potentially considered semi-natural due to the long anthropologic history in Europe where riparian recruitment is far below pristine amounts [1]. In comparison, Fox and Bolton (2007) [19] collected data from 150 stream segments in unmanaged basins of different sizes in Washington State, USA. In alluvial basins larger than 4 km$^2$, median values for LW volume ranged from 50 to 80 m$^3$ per 100 m of stream length. Under the assumption that natural, unaffected Central European streams are comparable to the surveyed streams in Washington State, these numbers could be adopted for Central Europe and Switzerland.

2.1. Quantitative Recommendations Based on Existing Literature

The above-mentioned LW quantities fail to provide accountable benchmarks with a focus on restoration projects. Based on Mende (2018) [20], the authors suggest adopting benchmarks elaborated by the Oregon Coastal Salmon Recovery Initiative (OCSRI) in association with the Oregon Department of Fish and Wildlife (ODFW) published by Thom et al. 2000 [21], dating from 1997 (see Table 1.). These benchmark values have been developed for restoration projects in forested basins in Oregon State, USA, based on habitat characteristics, including LW from reference streams with a high productive capacity for salmonid species. The authors opine that pristine Swiss plateau streams are comparable to unmanaged streams in Oregon or Washington State due to a comparable once-pristine land cover and topography. However, the quantities in Table 1 are slightly lower than the above-mentioned natural quantities found in Washington State.
Our experience based on various restoration projects shows that the use of these values as benchmarks in practice is possible (e.g., Scherlibach, Köniz-Switzerland, see Meier et al. (2018) [22]). They successfully deal with the interests of different stakeholders affected by stream restoration while still allowing for a significant upgrade in stream and riparian habitat quality without significantly influencing upstream hydraulics. Notably, the authors of the OCSRI and ODFW study stated that when comparing selected quantities to the benchmarks: “ecological potential for performance will vary depending on the ecoregion, geology, natural disturbance history, local geomorphic constraints on habitat, and the size and location of the stream within its catchment” [21]. Therefore, these quantities must always be applied with caution and interpreted in the context of a given catchment and the present stakeholders. From an ecological perspective, higher quantities of LW are preferrable to enhance sediment and nutrition catchment and habitat availability [6,7].

Table 1. LW benchmarks based on Thom et al. 2000 (Logs refer to LW with diameter >15 cm and length >3 m, key logs refer to diameter >60 cm and length >10 m) [21].

|                         | Undesirable | Desirable |
|-------------------------|-------------|-----------|
| Logs/100 m stream length| <10 Pieces  | >20 Pieces|
| Volume/100 m stream length| <20 m³     | >30 m³   |
| Key logs/100 m stream length| <1 Piece   | >3 Pieces|

Seidel (2017) [23] proposed similar values for the specific introduction of wood volumes and logs in restoration projects for smaller low-land streams in Germany, based on Dahm et al. (2014) [24]. For the proposed values an assessment is made between different degrees of restrictions for (lateral) riverbed dynamics.

3. Use and Goals of Different Engineered LWS

Based on our practical daily business experience from various restoration projects in different streams of different sizes, and our involvement in the recent development of state-of-the-art techniques concerning in-stream LW, we would like to share the following recommendations and approaches.

Since the natural input of LW and key logs into stream beds in Switzerland is far lower than natural amounts [1], the active introduction of engineered LWS during restoration projects is fundamental (“hard engineering”). LWS can be introduced under various forms such as single rootstocks, engineered log jams or key logs (preferably with rootstocks). Key logs especially act as important initial structures for trapping smaller LW, forming complexes and long-lasting dynamic LWS (e.g., Figure 1). Therefore, the use of appropriate quantities of LWS to reactivate instream LW processes is crucial in restoration projects. However, such hard-engineered measures need close observation depending on size and placement (e.g., flood risk) as well as maintenance (e.g., additional anchoring or replacement). Practice-based experiences by Linsin (2018) [25] show that the lifespan of hard-engineered LWS is estimated to be at least 10–25 years. Lifespan mainly depends on bed load, hydraulic stress, wood type, and log diameter, but also on water exposure. LWS are constantly evolving and remain ecologically valuable even with gradual decay. We therefore expect the effective duration of LWS to be longer and estimate that LWS, with an evolving vegetation cover and rooting (e.g., willows or black alder), can especially form even longer lasting structures (e.g., islets). In addition, to guarantee the long-term effects of LWS, the enhancement of natural inputs of LW into streambeds should also be considered during the planning process. This objective calls for a closer collaboration between stream maintenance and forestry after the completion of restoration works.
Figure 1. Evolution of an introduced LWS in the span of 2 years (a) before the restoration; (b) shortly after introduction; (c) after approx. 6 months; and (d) after 2 years; Scherlibach stream; Photos: M. Mende.

The scope of application field for LWS in restoration projects is broad. LWS can be used for instream river restoration, for bank protection, or to enhance stream bed structuring after a mechanical modification (e.g., widening).

The size of LWS and the distancing between LWS always needs to be studied in the context of the characteristics of a given stream reach and the intention of a project. The design of engineered LWS is an ever-changing innovative process that should try to imitate naturally occurring processes which needs to be adapted to local circumstances and therefore cannot be standardized. LWS affect flow patterns significantly. Especially in smaller streams LWS can form channel-spanning log jams and cause a significant backwater rise. Predictions based on physical models are proposed, for example by Follet et al. (2020) [26]. The placement and orientation of instream LWS with regard to scouring and possible (bank) erosion processes needs to be studied thoroughly in advance (e.g., based on Gallisdorfer et al. [27] or Bennet et al. (2015) [28]). The wrong placement of a LWS could be detrimental for bank stability and therefore cause more structural damage than ecological value. It is therefore essential that planning engineers are present on site during the execution phase to discuss solutions and placements with machine operators and workers, according to the local conditions.

Based on our experience, we suggest considering the following aspects for every single LWS in the planning and execution phase to create an optimal ecological effect:

- Placement: LWS have the best morphological effect when placed perpendicular to the flow direction (scouring, cover for fish, driftwood rack, etc.) instead of parallel to the flow direction (see Figure 2a). Thus, the main part of LWS should be placed directly in the main current (thalweg, low water channel or concave banks) to have the most positive effect for the aquatic fauna and especially fish. LWS placed parallel to the flow direction (e.g., bank protection) should be completed with additional LW
logs perpendicular to the flow direction (e.g., Figure 3). For a profound physical explanation of the influence of perpendicular log placement on the flow and wake characteristics, see Schalko et al. (2021) [29].

- **Heterogeneity**: LWS should consist of key logs and single LW logs but also smaller trapped LW to form ecologically valuable structures (e.g., cover for fish or nutrition for invertebrates). Key logs are the structural and static backbone of every LWS. Especially when insufficient small LW input in the stream bed is expected, LWS and especially key logs are ideally combined with packed branches as an initial measure (e.g., Figure 4);
- **Trapping effect**: LWS should be built in a rough way so that single LW logs can act as a trap, especially for smaller LW. The use of key logs guarantees a better effect. In addition, Schalko et al. (2021) [29] showed an increase in residence time and deposition of fine particles (e.g., organic matter and nutrients) for emergent logs positioned at the channel sidewall;
- **Size**: Rougher and bigger LW logs (especially key logs) are more durable and therefore lead to more long-term morphological and ecological effects. The definition of an acceptable range of diameter and length for (key) logs depends on the stream size, the hydraulic regime, the ecoregion, but also on the availability. Minimum values are given in Table 1;
- **Naturalness**: LWS imitating naturally occurring structures are clearly preferrable to the authors and should best be anchored avoiding unnatural materials (e.g., steel anchors, ropes, steel parts etc.). Naturally retained LW usually stacks up in piles (see Figure 2b).

![Figure 2](image-url)

**Figure 2.** (a) Example of a LWS placed parallel to the flow direction that is hydraulically and morphologically ineffective at low discharges; Scherlibach stream; Photo: Courtesy of W. Dönni. (b) Example of naturally retained and piled up LW; Töss River; Photo: Courtesy of L. Bammatter.
There will always be a tradeoff between the natural look and the ecological benefit of engineered LWS (e.g., Figure 5). On the one hand, in the context of river restoration and rehabilitation where engineered structures are used to enhance or reinitiate natural processes to support or even reestablish desired habitats, natural appearing LWS are clearly preferrable to the authors. For example, cutting surfaces should be embedded or hidden, anchoring material such as rock anchors or ropes should not be used or at least not be visible and engineered LWS design should mimic natural structures as much as possible. On the other hand, experiences with obviously artificially made engineered log jams show that solid and possibly long-lasting structures such as groins for bank protection or even islets with deeply founded head protection come with obvious ecological benefits too (e.g., deep pools, cover, microhabitats), while natural processes slowly take over and vegetation cover evolves. The choice of the ideal LWS should therefore also be made considering the surrounding landscape, including the riparian zone as well as the proximity of settlement areas to create a coherent overall appearance. In suitable places such as recreational areas, engineered LWS could even be showcased as constructed landscape components which still offer maximum ecological benefits, whereas in untouched areas with restricted human access, natural looking elements are preferable.
4. Anchoring Engineered LWS

Kail et al. (2007) [10] state that it is preferrable from an ecological point of view that LW and even LWS can form and be displaced at higher discharges (“soft engineering”) to better mimic the naturally occurring characteristics (type, size) and transport processes of driftwood. Nevertheless, due to the restrictions regarding flood protection and an almost negligible natural LW supply based on the storage of driftwood at a broader catchment scale, LWS usually need to be anchored and kept in place when mechanically introduced into stream beds (“hard engineering”). Our experience shows that two different ways of anchoring LWS can be distinguished:

4.1. Riverbed

- Deep embedding: Wherever the riverbed substrate allows it, anchoring can be achieved by a sufficient embedding of the LWS in the riverbed. If necessary, it can be combined with additional weighting by using large boulders that are covered with substrate;
- Piling: If deep embedding is not possible or when piles themselves are foreseen as structural elements (e.g., as a trap or for butting), piling into the river substrate is an alternative;
- Alien means of anchoring: Especially where streams flow over a rocky riverbed with an insufficient riverbed substrate for embedding or piling, LWS can be attached to large boulders by using rock anchors, anchored directly into the bedrock or attached to riparian trees or boulders with ropes. However, it should be considered that LWS attached with only ropes are usually movable.

4.2. Riverbanks

- Embedding: LWS can be deeply embedded in the riverbank and, if necessary, combined with additional weighting by using large, covered boulders;
- The combination of embedding with piling or alien means of anchoring: LWS can be embedded in the riverbank and combined with further anchoring methods such as piling (especially for long-reaching LWS with leverage) or be anchored to additional boulders;
- Usually, it is preferrable to combine LWS in riverbanks with willow cuttings or budwood to establish a bio-engineered long-lasting bank structure with sufficient rooting.

Again, from an aesthetic point of view (to the authors), as well as regarding the potential injury risks for humans and fish (e.g., sharp edges), naturally occurring means of anchoring LWS should always be preferred and steel parts should not be used or at least
not be visible (e.g., no use of stainless steel) whenever possible. When constructing complex LWS such as engineered log jams, long-lasting timber-based woodworking joints can be used. Alternatively, arming steel can be hammered into logs to joint logs together (yet protruding ends need to be cut and should best be hidden in the trunk). Steel cables should be used with caution, especially in streams with hydropower plants since they can possibly damage the turbines. Alternatively, plastic ropes or natural fiber ropes can be used, which in turn are more prone to natural degradation or abrasion and, unfortunately, potential vandalism. Fallen riparian trees hanging into the active stream bed due to bank erosion processes, wind or even beavers should advantageously be fixed with ropes and therefore be kept in the stream bed rather than extracted. Dead riparian trees can also be anchored using thriving willow cuttings depending on stream power.

The spectrum of potential anchoring and jointing methods is broad, and innovation and improvisation are the key to success. This calls for a close collaboration between engineers and machine operators during construction works. Additionally, for anchoring it is essential that planning engineers are present on site to discuss with machine operators and workers, solutions and placements according to the local conditions.

5. Examples of Different Structures and Outcome

The authors would now like to share some practical insight on three completed restoration projects in the Canton of Solothurn, Switzerland. In these projects, large quantities of LW and complex LWS were introduced into the stream beds.

5.1. Aare River

Due to hydropower production along the river, most of the perimeter between the cities of Olten and Aarau consists of a residual flow stretch with a considerably high flood discharge ($Q_{100}$ approx. 1400 m$^3$/s vs. $Q_{\text{residual}} = 12$ m$^3$/s (winter) resp. 25 m$^3$/s (summer)). LW was locally available and partly used for bank protection and to enhance morphological diversity with LWS in the form of tree groins. For the tree groins, entire firs (tree dimensions: $D > 50$ cm, $L > 15$ m) were introduced so that they are almost completely submerged at $Q_{\text{residual}}$ and therefore longer lasting. The tree groins were anchored in the bank using roof-like crossed piles. In the riverbed, additional butting piles plus additional covered boulders for weighting were used (see Figure 6). Bank protection in the upper part was achieved by additional bioengineering using thriving willow cuttings. These structures not only protect the riverbank from erosion but also retain LW, offer cover for the aquatic fauna, and induce deep pools in the backwaters. As a comparable example for the outcome, see Figure 7 with similar structures from the Thur River.

![Figure 6. Draft of a submerged tree groin (for a better illustration of rooflike crossed piles see Figure 9b); Aare River; IUB Engineering AG.](image-url)
5.2. Emme River

In the context of a large flood protection and restoration project the last 4.8 km long stretch of the Emme River (residual flow stretch, \( Q_{\text{residual}} = 1.8–2.3 \, \text{m}^3/\text{s} \)) upstream of the confluence with the Aare River has been modified and restored. Due to riparian forest clearings remediating three disaffected dump sites along the river and thus also making local widening possible, substantial LW quantities were available and (re-)introduced into the river ecosystem (see Table 2). The majority of LW was used for bioengineered bank structuring (mainly to cover ripraps and to structure unprotected natural riverbanks, e.g., Figure 8). The rest was used for riverbed structures.

Table 2. Wood quantities used at the Emme River (Wehr Biberist-Aare).

|                      | Approx. total quantity   |
|----------------------|--------------------------|
| Branches             | 5450 m\(^3\) (stacked)  |
| Thriving willow cuttings | 1090 m\(^3\) (stacked) |
| Rootstocks (“logs” and “key logs”) | 1970 pieces |
| Sprouting rootstocks  | 1640 pieces              |
| Entire trees          | 69 pieces                |

The restored river stretch is characterized by a slope of 4% and rapidly rising hydrographs with high discharge peaks (\(HQ_{100}\) approx. 650 m\(^3\)/s). During high discharge events, a lot of driftwood can be mobilized and transported. The annual bed load transport is substantial with approximately 13,000 m\(^3\)/year.
A total of approximately 125 LWS were placed in the riverbed in various forms. Guidelines by the contracting authorities demanded the avoidance of alien anchoring materials (e.g., steel anchors or ropes causing a potential risk to downstream hydropower plants). LWS, such as rootstocks with long stems, were therefore anchored by deep in-bed founding with overlying boulders for additional weighting. More complex structures such as LW islets and tree groins (log/tree dimensions: \( D > 50 \text{ cm}, L > 15 \text{ m} \)) were anchored in the gravel bed by mechanical piling (see Figure 9) and sometimes additional weighting boulders for even larger structures.

![Figure 9](image-url)

**Figure 9.** (a) Mechanical piling to anchor LW islets in a pebbly riverbed substrate; Emme River; Photo: M. Mende. (b) Draft of a LW islet; Emme river; IUB Engineering AG.

The transformation from LWS with engineered, artificially made characteristics, to a more natural appearance took place soon after the introduction of the driftwood trapping process (see Figure 10). Yet, in terms of natural appearance, these structures surely offer some additional potential.

![Figure 10](image-url)

**Figure 10.** (a) LWS islet right after completion; Emme River; Photo: M. Mende. (b) Evolution of a LWS islet approx. 6 months after completion; Emme River; Photo: M. Mende.

The LWS islets were placed in a stretch where lateral erosion and dynamic widening is desired. Increased flow resistance and higher water levels can therefore be accepted and are no major concern. Morphological diversity was established shortly after the occurrence of two events with higher discharges (both approx. \( Q = 100 \text{ m}^3/\text{s} \) whereas \( HQ^2 \approx 270 \text{ m}^3/\text{s} \)). Deep pools, gravel bars and diverse flow patterns formed (see Figure 11).
5.3. Witibach Stream

The Witibach stream flows into the Aare river and offers cooler temperatures during the summer months. Trout especially retreat into this stream for a temperature refuge. The stream initially offers little structural and morphological diversity and its banks are protected with a riprap barely offering any cover for fish. A stretch of 1.6 km had to be restored with instream measures and a strong focus on LW. Besides improving the structural variety of the stream, the aim of introducing important quantities of LW (see Table 3) was to significantly increase the instream wood surface to enhance biologically driven self-purifying processes. This way, the water quality can be significantly improved. The riparian zone was completed with additional tree and bush plantings to enhance shading and introduce networks of roots (especially black alder) into the stream in the long term.

Due to the presence of an underlying confined aquifer, the partially existing concrete streambed and the riprap bank protection could not be removed. With the addition of an approx. 50 cm gravel substrate layer, the streambed was locally elevated and structured with LW and LWS (log dimensions: $D > 30$ cm, $L > 4.5$ m, tree dimensions: $D > 20$ cm, $L > 5$ m).

| Wood type                       | Approx. total quantity |
|---------------------------------|------------------------|
| LW (loose branches and fascines)| 235 m$^3$              |
| Rootstocks                      | 84 pieces              |
| Large logs                      | 96 pieces              |
| Entire trees                    | 47 pieces              |

Because of a culvert under the adjacent small airport’s landing strip, anchoring the LWS was crucial. Deep-founded embedding in the streambed or in the banks was not possible. All the LWS were therefore weighted with boulders (sometimes completed with rock anchors) and wedged between the banks (see Figure 12).
Unfortunately, this type of anchoring by weighting resulted in an important increase in visible boulders in the stream that naturally would not occur to this extent. Large logs were mainly used to create structures inducing diving currents and scour (see Figure 13). Because of the advantageous cost–efficiency ratio, the logs of complex LWS were jointed with hammered armoring steel. That way, the shape of the LWS could be fitted accurately into the existing stream bed while banks were kept intact in most places. In addition, large quantities of packed branches were used as explained above to guarantee an instant supply of smaller LW (see Figure 4). In the future, the evolution of these structures and the (naturally low) LW recruitment and input need to be monitored closely to maintain the ecological function of these LWS.

6. Conclusion

Engineered LWS as a low-budget solution in stream restoration projects are becoming widely used and their ecological benefits are unquestioned. Quantitative specifications such as placement, size, type, and distancing of LWS vary between stream types and depend on the aim and size of a given project but also on available budget. Various successful projects showed that the use of LWS can be combined with ambitious flood protection objectives even in confined river stretches (e.g., in settlement areas). Experience shows that LWS have the best morphologic effect when partially placed somewhat perpendicular to the flow direction of the main current. The mechanical introduction of LWS
with heavy machinery ("hard engineering") is an initial step to reactivate natural LW in-stream processes. To re-establish a naturally occurring LW input into stream beds and therefore tackle the problem of poor LW quantities in river ecosystems at its roots, further action should be taken to guarantee an increased flux and replacement of instream LW ("soft engineering"). The authors therefore call for a closer collaboration between authorities, hydropower operators, hydraulic engineers, stream maintenance and owners or managers of riparian zones (i.e., forestry, agriculture). For example, the reintroduction of extracted LW at racks of hydropower plants in the form of hard-engineered LWS could be discussed to keep as much LW in stream beds as possible rather than dispose of it. Hydropower plants, where LW could be passed through rather than extracted, should be identified with a suitable risk assessment.

In addition, by reestablishing morphologically complex stream segments with low unit stream power in restoration projects (e.g., by widening of the active channel width in case of higher discharges), more LW could be retained and stored naturally in the channel or kept mobile during frequent flood events thus offering more naturally occurring structures and processes.

In this context, and to enhance the acceptance of LW presence in streams (even where hydropower is present), a deepened understanding of natural wood regimes as proposed by Wohl et al. (2019) [30] would be helpful. The definition of a suitable balance of interests between risk management and ecological objectives remains a key subject in every restoration project, as well as for further stream maintenance.

7. Outlook

This article provides a practice-based qualitative insight into questions and challenges encountered during the planning process and the execution phase. As an outlook it would be interesting to gain further knowledge, based on field work or physical experiences, on the following specific topics:

- The beaver population is on the rise in Switzerland and the species is protected. Beaver dams but also artificially made beaver dam analogs could represent a valuable source of LW in streams. It would be interesting to know whether and how fish migration across beaver dams is restricted;
- What exact design of (complex) LWS depending on flow characteristics and placement in the current is required to specifically induce the emergence of a desired mesohabitat, such as deep pools in salmonid streams, without significantly increasing flood risk? Schalko et al. (2021) [29] provides the first interesting insight on this topic;
- The effect of LW presence in streams on fish abundance has been researched. Yet so far, no information is available on how specific designs of LWS (mainly key logs for scouring, submerged LWS, dense branches, driftwood rack, rootstocks, and engineered log jams, etc.) influence the presence of different species, guilds, age classes of fish. Are there any observable patterns? Especially in confined stretches such information would be valuable to foster target species;
- A monitoring over a long period of LWS should cover the following aspects: Effect of driftwood rack, morphological change depending on discharge (e.g., minor flood events) and with the evolution/decay of an LWS, the structural evolution of the LWS (abrasion, decay, vegetation cover, and rooting, etc.), and the presence of nearby fish populations.

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