Restoration increases transient storages in boreal headwater streams

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Abstract

Bed siltation can drastically alter the physical conditions of headwater streams and is therefore a stressor for stream ecosystems. We studied 32 headwater streams that represented near-natural (reference) (N = 11), sediment-impacted (N = 12) or wood (N = 4) or stone-restored (N=5) streams to quantify how extensive siltation and restoration with either large woody debris (LWD) or boulder structures influence transient storage conditions. We carried out repeated stream tracer experiments, field measurements of habitat characteristics, and numerical simulations to determine the effects of siltation and restoration on total transient storage (TTS). Compared with reference streams, impacted streams had a smaller storage zone cross-sectional area (As/A) ratio and fraction of median travel time due to transient storage (F200), whereas restored streams had transient storage conditions similar to near-natural conditions. Both of the two restoration methods had positive but differing impacts on bed sediment and transient storage properties. The LWD restoration created diverse TTS conditions whereas boulder restoration decreased fine sediment cover. Addition of both LWD and boulders could thus aid the recovery of headwater streams from excessive sediment input and increase transient storage and in-stream habitat complexity.

Keywords: restoration, transient storage, headwaters, sedimentation, siltation, modelling

1 Introduction

Increased sediment deposition to stream beds from human alteration of catchment land use is a global concern and poses a particular challenge for the restoration of headwater streams with limited sediment transport capacity. Headwaters form ecotones with their terrestrial surroundings and often support unique elements of regional biodiversity (Turunen et al. 2017). Because of their intimate links with the surrounding catchment, headwater streams are highly sensitive to anthropogenic land use stressors. While sediment transport and deposition is a natural phenomenon and is essential for many stream processes, any additions to natural transport rates may alter the stream bed and hydraulic conditions and, consequently, the stream biota (Jones et al. 2012).

The impact of increased sediment flux on stream biota is typically related to deposits rather than suspended material. Extensive sediment load reduces natural depth variation (Marttila et al. 2012) and can be a stressor for stream organisms (Louhi et al. 2011, Jones et al. 2012). Decreased depth variation reduces availability of deep pools and movement of sediments causes streambed instability. Furthermore, deposits influence transient storage processes, as well as water exchange between the storage and the main channel (Brunke and Gonser et al. 1997). In natural streams, variations in substratum and streambed morphology create diverse transient stores within the hyporheic zone and backwater areas, eddies and pools (Bencala and Walters 1983), providing habitat for benthic algae and accumulation zones for organic matter (Mulholland et al. 1994). Transient storage is also essential for solute transport and many biogeochemical processes in stream networks (DeAngelis et al. 1995).

Total transient storage (TTS) zones are features where water velocity is slower than in the advective flow of the main channel (Bencala and Walters, 1983). These zones, such as hyporheic transient storage (HTS) and surface transient storage (STS) zones (e.g. side pools, eddies, vegetation, debris dams, wood material), provide shelter and refugial habitats for stream biota and are essential for several biogeochemical processes (Johnson et al. 2016). A major benefit of woody structures is the control of local flow conveyance and shaping of the bed structure. In stream restoration, estimation of transient storage properties has received limited attention, despite its potential for measuring restoration success (Mason et al. 2012). In previous studies, Bukavestas (2007) demonstrated changes in median travel times in channelized streams after restoration, whereas TTS was largely unaffected, except in reaches where backwater areas were created. Restoration has been shown to enhance transient solute exchange (Becker et al. 2013), increase residence time (Mason et al. 2012), and extend the spatial and temporal extent of hyporheic flow paths and, consequently, TTS (Smidt et al. 2015). In general, restoration alters TTS because of increased heterogeneity in flow patterns.

Most restoration projects in Finland have targeted medium to large rivers, while headwater streams have received much less attention. Another recent development in stream restoration has been the adoption of a more holistic approach to evaluate restoration success, by accounting for both ecological, sociological and cultural services provided by stream ecosystems (Palmer et al. 2014). Nevertheless, there is still a lack of even a basic understanding of how restoration modifies the transient storage properties of streams, especially in headwaters where sediment deposits affect transient storage conditions (Hünken and Mutz 2007). Addition of boulders and/or large woody debris (LWD) are the most typically used in-stream restoration measures. Unlike natural streams, streams draining forestry-impacted catchments are typically devoid of LWD (Turunen et al. 2017). Large woody debris modifies habitat characteristics (Pilotto et al. 2014), traps sediments and organic matter (Koljonen et al. 2012) and controls hyporheic-zone exchange processes (Mutz et al., 2007). Therefore, the benefits of LWD for restoration have been recently acknowledged (Louhi et al. 2017).

The aim of this study was to improve our currently limited understanding of the potential changes in reach scale transient storage conditions caused by (i) siltation from land use and by (ii) headwater stream restoration. We hypothesize TTS conditions and bed sediment conditions should differ between i) near-pristine (reference) streams, ii) streams impacted by anthropogenic land use-induced sedimentation, and iii) streams restored with additions of either boulders or LWD. We expected i) greater fine sediment accumulation in impacted streams, ii) sediment deposits to have impaired reach-scale TTS conditions in impacted streams, and iii) that restoration measures have shifted TTS conditions closer to pristine. We also examined whether transient storage modelling via solute breakthrough analysis could be a beneficial tool for evaluating restoration success, especially in headwater streams.

2 Methods

2.1 Study streams

All the study streams lie within the mid-boreal ecoregion in north-east Finland, in the headwaters of the River Iijoki basin (total catchment area 14,191 km^2) (Fig. 1). The selected streams represent typical headwater streams of the region, being circumneutral and slightly colored by dissolved organic carbon (DOC) due to high peatland cover in stream catchments. By ‘headwater’, we refer to first- and second-order streams by Strahler classification, varying from 0.5 to 3.5 m wide. The ground vegetation near stream channels is composed of forbs, *Sphagnum* moss, sedge (*Carex* sp.), and willow

(*Salix* sp.) species, whereas tree stands are mixed stands of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst. (L.)), and downy birch (*Betula pubescens* Ehrh.). The geology of the region consists predominantly of glacial fine lodgement till and esker formations, with peat in sloping or valley fens. Long-term mean annual precipitation is 695 mm, mean air temperature 0.2°C, and mean evapotranspiration approximately 230 mm, resulting in base flow throughout the year. Permanent snow cover typically lasts from December to April, with snowmelt-induced spring floods in early May.

The main anthropogenic pressure in the region generally, and also in the catchments of our study streams, is forestry. Finland has a strong tradition of peatland drainage. Many peatlands, including those in the study region, were drained by ditching during the 1960-1980s to support forest growth, resulting in extensive impacts on headwaters. Peatland drainage operations typically increase inputs of sediments and nutrients to downstream water courses (Marttila and Kløve, 2010). In the study region, many ditch networks in the past drained directly into a stream channel and some stream sections were straightened to improve water withdrawal. While the finest sediments have flushed from the stream network since drainage, sand-sized particles have deposited within the streambeds. This extensive deposition has reduced water depth, decreased habitats for fish and invertebrates, and covered natural stream substrates such as wooden debris and aquatic mosses (Marttila et al. 2012). Drainage activity largely ceased during the 1990s but old forest drains are still being maintained in economically productive areas.

In this study, we selected nine first-order streams that had been impacted by fine sediment accumulation and were restored 3-7 years (median: 6 years) prior to sampling. Four of the streams were restored using mainly wooden restoration structures (hereafter Res-w) to i) increase flow scour to the stream bed, and thereby potentially promote transport of deposited fine sediments, and to ii) increase TTS. The volume of added wood was on average 7 $dm^3\ m^{-2}$ (range: 4.7-9.1 $dm^3\ m^{-2}$). Five of the streams were restored using stony structures (Res-b), consisting of boulders (Ø 30-50 cm), large cobbles (Ø 10-20 cm), and gravel (Ø 3-7 cm), with the aim of increasing in-stream heterogeneity. Some wood (average 3 $dm^3 m^{-2}$, range: 1.3-6.7 $dm^3 m^{-2}$) was also present naturally in these streams, but much less than in the wood-restored streams. Restoration focused on woody structures to increase variation in water depth and enhance sortation of the settled bed sediment (Tammela et al. 2010). Restoration actions were extended to the surrounding catchment to prevent transport of additional sediment inputs from the drained areas. These actions were carried out at all sites and typically included filling of old ditches and constructing overland flow fields. Additionally, we sampled 11 near-natural reference (Ref) streams with near-absence of drainage activities in their watersheds, as well as 12 streams impacted (Imp; no restoration) by fine sediment deposition from drainage. The latter streams were in a similar condition to the restored streams prior to their restoration.

2.2 Tracer measurements

Channel hydraulics and transient storage variations in streams were studied by injecting a conservative tracer pulse (NaCl) into the stream (Stofleth et al. 2008). All tracer tests were conducted during base flow conditions between August and October 2013. The selected sampling reach was a 300-m long section of a stream containing both riffle and pool areas, and influenced by substantial sediment siltation (except reference sites). We selected study streams and reaches with similar geomorphology (width:depth ratio, bankfull depth and width, and baseflow conditions, Table 1), allowing a better comparison between different stream groups. In all streams, channels were well defined, allowing us to quantify bank-full statistics. Channel gradient was on average higher in the boulder restored streams, but even then the differences were minor. The study reach was divided into six 50-m sections, and cross-sections and detailed channel properties were measured for each section. Five electrical conductivity (EC) data loggers (HOBO U24.001) were installed to the main flow, in the middle of each cross-section (0.6 x water depth), and EC was measured at 10-s intervals. Sites for logger placement were carefully selected and unmixed zones were avoided (see Becker et al. 2013). A 10-min constant rate injection was added to the upper part of the study reach and EC was measured until the pulse disappeared completely from the lowest cross-section location. Locations for the tracer injection and the conductivity logger were selected based on mixing conditions in a stream so that the tracer immediately achieved laterally well mixed conditions. Furthermore, movement of the tracer pulse was monitored with hand-held conductivity meters along the reach during the experiment to ensure constantly well-mixed conditions throughout the study reach. Suitable tracer mixing conditions were also tested in a separate trial before the tracer tests, and we concluded that the tracer remained well-mixed throughout the entire reach. The pulse was repeated 2-3 times to minimize random measurement error. Each sensor was calibrated with stream water and EC values were transformed to NaCl concentrations.

2.2.1 Stream channel characteristics

All six cross-sections selected for the tracer experiment were measured for water depth, width, and flow velocity (MiniWater®20, Schiltkecht, Switzerland), and discharge was calculated based on these measurements. The cross-sections were placed at 50 m intervals and they included both riffles and pools. Bankfull depth and width were estimated from stream banks using standard procedures. Sediment grab samples (0-5 cm depth) were taken from five locations per cross-section using a small scoop, and they were sieved for particle size distribution in the laboratory using phi intervals of 31.5 mm, 16 mm, 8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm and <0.063 mm. Sediment depth at each sediment sampling location was measured with a metal measuring stick pushed into the bed sediment. Fine sediment cover was estimated by placing 15 plots, each measuring 0.5 m x 0.5 m, across the sampling reach. For each quadrat, we estimated visually the percentage (%) of fine sediment cover.

2.3 Data analyses

We used a one-dimensional solute transport model (OTIS, Runkel 1998) to estimate transient storage in the study streams. OTIS employs a finite-difference model to solve paired partial differential equations describing solute transport in channels (see https://water.usgs.gov/software/OTIS/). The OTIS model is commonly used in riverine environments to estimate transient storage values. Although the model only accounts for a single-storage zone, and thus cannot separate surface transient storage (STS) and hyporheic transient storage (HTS) exchange, it still offers a flexible tool to estimate total transient storage (TTS) change. The model calculates estimates of the storage zone cross-sectional area (As, m^2), dispersion coefficient (D, m sec^{-2}), and storage zone exchange coefficient (α). We used these estimates to determine the following storage parameters: dimensionless residence time (τ_R) (= TU/L, where T = As/αA (Harvey et al. 1996), L is reach length, m, and U is flow velocity, m s^{-1}) and the fraction of the median travel time due to transient storage F_{med} (Runkel, 2002). The F_{med} parameter reflects the interaction between advective velocity and transient storage. For the purposes of comparing values of F_{med} from different streams and experiments, we used a reach length L = 200 m to standardize the values (Runkel, 2002); thus, all values reported are F_{200}.

We tested for differences between treatments in the physical stream characteristics and sediment condition responses by using generalized linear models with gaussian error distributions and identity link function. Differences from reference streams were tested using treatment contrasts, and effect sizes are reported in terms of differences of a treatment from reference streams, together with the 95% confidence interval for the differences.

3 Results

3.1 Bed sediment and channel characteristics

Peatland drainage has transported fine sediments into both impacted and restored streams and bed sediments in these streams were therefore dominated by sand-sized particles. Sediment size distribution (d50) did not differ between reference and impacted streams (effect size = -0.3, 95% confidence intervals (CI_{95}) = -0.8-0.06, t =-1.7, P = 0.102), and reference and boulder restored streams (effect size = -0.5, CI_{95} = -1.0-0.04, t =-1.8, P = 0.078). Wood-restored streams had significantly finer sediments than did the reference streams (effect size = -0.6, CI_{95} = -1.2- -0.05, t = -2.1, P = 0.043).

Fine sediment cover (%) varied from 9.3 to 100 % (20, 52, 22, and 63 % for reference, impacted, boulder-restored, and wood-restored streams, respectively) (Table 1, Fig. 2). Fine sediment cover in reference streams was significantly lower than in impacted (effect size = 30 % (i.e. difference in percentage cover of fine sediment), CI_{95} = 18-42 %, , t=4.9, P < 0.001) and wood-restored streams (effect size = 42 %, CI_{95} = 26-60 %, t=5.0, P < 0.001), but similar to that in boulder-restored streams (effect size = 2 %, CI_{95} = -13-18 %, t = 0.3, P = 0.780). The boulder-restored streams had less sediment cover than the impacted streams (t=-3.57, P = 0.001). LWD volume was significantly higher in reference than in impacted (effect size = -0.008 m^3, CI_{95} = -0.012- -0.004, t = -4.1, P < 0.001) and boulder-restored streams (effect size = -0.008 m^3, CI_{95} = -0.013- -0.003, t = -3.18, P = 0.004), whereas it did not differ from wood-restored streams (effect size = -0.002 m^3, CI_{95} = -0.007-0.003, t = -0.74, P = 0.465). LWD volume was significantly higher in wood-restored than in impacted streams (t = 2.19, P = 0.037).

There was considerable variation between treatments in channel morphology and several key environmental variables (Table 1). The width:depth ratio was significantly higher in reference than in impacted streams (2.11) (effect size = -0.93, CI_{95}=-1.7- -0.2 t = -2.4, P = 0.022), and nearly so when reference was compared to boulder-restored streams (2.07) (effect size = -0.97, CI_{95}=-1.7- -0.2, t = -2.03, P = 0.052), whereas wood-restored streams (2.55) did not differ from reference streams (effect size = -0.48, CI_{95}=-1.5- 0.5, t= -0.945, P = 0.353) (Table 1, Fig. 2).

3.2 Transient storage modelling

Restoration did not affect dimensionless residence time (generalized linear model, $P > 0.097$ for all comparisons) (Fig. 3a), partly because of considerable variation between streams. The As/A ratio in reference streams was significantly higher than in impacted streams (effect size = -2.9, CI_{95}= -4.8-0.9, t = -2.92, P = 0.007) and also higher than in boulder-restored streams (effect size = -2.4, CI_{95}= -4.9-0.04, t = -1.93, P = 0.064), whereas reference streams and wood-restored streams did not differ (effect size = -0.3, CI_{95}= -3.0-2.4, t = -0.21, P = 0.823). Boulder-restored streams did not differ from impacted streams (t = 0.34, P = 0.738) but wood-restored streams had a slightly, albeit non-significantly, higher As/A than the impacted streams (t = 1.90, P = 0.069). Boulder- and wood-restored streams did not differ from each other (t = 1.36, P = 0.184).

F200 was higher in reference than in impacted streams (effect size = -0.2, CI95= -0.4- -0.04, t = 2.42, P= 0.022), but boulder (t = 0.726, P = 0.474) and wood restored (t = 0.989, P = 0.331) streams did not show any increase in F200 compared with the impacted streams.

4. Discussion

4.1 Impaired in-stream bed sediment conditions

Extensive siltation (mean siltation depth 15 cm, max. 51 cm, d_{50} = 0.78 mm) following peatland forest drainage operations had changed local bed conditions and decreased transient storage conditions in our impacted streams. Restored streams showed lower sediment cover than the impacted streams, but did not achieve the bed characteristics of pristine streams. Bed sediments in both impacted and restored streams consisted predominantly of sand-sized particles and restoration efforts thus did not show any noticeable effect on the particle size distribution of bed sediments. This was presumably caused by extensive sediment inputs (up to 51 cm siltation depth) and the streams likely need much more time to recover from the initial drainage disturbance. The mean sediment cover in the impacted streams was 52%, but up to 100% cover was observed in some streams. In reference streams, only around 20% of the surface area was covered by fines, suggesting a substantial change in bed substrate cover as a result of peatland drainage. While boulder restoration clearly reduced bed sediment cover, only a few wood-restored streams had recovered to close-to-pristine bed conditions.

4.2 Restored sites show improved transient storage conditions

Our results indicate that restoration structures increase total transient storage conditions (TTS) as reflected in higher values of As/A (Fig. 3), but had no effect on the residence time. This accords with Bukaveckas (2007), who also found no major effect of restoration on travel time. Restoration in our case mainly involved addition of LWD structures such as underminers (Tammela et al. 2010) and deflectors, or boulders that modify local flow conditions and bed topography. The overall mechanism for transient storage in restored reaches was most likely a combination of increased surface transient storage and hyporheic transient storage zones around restoration structures. However, the OTIS model cannot separate different transient storages and thus we cannot analyze variation between storage types. Becker et al. (2013) also observed faster transient storage exchange and increased transient storage conditions in sites restored using various flow-steering structures. In our restored streams, the main physical change was increased scouring close to the added structures and increased variation in water depth. Such local bed modification did not always result in clear impacts on the reach scale but even a local reduction in fine sediments creates diversity in terms of habitat patchiness, thus yielding favorable restoration outcomes. Our results emphasize the need for more intensive restoration efforts in boreal headwater streams. If restoration aims to reach near-natural bed conditions, then clearly more wood and boulder material should be added to streams that currently suffer from siltation problems.

Using a larger amount of LWD resulted in a slightly higher A_s/A ratio, indicating that more wood should be added to improve transient storage conditions. In boulder-restored streams the cover of bed surface sediments generally reduced, reinforcing the importance of using multiple restoration measures to improve both benthic and riparian habitat conditions (Turunen et al. 2017). Boulder-based restoration seems to be more effective than wood-based restoration at restoring benthic habitat structure in sediment-stressed streams, with benefits for the recovery of in-stream biota such as bryophytes and benthic invertebrates (Turunen et al. 2017). However, wood-based restoration changes riparian plant communities towards those of natural streams, suggesting changes in riparian soil moisture and flood regime (Turunen et al. 2017). Individual wooden structures (Tammela et al. 2010) may be effective for only a few meters from the structure, creating localized transient storage areas. This was particularly evident in silted headwater streams with limited transport capacity.

Our modelled values are largely in agreement with previous studies in corresponding environmental conditions. Values of A_s/A averaged 3.05±2.61 (SD), which is higher than reported for sandy (0.32±0.22) or coarse-bed streams (0.47±0.64) (see Stofleth et al. 2008 for a comparison). However, our study streams are boreal headwater streams, where the width:depth ratio is generally different from that of sand or gravel-bed streams (Marttila et al. 2010). Boreal , headwater streams typically have stable vertical banks that create a lower width:depth ratio and deeper water areas. The parameter F_{200}, a useful measure of TTS for inter-site comparisons (Runkel 2002), responded variably, but within the range of values generally reported for streams (Stofleth et al. 2008). The influence of storage properties typically tends to decrease as stream velocity increases (Runkel 2002). This was also evident for the F_{200} values in our data. This forms a potential source of temporal variation for TTS in the OTIS model output. For this reason, we conducted our experiments during base flow conditions and in similar stream reaches to ensure comparability across the streams. We also selected our study streams so that they represent similar geomorphological properties, allowing a better comparison between the groups. To our knowledge, this is the first study documenting transient storage conditions in boreal headwater streams, and thus our values cannot be directly compared with data for other types of streams.

Our results are in agreement with previous solute transport studies in that channels with woody obstructions had higher median travel times associated with transient storage (F_{200}) and proportionally greater transient storage areas (A_s/A) (Ensign and Doyle 2005, Stofleth et al. 2008). In those studies, solute retention was attributed to changes in surface storage, such as eddies, pool volumes, and meanders, rather than retention in the hyporheic zone. In the present study, the change in surface storage was indicated by a large A_s/A ratio and high storage zone exchange coefficient (α) in near-natural and wood-restored streams. In contrast, impacted and boulder-restored streams had smaller A_s/A, demonstrating the increasing influence of hyporheic zone storage in these streams. While LWD clearly influences transport of solutes, hyporheic exchange rates near the structures are too slow or small to influence reach-scale transient storage (Sawyer and Cardenas, 2012). While our analysis could not separate between different storage types, even a small proportional increase in hyporheic exchange can be ecologically and biogeochemically beneficial, as it increases habitat complexity of the stream bed (Wondzell 2011).

Headwaters form a major proportion of stream networks and are highly connected to the surrounding terrestrial environment; thus any disturbance to these small streams will also affect downstream habitats (Wipfli et al. 2007). Headwater streams offer multiple ecosystem services beyond local stream channels, and their protection and restoration are therefore essential for maintaining the integrity of river networks (Hill et al. 2014). Adding LWD and boulders is important for stream biota and also has benefits for local hydraulic conditions, thermal conditions (Sawyer and Cardenas, 2012) and total transient storage conditions, as shown in this study. Moreover, the benefits of channel restoration are not limited to the stream, but extend to the riparian zone (Hasselquist et al. 2015, Turunen et al. 2017) and to downstream areas (Alexander et al. 2007). Indeed, future restoration operations, especially in headwaters, should be performed simultaneously in channels and the riparian zones.

5 Conclusions

Restoration with either wood or boulders resulted in several positive impacts on bed sediment and transient storage conditions, creating more diverse total transient storage conditions and decreasing fine sediment depth and cover. Restored sites showed a higher storage zone cross-sectional area (As/A) than impacted streams, but had no effect on residence times. LWD had a stronger effect on TTS conditions than did boulder additions, whereas boulders were more effective at reducing fine sediment cover.

These results emphasize the need to combine multiple measures in the restoration of headwater streams, since different restoration methods had different effects on stream TTS and bed substrate characteristics. Additionally, boulder vs LWD restoration have divergent impacts on stream biota (Turunen et al. 2017). The restored streams had less added wood than in pristine conditions, and we recommend using more LWD in headwater stream restoration. While our study does not provide direct information to guide stream managers about the optimal amount of wood to be added, previous studies have suggested values exceeding 30 m^3 ha^{-1} (Louhi et al. 2017) which is still much lower than what was observed by Liljaniemi et al. (2002) in historically unmodified, pristine streams in the Russian Karelia. Finally, our study shows that transient storage modelling can be used to evaluate the success of hydro-physical restoration.

Acknowledgement

We thank Eero Moilanen, Eero Hartikainen, and Matti Suanto for their generous help in selecting the study streams and Lari Tajakka and Heli Harju for field and laboratory assistance. This work was funded by the Academy of Finland (AKVA grant no 263597). We thank the two anonymous reviewers for constructive comments that helped improve the quality of this paper.

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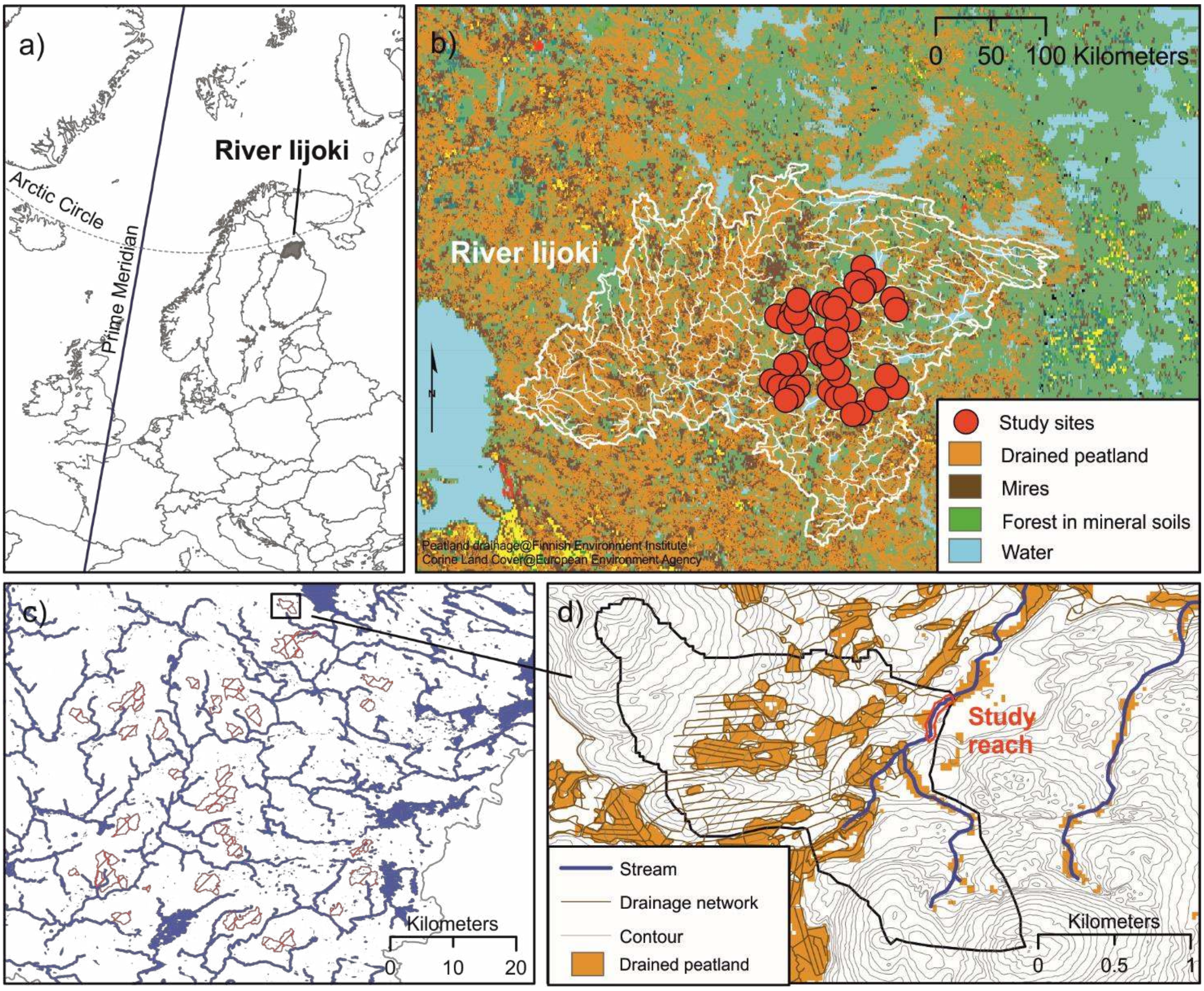

Figure 1. a) Location of the study area in Finland, and of b) study streams and c) catchments in the River Iijoki basin. A representative study reach (the restored stream Vantunlamminoja) is also shown (d).

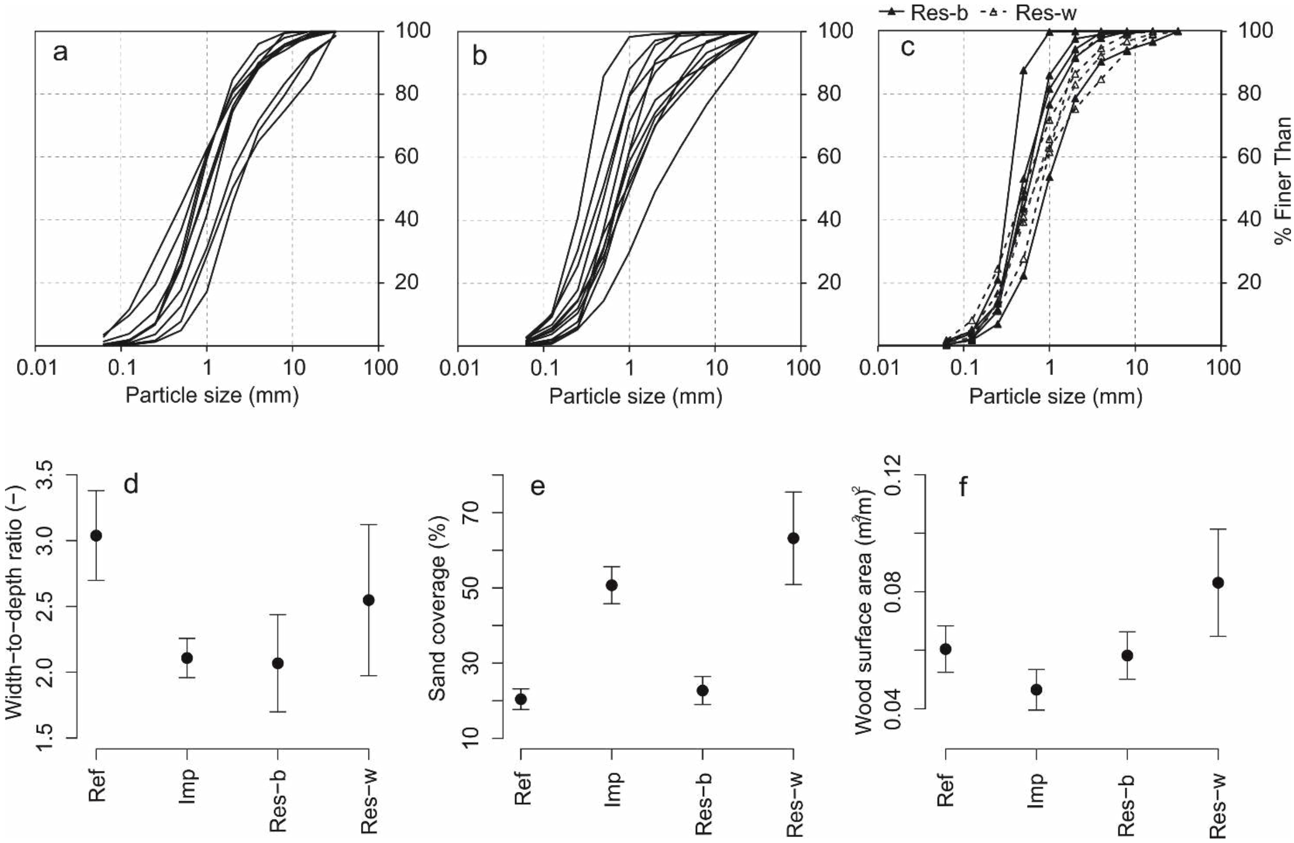

Figure 2. Cumulative particle size distribution of bed sediments in a) reference, b) impacted, and c) boulder-restored (Res-b) and wood-restored (Res-w) streams. Also shown are d) width-to-depth ratio, e) sand coverage and f) wood surface area in each treatment.

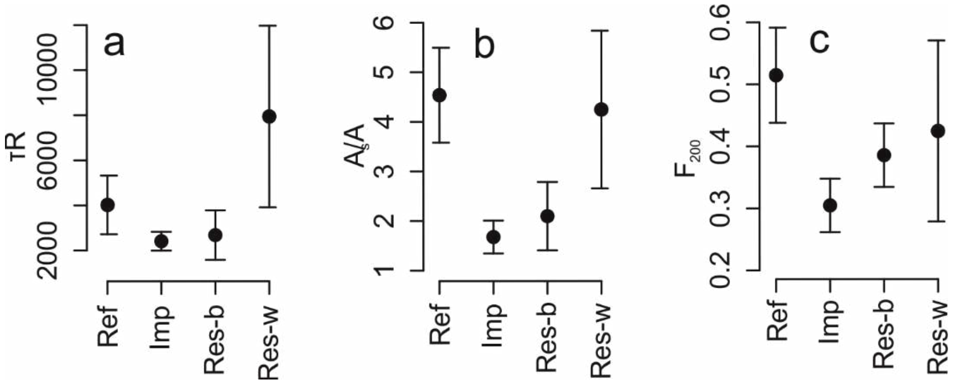

Figure 3. Variation in a) dimensionless residence time (τ_R), b) As/A ratio, and c) fraction of median travel time due to transient storage (F_{200}, standardized to 200 m) in reference (Ref), impacted (Imp), boulder-restored (Res-b), and wood-restored (Res-w) streams.

Table 1. Means and standard deviations of environmental variables for each stream group.

Treatment	Reference	Impacted	Boulder-restored	Wood-restored
Catchment area (km^2)	3.4 ± 1.6	4.5 ± 2.2	3.7 ± 1.9	2.9 ± 1.5
Channel gradient (-)	0.0094 ± 0.01	0.0053 ± 0.005	0.007 ± 0.007	0.01 ± 0.01
Bankfull depth (m)	0.54 ± 0.12	0.65 ± 0.17	0.65 ± 0.17	0.55 ± 0.1
Bankfull width (m)	1.55 ± 0.37	1.35 ± 0.32	1.30 ± 0.45	1.29 ± 0.25
Discharge during test ($L\ s^{-1}$)	0.98 ± 0.22	1.07 ± 0.31	1.16 ± 0.32	0.67 ± 0.19
D ($m^2\ s^{-1}$)	0.25 ± 0.25	0.15 ± 0.11	0.06 ± 0.05	0.03 ± 0.02
α (s^{-1})	$4.1\times10^{-4} \pm 3\times10^{-4}$	$2.8\times10^{-4} \pm 1\times10^{-4}$	$3.7\times10^{-4} \pm 2\times10^{-4}$	$4.9\times10^{-4} \pm 4\times10^{-4}$
Dal (-)	2.82 ± 2.62	1.36 ± 0.59	4.10 ± 5.45	1.25 ± 0.97

D is dispersion coefficient; α is storage zone exchange coefficient; Dal is Damkohler number.