UMEÅ UNIVERSITY

STREAM RESTORATION IMPACTS ON AND POST-RESTORATION ADJUSTMENT OF GEOMORPHOLOGY, GEOMORPHIC COMPLEXITY & HYDRAULICS

Hydromorphological monitoring of ReBorN LIFE Project

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Executive Summary

River restoration is essential to recreate habitats lost as a result of human impacts and maintain river resilience to a warming climate. The ReBorN LIFE project was an ambitious program to restore boreal rivers in northern Sweden impacted by timber floating. As part of the ReBorN project, physical restoration was completed on 243 km of river. Post-restoration monitoring is important to evaluate the success of restoration and guide future restoration. Monitoring of the effects of restoration on river geomorphology (channel form) and hydraulics was undertaken by Umeå University, led by a fluvial geomorphologist, Lina Polvi Sjöberg, PhD. This report outlines the methodological approach, results and conclusions from this work.

Monitoring was conducted at eight sites within the Lögde River catchment chosen to be representative of characteristics across all restored rivers. In order to reduce potential variation among sites, the monitoring was constrained to one catchment. Each site consisted of a river section that was approximately 10 times the original channel width in length. The sites were surveyed on three occasions: before restoration, 1 year post restoration and either 2 or 3 years post restoration. Morphological surveys included mapping of river channel banks, cross-sections, longitudinal profile and instream wood. Hydraulic surveys included measurements of velocity at two depths at each of 10 points along five transects at each site. Furthermore, photographs were taken and expert judgement used to interpret fluvial forms and processes. This report considers changes to channel geomorphology, hydraulics and geomorphic channel complexity as a result of modification during restoration and in the 2-3 years following restoration, providing a preliminary indication of how channels adjust following restoration.

The main results of the study are:

1) Restoration was successful in removing the lateral constraints imposed during timber floating. River width increased at all sites. Only two sites experienced less than the target of 0.126 ha km^{-1} additional channel area and on average the increase was 2 ha km^{-1}.
2) Side channels and islands were reconnected and maintained in the two to three years following restoration. These reconnected side channels increase habitat diversity and likely provide important refugia for fish.
3) Geomorphic complexity typically increased during restoration. However, increases in the variability of channel width were minimal, because width was increased by a similar amount along both banks at many sites. Similarly, lateral variability in the location of the deepest part of the channel (thalweg) decreased with restoration. Future restoration should consider increasing complexity in these dimensions.
4) Hydraulics show high variability between sites and no clear differences in flow velocity or turbulence (i.e., variation in velocity) following restoration.
5) Following restoration, rivers continued to adjust morphologically. Across most sites, there was a net decrease in river width (two sites had net increase in channel width and area). During restoration rivers were widened but there was no reduction in depth, meaning that river capacity was probably oversized. Field observations indicated the formation of an inset bankfull channel; this risks reducing connectivity between the river and the floodplain/riparian areas (contrary to aims of restoration)

by reducing frequency of overbank flooding. We suggest that more sediment should be added to the channel beds to decrease channel depth and thus mitigate this.

6) Following restoration, there was a slight decrease in geomorphic complexity. Banks and longitudinal profiles became smoother and channel sediment settled causing grain interlocking, which is common after a series of low to medium flows.
7) Inter-site variability was high and no large (or statistically significant) differences were found between main channel and tributary sites or sites above or below the former highest coastline.

We conclude that the ReBorN project has been successful in restoring channels towards their pre-disturbance state by increasing width and geomorphic complexity. Longer term monitoring is required to understand whether these rivers will continue to adjust channel design or settle on a new state. This is especially true in northern Sweden where channel geomorphology does not fit responses found in alluvial channels elsewhere. This is possibly the first study to consider the morphological response of rivers to restoration in boreal, post glacial landscapes.

Contents

1. Introduction

Rivers connect the landscape by integrating water, sediment and biota from the surrounding catchment. Rivers and riparian zones contain high biodiversity and provide several ecosystem services for people, including clean drinking water, habitat for species and maintenance of genetic diversity, carbon sequestration, moderation of extreme events and regulation of water flow (United Nations, 2005). However, rivers have been subject to multiple anthropogenic pressures at spatial scales ranging from climate change, catchment land use (Allan, 2004), damming (Nilsson et al., 2005) and direct channel modification (e.g. Gardeström et al., 2013). Because rivers and their floodplains are one of the most impacted ecosystems in the world (Dudgeon et al., 2006), there have been and are numerous ongoing restoration efforts (e.g., Bernhardt et al., 2005; Gardeström et al., 2013; Nilsson et al., 2017a). However, many river restoration projects do not have accompanying monitoring or follow-up, reducing our ability to learn from and improve restoration practices (Nilsson et al. 2015).

Depending on the restoration goals, monitoring can examine several different aspects of river health, including biodiversity, species composition and abundance. Another important aspect of post-restoration monitoring is examining physical characteristics, such as the channel form, hydraulics and geomorphic complexity (Polvi et al., 2014). Typically, anthropogenic impacts have left channels simplified (e.g., straightened and narrowed) and therefore a key restoration goal is to increase geomorphic channel complexity. An increase in channel complexity usually accompanies lowered flow velocities and greater heterogeneity in flow velocity due to increased roughness. In addition to restoring more complex channel forms, restoration often aims to increase channel dynamics and restore natural geomorphic process (Wohl et al., 2015). Because naturally functioning rivers are dynamic systems and erosion is a natural process (Florsheim et al., 2008; Williams et al., 2020), a restored river should ideally show signs of active erosion and deposition and not be locked into a new form, even if the new form has higher geomorphic complexity.

In this report, we present our findings of hydrogeomorphic monitoring of eight river sites in the Lögde River catchment in northern Sweden, which were restored as part of the ReBorN LIFE project. Because a river's potential morphology and degree of dynamism is a factor of several filters, including climate and geology that control hydrology, topography, ecoregions, and past geomorphic processes (e.g., glaciation), we must understand a river's form and process within a catchment-scale and catchment-specific perspective (Polvi et al., 2020). In the next sections we provide background on the geomorphic setting of restored streams in the ReBorN LIFE project in northern Sweden, followed by the history of anthropogenic impacts and finally our project aims and objectives.

1.1 Geomorphic background

Former continental glaciation has left a legacy landscape that strongly affects river form and how rivers respond to restoration. Three aspects of the landscape in northern Sweden reflecting continental glaciation have a direct influence on potential channel morphology; 1) the former highest coastline, 2) abundant deposits of coarse till in the form of moraines, eskers and other glacial landforms, and 3) abundant mainstem glacial lakes. Since deglaciation, there has been ongoing land uplift in response to removal of a large mass of ice (i.e., isostatic rebound), which has caused uplift of up to ca 270 m and ongoing rates of up to 1 cm/yr. Areas above the former highest coastline (FHC) have only been affected by glaciation whilst land below the FHC has been below sea level after glaciation and has also been affected by coastal/deltaic processes. Streams on either side of the FHC therefore exhibit different characteristics; above the FHC, surficial geology is predominantly glacial deposits of coarse sediments (e.g. boulders), whilst below the FHC rivers contain finer deltaic sediments (Polvi, 2021). Rivers above the FHC with coarse sediment (including boulders >1 m) are known as semi-alluvial in that the rivers are not able to transport the boulders and thus their channel form does not reflect the current hydrological regime. These semi-alluvial channels do not exhibit classic relationships between, for example, discharge and channel width or channel slope and median grain size or the type of bedforms (e.g., pool-riffle, step-pool), as is common in alluvial channels (Polvi, 2021). However, channels below the FHC that contain finer sediment should exhibit more tendencies to alluvial patterns and adjustment. Finally, the abundant mainstem lakes in northern Sweden can affect the potential for channel adjustment. Mainstem lakes buffer high flows and can trap fine sediment, thus limiting the potential for high flows to transport coarse sediment.

1.2 History of anthropogenic impacts and restoration

Virtually all rivers in northern Sweden have experienced a long history of modification during the timber-floating era (mid 1800s to ~1970s). In order to facilitate timber transport and allow logs to float more easily downstream, rivers had much of their geomorphic complexity removed. This was accomplished using manual methods, dynamite and clearing using bulldozers through straightening, channelization, closing off side channels, and removal of boulders and instream wood (Törnlund and Östlund, 2002; Nilsson et al., 2005). This anthropogenic impact directly affected rivers, resulting in narrower, channels with higher flow velocities and lower geomorphic complexity (Gardeström et al., 2013; Polvi et al., 2014). Higher flow velocities are problematic for fish as they cannot rest, and lower geomorphic complexity translates to fewer habitat types and thus lower biodiversity.

River restoration is important to increase biodiversity, providing habitat for multiple species (including salmonids) and to make rivers more resilient to future climate change, by providing areas for overbank flooding, a larger species pool that is more robust against disturbances, and ecosystem services for society. Restoration of timber-floated channels has been ongoing in northern Sweden since the 1980s and 1990s but really gained traction in the 2010s as evidenced by several large EU LIFE projects (e.g., Vindel River LIFE). Although millions of Euro have gone towards on-the-ground physical restoration and dam removal, much less has been invested in monitoring the results. The monitoring which has been conducted often in parallel research projects by universities (Umeå University and the Swedish University of Agricultural Sciences), and most of the monitoring has focused on various types of biota (e.g., fish, benthic macroinvertebrates, riparian vegetation) and not on geomorphic forms and processes.

1.3 Geomorphic complexity & temporal change

Geomorphic complexity is a measure of the variation in geomorphic form and can thus be used as a proxy for habitat heterogeneity. Complexity can be considered across multiple scales and dimensions. On a reach scale (lengths of river approximately 10 times the channel width), the main physical complexity dimensions include the planform, cross-section, longitudinal profile, instream large wood/boulders, sediment distribution and hydraulics (Polvi et al., 2014; Wohl 2016). For example, to describe a channel geomorphically, one can measure the average channel width, but to describe the geomorphic complexity, one would report the variation in the channel width (e.g., coefficient of variation of the width). A goal of stream restoration is often to increase biodiversity by increasing habitat heterogeneity. Although biota respond to habitat heterogeneity at different spatial scales (e.g., migrating fish respond to heterogeneity at much larger scales than benthic macroinvertebrates), quantification of geomorphic complexity across several dimensions will provide an appropriate overview of habitat heterogeneity for multiple organism types. It is important to not only focus on one metric or dimension of complexity (e.g., variation in width or instream wood), as different organism groups respond to different complexity dimensions or metrics (Hasselquist et al., 2018)

Most monitoring of restoration and restoration design principles have been developed for alluvial rivers that can adjust their beds and banks (e.g., Belletti et al., 2018; Williams et al. 2020). Very little research has been conducted on restoration of rivers flowing over sediments deposited by previous continental glaciation, despite these covering a substantial proportion of Sweden, Fennoscandia and even most high latitudes throughout the northern hemisphere (Hauer & Pulg 2018; Polvi, 2021). Alluvial streams are dynamic, modifying their bed and bank configurations to changes in inputs to achieve a channel form in dynamic equilibrium. However, studies on semi-alluvial channels suggest that these channels may not reach a dynamic equilibrium based on the current flow and sediment regime (Hauer & Pulg 2018; Polvi, 2021). Therefore, it may be more difficult to predict adjustment of semi-alluvial channels to restoration.

1.4 Assignment to Umeå University

Umeå University was assigned to assess the geomorphic and hydraulic response of rivers restored as part of the ReBorN LIFE project Restoration of Boreal Nordic Rivers. LIFE15 NAT/SE/000892. In order to monitor the impact of all the concrete conservation actions (C.1–C.4) on geomorphology and hydraulics, Umeå University had the task to measure channel morphology and velocity before restoration and 1- and 3-years post-restoration. The specific aims and scientific questions addressed are listed below.

1.5 Aims & scientific questions

We aimed to determine how river restoration influences the channel hydromorphology and complexity, both during and after restoration. Specifically, we addressed four research questions:

(1) What is the immediate effect of river restoration on channel hydromorphology and complexity? To address this question, we surveyed channel morphology, measured flow velocities and calculated geomorphic complexity before restoration (same summer or 1-year before) and 1 year after restoration.

(2) What is the long-term effect of river restoration on channel morphology and complexity? Do channels adjust hydromorphologically following restoration? To address this question, we surveyed channel morphology, measured flow velocities and calculated

geomorphic complexity two or three years post-restoration and compared with values from 1-year post-restoration.

(3) Does the degree of change (during and post restoration) differ between sites situated on mainstem versus tributary channels? To address this question, we compared results from all three survey years between four sites on the mainstem of a large river (Lögde River) and four sites on tributaries of the Lögde River.

(4) Does the degree of change (during and post restoration) differ between sites located in geologically distinct areas above and below the former highest coastline. To address this question, we compared results from all three survey years between four sites located above the FHC and four sites located below the FHC.

2. Methods

Monitoring of restoration was conducted for eight sites within the Lögde River catchment (Figure 1). In order to reduce potential variation among sites, the monitoring was constrained to one catchment. However, the Lögde River is also deemed to be representative of the other catchments restored as part of the ReBorN project; therefore monitoring of these eight sites should be representative of other in-channel restoration conducted within the project. Sites were equally divided between the mainstem and its tributaries and above and below the former highest coastline (FHC), resulting in two sites for each category (Table 1). Sampled sites including a large range in channel size; average width before restoration ranged from 7 m to 59 m. Due to all sites being located in the same catchment, mainstem sites below the FHC were substantially larger river channels than all other sites (LMB1 = 59 & LMB2 = 48 m pre restoration) including both tributaries and mainstem sites further upstream (mean 8.5 m width of 6 other sites). Channel slope varied from 0.5 to 2.2%.

Sites were surveyed before and after restoration (Table 1). Prior to restoration (Pre survey), sites were either surveyed the year before or the same summer as restoration, due to uncertainty as to when restoration would take place. Following restoration, sites were surveyed one year (Post-A) and either two or three years after restoration (Post-B). Because restoration occurred later than originally planned at two sites, restoration follow-up had to be surveyed after only two years in order to complete the project by the deadline.

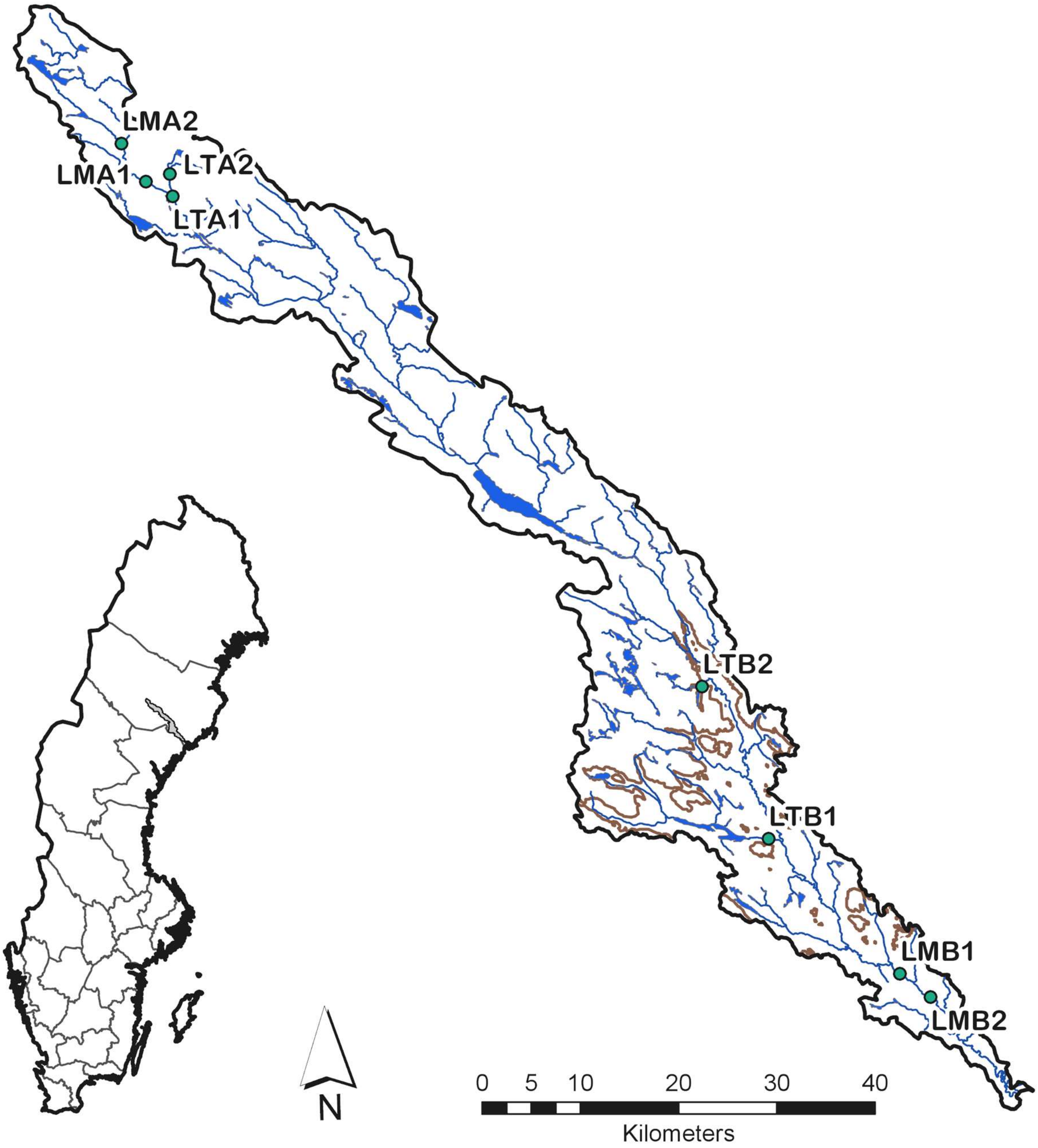

Figure 1. Location map of eight monitoring sites within the Lögde River catchment with streams and lakes shown. Brown lines/polygon show boundary of former highest-coastline. Map of Sweden shows counties and grey polygon shows location of the Lögde River catchment in Västerbotten County. Site acronyms (e.g., LMA1) are defined in Table 1.

Table 1. Details of the eight monitored sites. Sites were located on the mainstem Lögde River or a tributary and distributed above or below the former highest coastline (FHC). Sites were surveyed at three occasions; pre-restoration, approximately 1 year post restoration (Post-A) and either two or three years post restoration (Post-B, year interval shown in brackets).

Site	Site name (location)	Mainstem or Tributary?	FHC	Pre survey date	Restoration completed	Post survey date	
						Post-A	Post-B
LMA1	Lögdån (Sandsjö Tallåsen ovan Storbäcken)	Main	Above	2017	2018	2019	2021(3)
LMA2	Lögdån (above LMA1)	Main	Above	2018	2018	2019	2021(3)
LTA1	Storbäcken nedre	Tributary	Above	2017	2018	2019	2021(3)
LTA2	Storbäcken övre	Tributary	Above	2018	2019	2020	2021(2)
LMB1	Lögdeälven uppströms Rundbäcken (nära Höglund/Högåker)	Main	Below	2017	2017	2018	2020(3)
LMB2	Lögdeälven nedströms Klösforsen	Main	Below	2018	2019	2020	2021(2)
LTB1	Mjösjöån	Tributary	Below	2017	2018	2019	2021(3)
LTB2	Blåbergsjöån	Tributary	Below	2018	2018	2019	2021(3)

2.1 Field Methods

The length of each river site surveyed was ten times the channel width before restoration. Channel geometry was surveyed with a real time kinematic (RTK) GPS or a total station (TS). For channels surveyed with a TS, we placed out ground control points (metal spikes) to be able to return and re-survey the same site and compare data between years. Channel banks were surveyed at bankfull (top of the banks) so as to be independent of water discharge, which may vary between surveys. The longitudinal profile was measured along the thalweg (deepest part of the channel). The thalweg was not surveyed for LMB1 and LMB2 due to high water levels restricting access. The morphology of five cross-sections at each site were measured using either the RTK-GPS, TS or an acoustic Doppler current profiler (ADCP) boat (Figure 2). The ADCP was pulled across the channel using a small raft, and measured the channel bed topography and velocities in a vertical profile along the entire transect. Because the ADCP can only be used when the depth is at least ~30 cm across the entire transect, it was only used at the two largest sites (LMB1 & LMB2) before restoration and at one of the sites 1 year post-restoration. At each cross-section, depth relative to bankfull and flow velocity were measured. Velocity was measured at 10 points across five cross-sections at 20 and 80% of the water depth, either using an electromagnetic flow meter or obtained from ADCP vertical velocity profiles (Figure 2). At the velocity measurement locations, three measurements were taken for 10 seconds each. The location, length and diameter of instream wood that exceeded 1 m in length and 0.1 m in average diameter were also measured with the RTK-GPS or TS.

Figure 2. Field photos of methods: (a) & (b): Total station and pole with prism used to take points (both photos from site LTA2 in 2018); (c) ADCP setup used in LMB2 in 2018; (d) velocity measurements using an electromagnetic flowmeter in a side channel in LMB1 2020; (e) RTK-GPS used to take points of channel bankfull edge and cross-sections in larger reachers (LMB2 in 2021).

2.2 Analysis methods

We considered change in general channel characteristics (Table 2) and complexity parameters (Table 3) during two time intervals; (1) *during restoration* by comparing the *Pre* and *Post-A* surveys and (2) *post restoration* by comparing Post-A and Post-B surveys, to understand whether river channels adjust hydromorphically following restoration.

River planform maps were analyzed in ArcGIS Pro. The same length of channel was considered during each survey interval. Islands were subtracted from the channel area to give the planform channel area, A_p. A centerline for the pre-restoration channel was calculated and smoothed over 10m. Twenty transects spaced evenly along the smoothed thalweg were used to measure mean channel width W_p and complexity metrics (Table 3). Comparison of channel planforms facilitated measurement and mapping of areas with new channel area (A_n) and channel area lost (A_l) during and post restoration. A_n is a measure of the total sum of new channel area and does not consider any channel lost in the same interval (and vice versa, A_l); thus A_n and A_l provide separate information and together account for changes in A_p.

Cross-sections were considered relative to the bankfull elevation; the capacity of the channel. Cross-section area (A_{xs}) and the max depth (D_max) were calculated and averaged over the five cross-sections. For LMB1 and LMB2, pre-restoration channel morphology was measured with the ADCP boat; ADCP cross-sections were first interpolated at 2 m and 1.3 m intervals, respectively (matching average spacing of points in RTK surveys for each site). The water depths were then converted to bankfull depths and combined with RTK surveys of the channel between the water surface and bankfull perimeter.

2.2.1 Hydraulics

Where velocity profiles were collected using the ADCP, point values in locations equivalent to those collected by the flow meter were extracted to enable comparison. Therefore, for 10 evenly spaced locations across the five cross-sections, water velocity was measured at 20 and 80% of depth. At each point location, within each cross-section the mean of the 20 and 80% velocity measurements was calculated to give depth averaged velocity (U_{da}). The mean and standard deviation of *da* at each cross-section (across the ten measurement points) were calculated and subsequently averaged across the five cross-sections to give U_{da}_M, U_{da}_SD and U_{da}_CV (Table 2).

2.2.2 Instream wood

For each wood piece, wood length was calculated according to Equation 1, where x, y and z are the coordinates of each end of the wood piece.

$$L = \sqrt{(x_1 - x_0)^2 \ + (y_1 - y_0)^2 + (z_1 - z_0)^2} \qquad 1$$

In the few cases where only one end of the wood was measured, wood length was recorded as the reach average, and if wood diameter was not recorded, this was also taken as the average. Subsequently, the volume of each wood piece was approximated according to the volume of a cylinder with a length *L* and diameter measured in the field.

Wood pieces were filtered such that each piece protruded into the bankfull channel by at least 0.5 m and were at least 1 m in length and 0.1 m in width. The total volume of wood within the channel Vol_{wd} as well as the density $Dens_{wd}$ were compared between years.

Wood distributions were also analysed in ArcGIS Pro. To calculate clustering of wood ($Clust_{wd}$), clusters were classed as groups of more than three logs within a 1 m buffer of each other (to allow for potential un-measured side branches and measurement error). Although individual pieces of wood were not tracked between survey intervals, wood mobility was approximated by overlaying successive wood surveys and calculating the proportion of overlap (by area), giving the wood retention index RI_{wd}.

Table 2. General characteristics of river hydromorphology

Category	Metrics	Notation	Units	Description
Planform morphology	Average planform width	W_p	m	Mean width across 20 evenly spaced transects
	Planform area	A_p	m^2	Horizontal area of channel contained within banks and upper and lower survey limits
	Area of new channel	A_n	m^2	Area of new channel created since previous survey
	Area of channel lost	A_l	m^2	Area of channel lost since previous survey
Cross section morphology	Average cross section area	A_{xs}	m^2	Mean vertical area of channel between banks (channel capacity)
	Average max depth	D_max	m	Maximum depth within cross section
Hydraulics	Average velocity	U_{da}_M	m s^{-1}	Velocity was first depth averaged by taking the mean of 0.2 and 0.8 m velocity measurements at each location. The Mean of this was then calculated for each site.
	Velocity SD	U_{da}_SD	m s^{-1}	Standard deviation (population) of depth averaged velocity measurements
	Velocity CV	U_{da}_CV	-	Coefficient of depth averaged velocity
Instream wood	Total wood volume	Vol_{wd}	m^3	Sum of volume of all wood.
	Wood density	$Dens_{wd}$	# m^{-2}	Pieces of wood per m^2 of channel.
	Number of wood clusters	$Clust_{wd}$	#	Count of groups of wood with more than 3 pieces within 1m of another piece.
	Wood retention index	RI_{wd}	%	Percentage of wood area in survey interval postA that is overlaid by wood in survey interval postB

2.2.3 Complexity characteristics

We also quantified the geomorphic complexity at each site for each year. Geomorphic complexity is calculated as the variation around the mean values of each metric. Complexity measures and their calculations are shown in Table 3 (following Polvi et al., 2014).

For the planform analysis we considered the width standard deviation (W_p_sd), width coefficient of variance (W_p_cv), width residuals (W_p_res) and average width concavity (*AWC*) of transects. We also calculated the multithread index (*MTI*) and ratio of bank length to channel length (*Bratio*). For the cross-sections, we considered the chain and tape metric (CT_{xs}) and the coefficient of variation in depth (DCV_{xs})

Several metrics were also calculated to consider complexity of the longitudinal profile or thalweg. Sinuosity (P_{th}) provides a measure of lateral complexity of the thalweg, whilst six other metrics provide estimates of the vertical complexity of the thalweg relative to a straight line: R^2_{th}, sum of squared errors (SSE_{th}), mean squared error (MSE_{th}), thalweg SD (SD_{th}), thalweg roughness ($rough_{th}$) and thalweg concavity (ATC).

Table 3. Complexity characteristics calculated for each site

	Metrics	Notation	Equation	Units	Description
Planform complexity	Width SD	W_p_sd	-	m	Standard deviation (population) in channel width across 20 evenly spaced transects
	Width CV	W_p_cv	W_sd/Wp	.	Coefficient of variation of 20 width transects
	Width residual	W_p_res	$\frac{\sum_{i=1}^{n}(\lvert w_i - \pi \rvert lp)}{w}$	.	Sum of deviations in width multiplied by their proportion of influence and scaled by mean width
	Average width concavity	W_p_awc	$\sum_{i=1}^{n}\left(\left\lvert\frac{\mathrm{d}^2 w}{\mathrm{d}x_i^2}\right\rvert lp\right)$	.	Proportionally weighted concavities at successive points along the width profile
	Bank length ratio	Bratio	$\frac{Lt}{Lr}$	.	Ratio of total bank length to reach length (along smoothed thalweg)
	Multithread index	MTI	-	.	Mean number of channels along 20 evenly spaced transects
Cross section complexity	Chain & tape	CT_{xs}	$\frac{Lt}{Ls}$		Ratio of topographic distance to straight line distance across cross section
	Depth CV	DCV_{xs}	D_sd/D_M		Coefficient of variation of depths across cross section
Long profile complexity	Thalweg sinuosity	P_{th}	$\frac{Lth}{Lr}$	-	Ratio of distance following thalweg to straight line distance
	Thalweg R-square	R^2_{th}	-	-	Goodness of fit of linear regression to longitudinal thalweg profile elevation values
	Thalweg SSE	SSE_{th}	-	-	Sum of squared errors between measured and predicted elevation values from linear regression
	Thalweg MSE	MSE_{th}	-	-	Mean squared error between measured and predicted elevation values from linear regression
	Thalweg SD	SD_{th}	$\sqrt{1/N\sum_{i=1}^{n}(z_i - 2_{min})^2}$	m	Standard deviation of thalweg elevations relative to highest point in the profile after detrending
	Thalweg roughness	$Rough_{th}$	$\sum_{i=1}^{n} = \lvert Z_{obs\_i} - Z_{pred\_i}\rvert lp$	-	Proportionally weighted deviations from predicted values
	Average thalweg concavity	ATC	$\sum_{i=1}^{n}\left(\left\lvert\frac{\mathrm{d}^2 Zi}{\mathrm{d}x_i^2}\right\rvert lp\right)$	-	Proportionally weighted concavities between successive points along the thalweg profile

2.2.4 Statistical analyses

For all variables, change between survey intervals was calculated by subtracting the later interval from the earlier, notated by Δ. For metrics of cross-section area, max depth, mean river width, planform area, area of new channel and area of channel lost, we calculated Δ as a percentage change from the earlier survey interval. Statistical analysis was conducted in R (version 4.1.0; R Core Team, 2021). To understand if, across all sites, a statistically significant change in river geometry and complexity has occurred during restoration (Question 1) and following restoration (Question 2) we used Wilcoxon signed rank tests as many variables exhibited non-normal distributions (Shapiro-Wilk test). These tests compared channel change to a null of 0 (no change to channel characteristics). Due to the sampling effort required to get data from each river we had to limit ourselves to eight sites. We therefore have four replicates of sites for questions 3 and 4 which, in conjunction with the high variability between sites, make significance testing of these questions challenging. For questions 3 and 4 we use paired Wilcoxon signed rank tests to ascertain if a significant difference exists between change occurring above and below the FHC (Question 3) and in mainstem and tributaries (Question 4). However, no differences were sufficiently large or consistent to result in statistical significance. Nevertheless, as field monitoring studies which consider more than a few sites are rare, these results are interesting regardless of statistics.

3. Results

3.1 Modifications during restoration

During restoration, river morphology changed substantially at all sites (See Appendix 1 for maps of planform change). As a result of restoration, river channels became wider (Figure 3; Table 4). This was also reflected in increases in the total planform area with new areas of channel gained (Figure 3). This resulted in an additional 0.07 - 10.81 ha km^{-1} of river area, with just two sites below the target of 0.126 ha km^{-1} (LTA2 and LTB2). The average gain in river area was 2.18 ha km^{-1} but this was heavily skewed by the two larger sites, below the FHC on the mainstem Lögde River (LMB1 = 10.81 and LMB2 = 5.00 ha km^{-1}). The other sites were more similar in width and had an average increase of 0.27 ha km^{-1}.

The extent of modification varied considerably between channels; from doubling the channel planform area (96% planform area increase; LMA1; Figure A1.1.; Figures 3 & 4) to an 8% increase (LMB2; Figure A1.4). However, even at LMB2 two side channels were opened up, resulting in a more complex planform. The pattern of widening also varied between sites, some were widened by similar amounts from both banks continuously along the surveyed reach (e.g. LMA1 and LTA1 Figure A1.1 and A1.5), whilst others were widened only slightly and gained more channel area through reconnection of side channels (e.g. LMB1, Figure A1.3) or were widened in specific locations (e.g. LTB1; Figure A1.7).

Channel planform became morphologically more complex with restoration. The number of channels at each surveyed site (MTI index) increased (Figure 5). There were also increases in bank complexity (bank length ratio; Figure 5). Furthermore, width SD increased although after controlling for the mean channel width (Width CV) there was no change in complexity of channel widths (Figure 5).

Rivers were widened during restoration but depth did not decrease resulting in an increase in the cross-sectional area of the channels (with one exception; LMB2; Figure 6i). In fact, the maximum depth increased on average (Figure 6ii). Chain and tape index indicates that there was little increase in the complexity of river bed morphology with restoration, half of the sites experienced a reduction of CTxs during restoration (Figure 6iv).

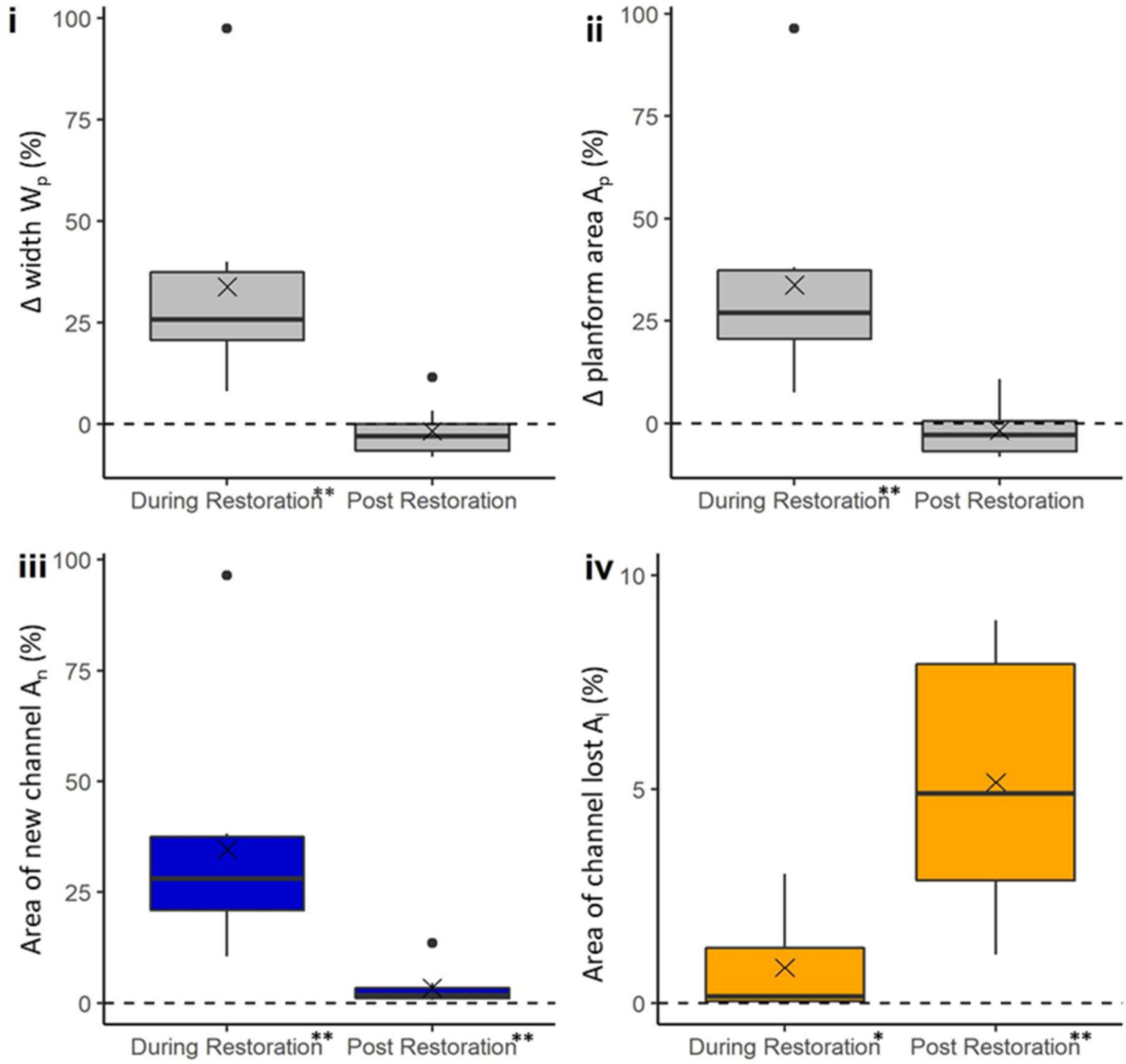

*Figure 3. Changes to channel planform during and after restoration. For all boxplots, boxes show the median and interquartile range, whiskers show the range excluding outliers (points) and the mean is indicated by ×. Significance is indicated by ´ 0.1>p>0.05; * 0.05>p>0.01; ** 0.01>p>0.001. During restoration, mean river width increased substantially (i) resulting in rivers with a larger channel area (ii). The area of newly excavated channel averaged 881 m² per site (iii), a small amount of channel area was filled in during restoration (iv). On average, channels decreased in width and planform area post restoration, as area of channel lost exceeded new channel.*

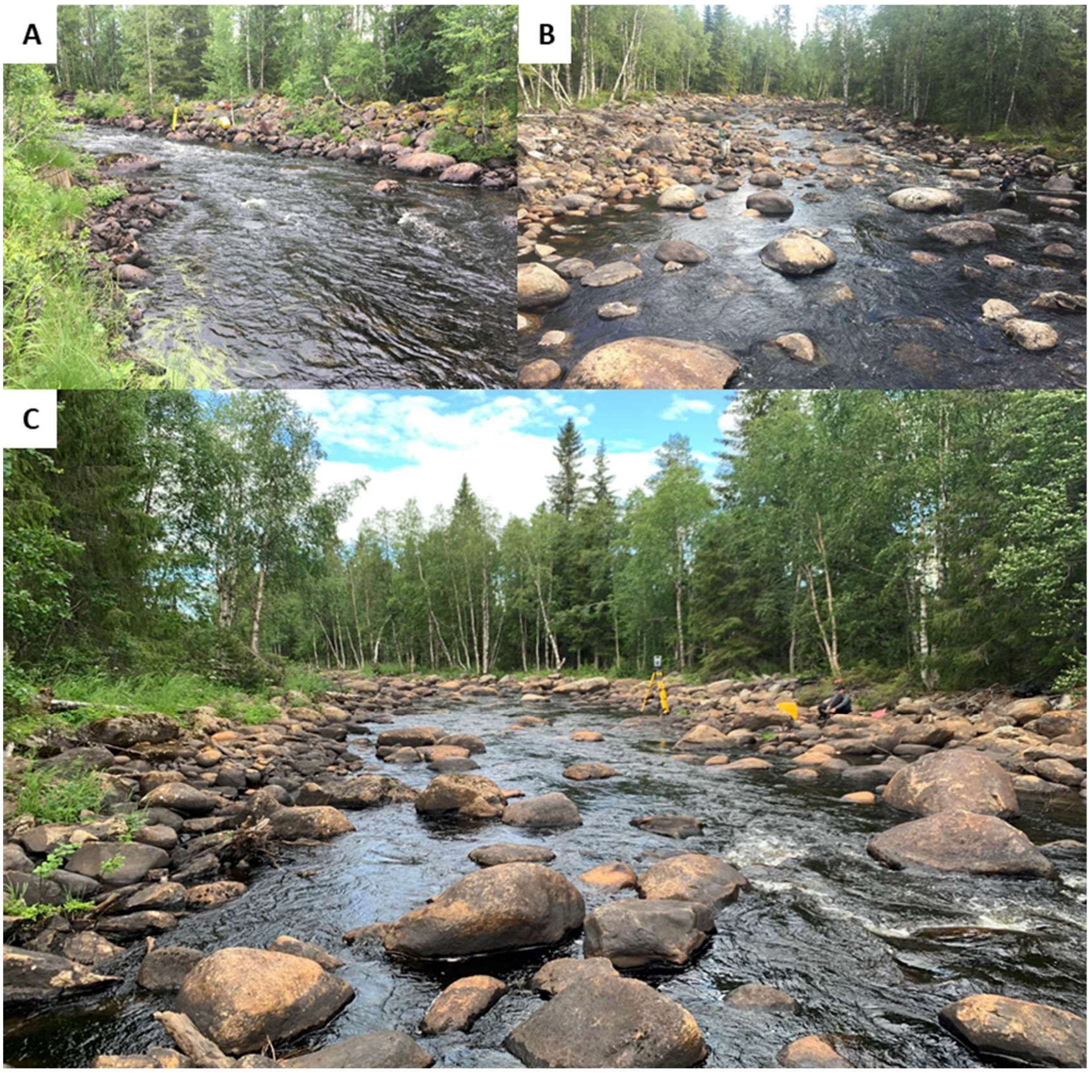

Figure 4. LMA1 in each survey year. (A) Prior to restoration LMA1 was artificially narrowed and constrained by boulder levees. (B) following restoration (Post-A) these levees were removed and the channel width doubled (increase of 97% over Pre). (C) River width was maintained over the next 3 years (Post-B). At this site, therefore, restoration doubled the area of river habitat per unit river length.

Significant changes to thalweg complexity were captured by the sinuosity, R^2, MSE, SSE and roughness (Table 4; Figure 7). Sinuosity was the only metric to indicate a reduction in thalweg complexity with restoration. The increase in thalweg SSE and MSE and decrease in thalweg R^2 also indicates an increase in complexity (larger R^2 values indicate lower complexity). Thus whilst lateral variability in the thalweg reduced, vertical complexity increased with restoration.

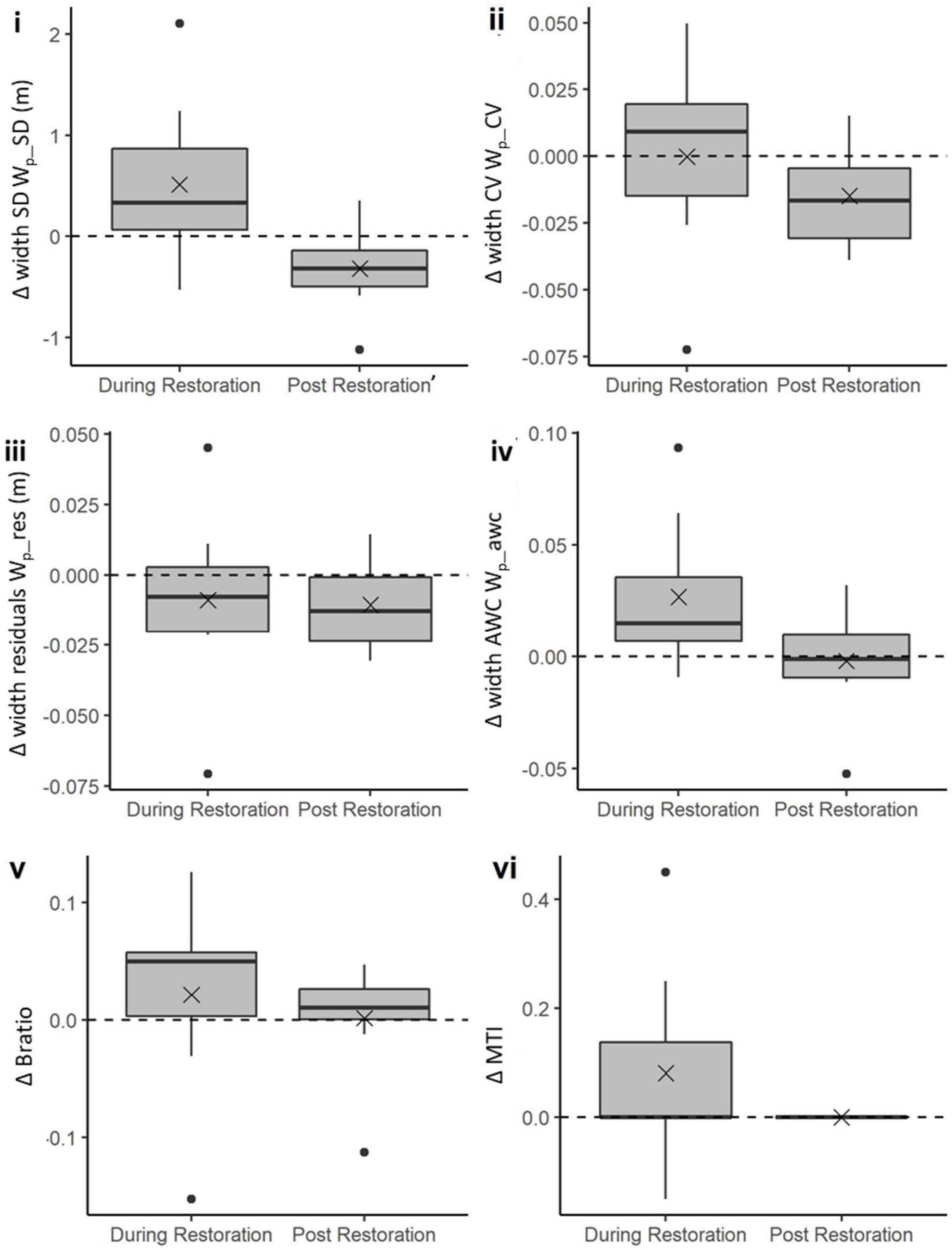

Figure 5. Changes to channel planform complexity during and after restoration.

*Table 4. Change in (i) general characteristics and (ii) complexity characteristics during and post restoration across all surveyed rivers. Values reported are means with SD (population) in brackets. Significance according to a Wilcoxon signed rank test is indicated by ´ 0.1>p>0.05; * 0.05>p>0.01; ** 0.01>p>0.001. Shading indicates whether a positive (salmon) or negative (blue) change occurred. For each metric, the period of change (during or post restoration) which experienced the greatest change has a darker shade. $^+$Thalweg statistics do not include sites LMB1 and LMB2.*

(i) General characteristics

	During Restoration	Post Restoration
Average planform width (%)	34 (26)**	-2 (6)
Planform Area (%)	34 (26)**	-2 (6)
Area of new channel (%)	35 (25)**	3 (4)**
Area of channel lost (%)	1 (1)*	5 (3)**
Average cross section area (%)	43 (58)	-4 (16)
Average max depth (%)	0.13 (0.21)	-0.01 (0.14)
Mean DA velocity (m s^{-1})	-0.04 (0.19)	-0.04 (0.05)´
SD DA velocity (m s^{-1})	0.02 (0.04)	-0.01 (0.03)
CV DA velocity	0.01 (0.23)	0.04 (0.10)
Total wood volume (m^3)	5.10 (6.76)**	-0.44 (0.53)
Wood density (# m^{-2})	0.02 (0.05)*	0.00 (0.01)
Number of wood clusters (# 100 m^{-1})	4.00 (6.36)	0.25 (0.97)

(ii) Complexity characteristics

	During Restoration	Post Restoration
Width SD (m)	0.51 (0.80)	-0.32 (0.42)´
Width CV	0.00 (0.03)	-0.01 (0.02)
Width residual (m)	-0.01 (0.03)	-0.01 (0.02)
Average width concavity	0.03 (0.03)	0.00 (0.02)
Bank length ratio	0.02 (0.08)	0.00 (0.05)
Multithread index	0.08 (0.17)	0.00 (0.00)
Cross section chain & tape	0.03 (0.08)	0.06 (0.16)
Cross section depth CV	0.04 (0.10)	0.03 (0.05)
Thalweg sinuosity$^+$	-0.04 (0.02)*	0.00 (0.02)
Thalweg R-square$^+$	-0.15 (0.18)´	0.06 (0.06)´
Thalweg SSE$^+$	0.66 (0.52)´	-0.30 (0.34)
Thalweg MSE$^+$	0.01 (0.01)´	0.00 (0.01)
Thalweg SD$^+$	0.09 (0.12)	-0.02 (0.04)
Thalweg roughness$^+$	0.03 (0.02)´	-0.01 (0.02)
Average thalweg concavity$^+$	0.01 (0.03)	-0.02 (0.02)´

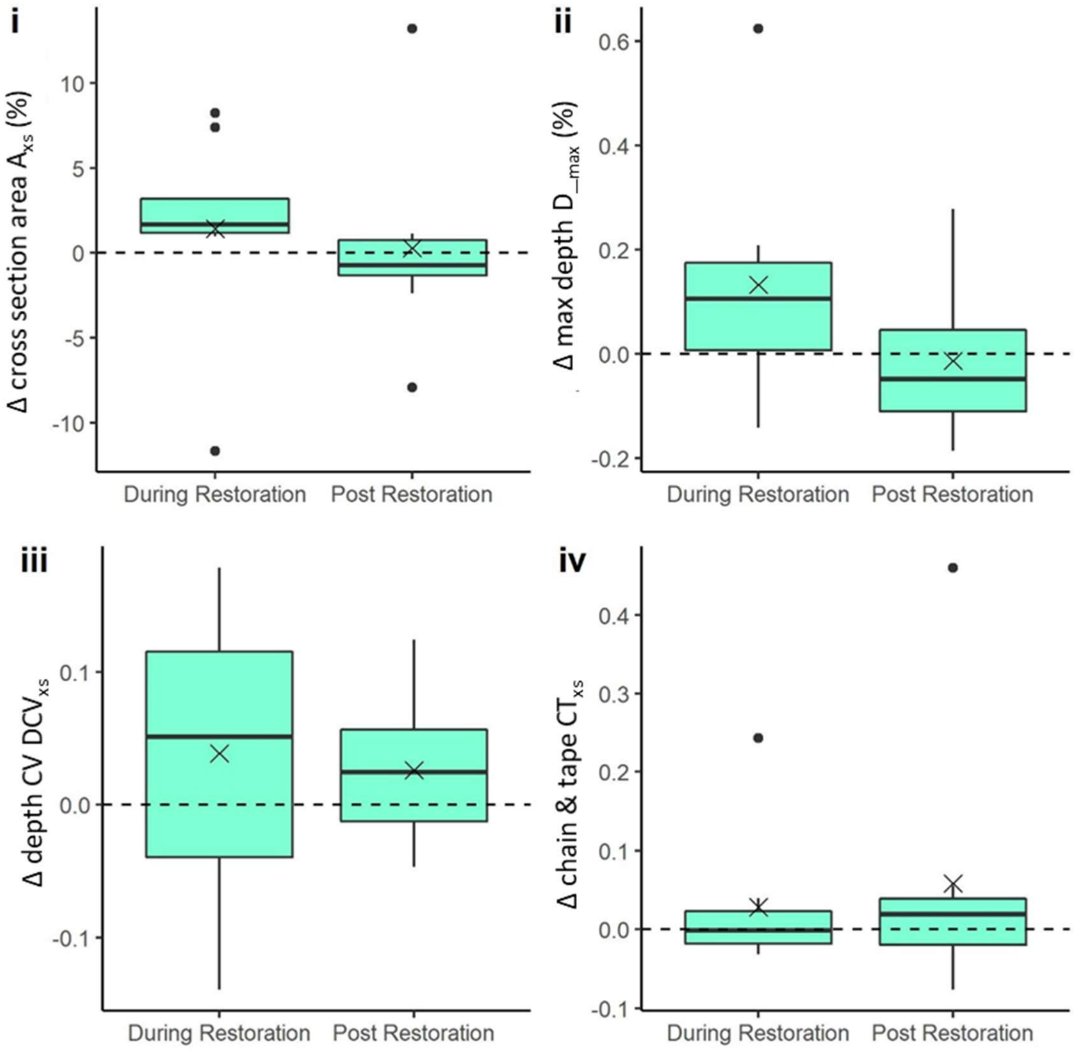

Figure 6. Changes to channel cross-section morphology and complexity during and after restoration. Typically, cross-sectional area increased during restoration (only LMB2 decreased). Max depth also increased as a result of excavation. On average, little change occurred to cross-section area and max depth post restoration but there were some large changes to cross-sectional area.

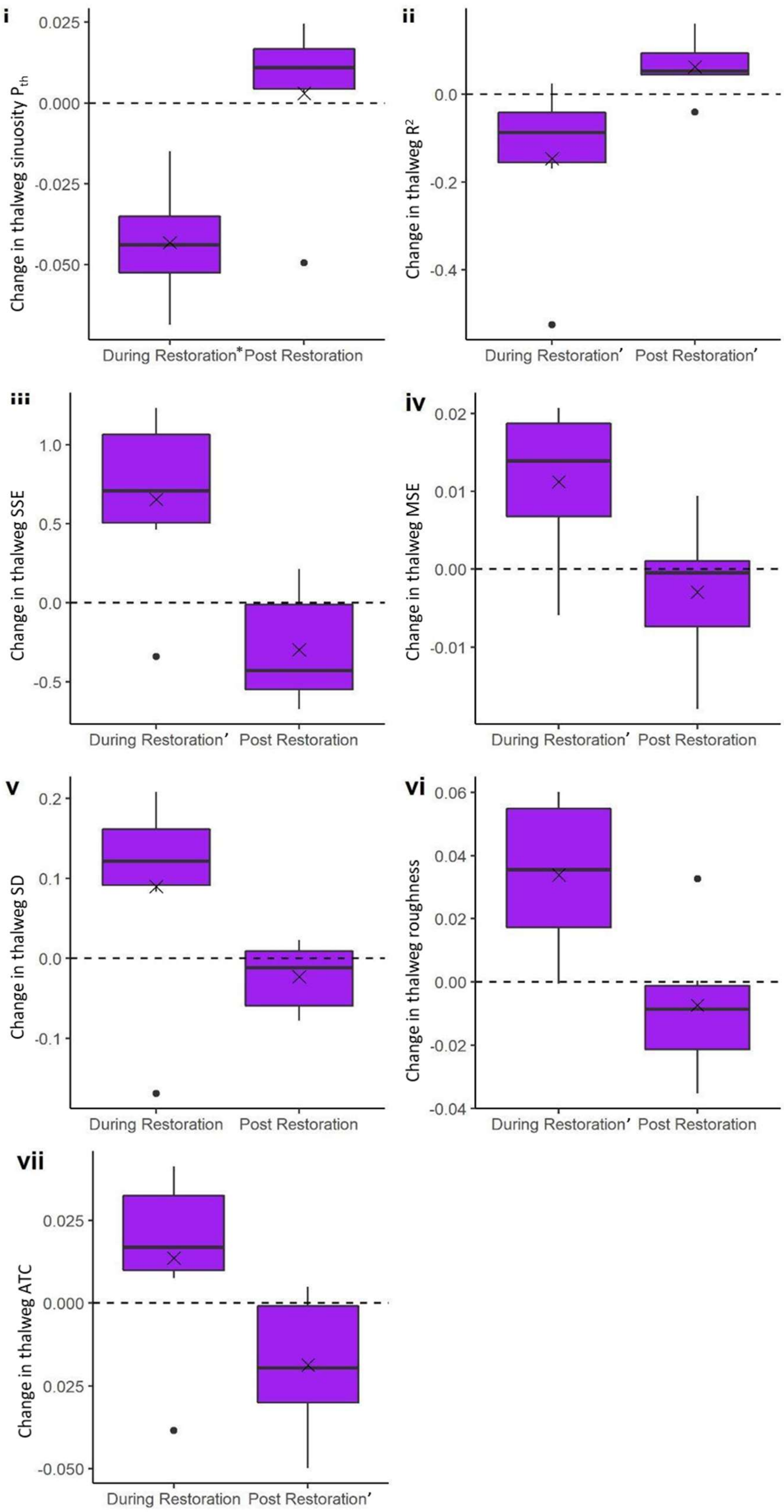

Figure 7. Changes to longitudinal profile (thalweg) complexity during and after restoration. Note that longitudinal profile data was not collected at LMB1 and LMB2.

Very few significant changes in hydraulics were found during restoration. During restoration, there was a slight decrease in the mean velocity and an increase in the standard deviation of velocity. Typically, SD of velocity is expected to increase alongside mean velocity and therefore the increase in SD suggests that restoration resulted in more complex flow patterns (Figure 8); however this was not evident in velocity CV, which should be a more accurate reflection of variation in flow regardless of mean velocity. The change in mean velocity showed very large variation, so there are large local differences in how much the mean velocity, velocity SD and CV changed.

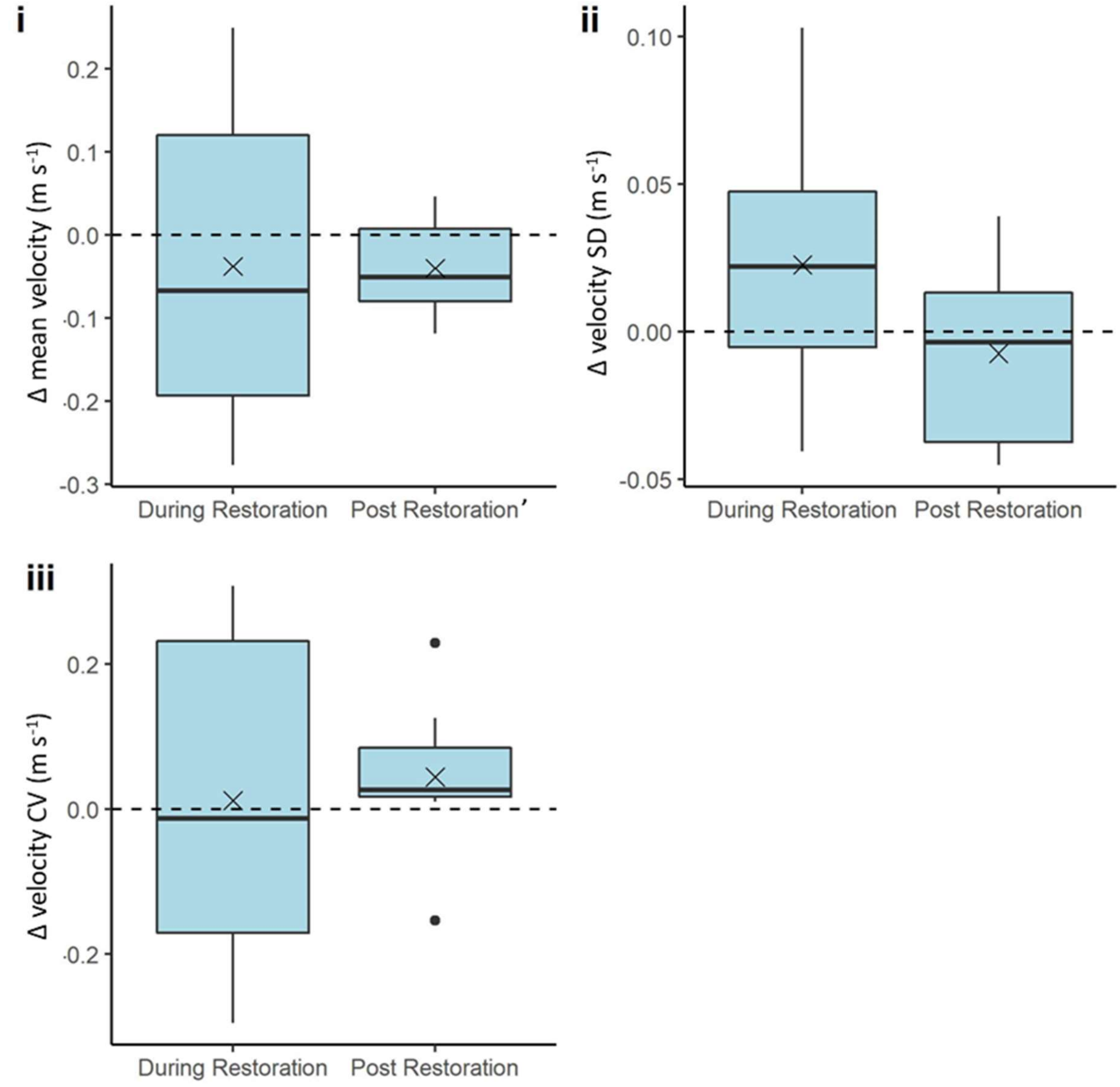

Figure 8. Changes to channel hydraulics during and after restoration. During restoration changes were variable between sites with a marginal average decrease in mean velocity (i) accompanied by a slight increase in standard deviation (ii) but no change in CV (iii). Following restoration, there was little change in velocity parameters.

During restoration, large wood was added to most sites. On average this was 48 pieces (equivalent to an extra 2.4 pieces per 10 m^2) but varied considerably between sites and one site had a net loss of 2 pieces. The maximum additional wood was added to LMB1, with 162 pieces or 19 m^3 volume (Figure 9). The increase in the number of wood clusters during restoration follows the increase in the amount of wood.

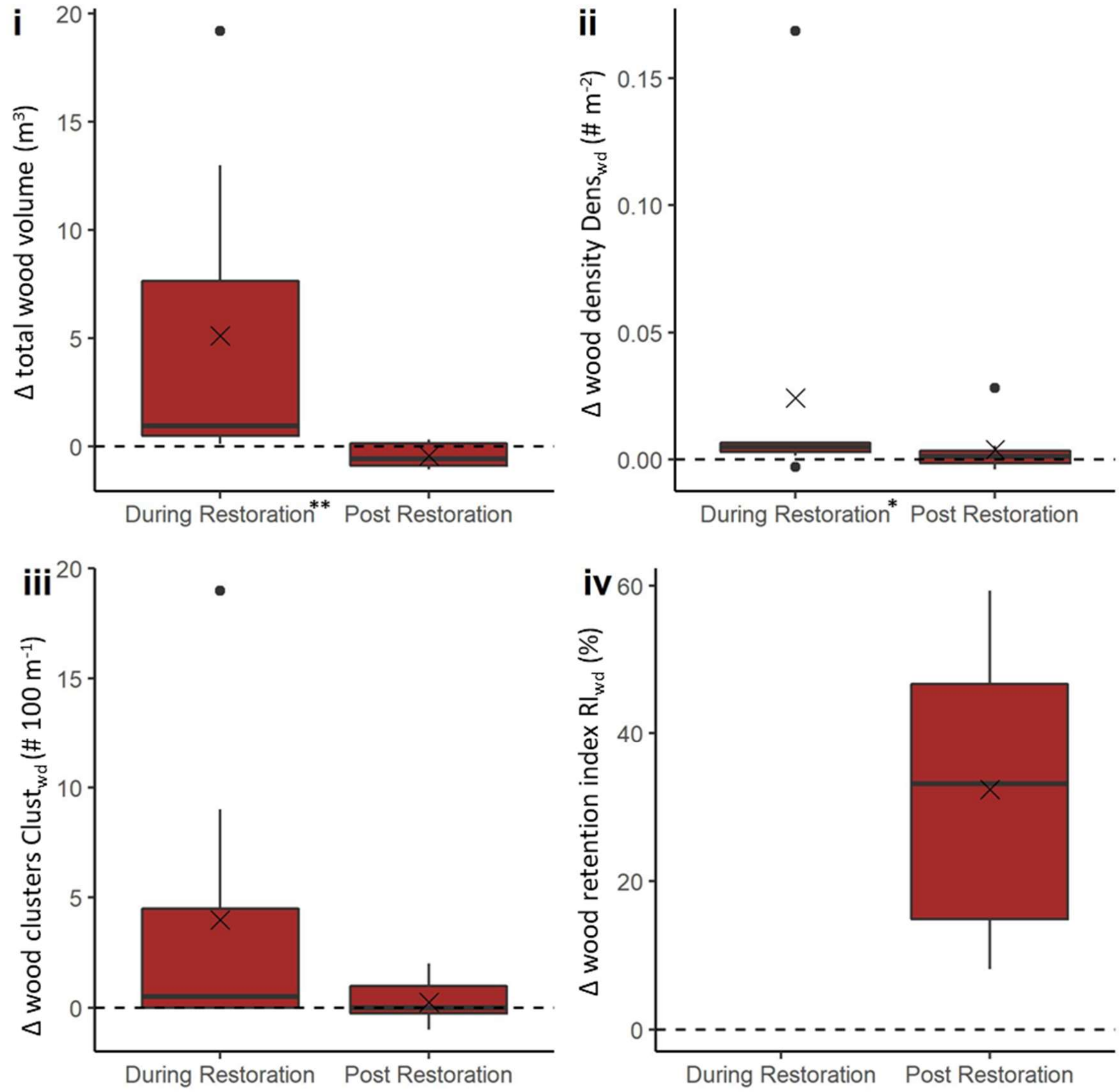

Figure 9. Changes to instream wood during and after restoration. During restoration, wood was added, increasing wood density (i) and volume (ii). The number of wood clusters (iii) is strongly associated with the quantity of wood and therefore also increases during restoration. RI_{wd} was not calculated during restoration because there was little to no wood in these rivers before restoration. Following restoration, there is a minimal reduction in total wood volume but a slight increase in wood density suggesting that overall wood populations remain similar.

3.2 Adjustment following restoration

In contrast to processes occurring during restoration, river width, planform area, cross-section area and depth typically decreased during the 2-3 years post restoration (Figure 3; Table 5). This varied between sites (Appendix 1) with 6 of 8 sites experiencing an overall reduction in area. In contrast, LMA1 & LMA2 both increased in channel area. LTA2 experienced the greatest loss in channel area at 8% (Figure A1.6). A reduction in channel width suggests that restoration may have oversized channels and they are now adjusting to a more equilibrium width.

Similarly, river channels on average became marginally less complex post restoration (Table 4). Width SD had a significant decrease in complexity post restoration (Figure 5i). Thalweg R^2 also increased, indicating a reduction complexity, and a marginal decrease is also shown by the other thalweg complexity metrics (Figure 7). In contrast, cross-section complexity increased slightly (Figure 6iii and iv). Both flow velocity and flow velocity standard deviation demonstrated little change post restoration (Figure 8) suggesting that the morphological complexity required to sustain more complex hydraulics were maintained.

There was also little change in instream wood post restoration, with on average a slight decrease in volume (Figure 9). The wood retention index estimated that on average 32% of wood area overlapped between *Post-A* and *Post-B* survey intervals, suggesting that 68% of wood has moved since installation (although transport distances are unknown and wood may not have moved out of the surveyed reach).

3.3 Influence of stream size: mainstem or tributary?

The selection of sites in this project meant that mainstem sites above the FHC were more similar in width to tributary sites. During restoration, sites on the mainstem Lögde River and its tributaries were increased in width by a similar proportion of channel size on average (Figure A2.1). However, changes to the width of mainstem channels during restoration was more variable. During restoration tributary channel cross-section area increased by a consistent 31%, but this was also far more variable in mainstem channels. There was little difference in changes to planform complexity between mainstem and tributary sites, except that more side channels added in mainstem channels (Figure A2.2). However, cross-section complexity (CV depth and chain & tape ratio) increased more in mainstem sites. Changes to the thalweg complexity were more pronounced in mainstemchannels than tributaries (e.g. a decrease in sinuosity indicating a reduction in lateral complexity but a decrease in R2 and an increase in SSE, MSE, SD, roughness and concavity indicating an increase in vertical complexity; Figure A2.5). Mean velocity decreased within main channels but increased marginally in tributaries (Figure A2.6). Wood was added in much greater volumes to mainstem than tributary sites (Figure A2.7).

River size was expected to be an important control on geomorphological adjustment following restoration. Mainstem channels varied in their adjustment, with two sites eroding further and increasing planform area, and the remaining two reducing in width. In contrast, all four tributary sites reduced in width (Figure A2.1). Longitudinal profile sinuosity increased post restoration in tributaries but continued to decrease in mainstem sites (Figure A2.5). Other channel metrics showed little difference between mainstem and tributary sites.

Table 5. Change in (i) general characteristics and (ii) complexity characteristics during and post restoration split into main and tributary channels. Values reported are means with SD (population) in brackets. Shading indicates whether a positive (salmon) or negative (blue) change occurred. For each metric, the channel size (main or tributary) which experienced the greatest change has a darker shade. Note: thalweg statistics do not include sites LMB1 and LMB2.

	During Restoration		Post Restoration	
	Main	Tributary	Main	Tributary
(i) General characteristics				
Average planform width (%)	37 (36)	31 (7)	-3 (6)	-6 (3)
Planform Area (%)	36 (35)	31 (7)	-2 (6)	-6 (3)
Area of new channel (%)	37 (35)	32 (6)	5 (5)	1 (1)
Area of channel lost (%)	1 (1)	1 (1)	3 (2)	7 (2)
Average cross section area (%)	53 (80)	33 (5)	0 (17)	-9 (13)
Average max depth (%)	21 (34)	14 (10)	-1 (11)	-3 (8)
Mean DA velocity (m s^{-1})	-0.17 (0.11)	0.10 (0.15)	0.00 (0.05)	-0.08 (0.03)
SD DA velocity (m s^{-1})	0.01 (0.03)	0.03 (0.05)	-0.01 (0.03)	0.00 (0.02)
CV DA velocity	0.15 (0.17)	-0.12 (0.20)	0.06 (0.14)	0.03 (0.02)
Total wood volume (m^3)	8.24 (8.16)	1.97 (2.28)	-0.19 (0.41)	-0.69 (0.51)
Wood density (# m^{-2})	0.00 (0.00)	0.04 (0.07)	0.00 (0.00)	0.01 (0.01)
Number of wood clusters (# 100 m^{-1})	7.00 (7.85)	1.00 (1.22)	0.50 (1.12)	0.00 (0.71)
(ii) Complexity characteristics				
Width SD (m)	0.77 (0.99)	0.26 (0.38)	-0.39 (0.54)	-0.25 (0.22)
Width CV	0.00 (0.02)	0.00 (0.04)	-0.01 (0.02)	-0.02 (0.02)
Width residual (m)	0.00 (0.01)	-0.01 (0.04)	-0.01 (0.02)	-0.01 (0.01)
Average width concavity	0.02 (0.03)	0.03 (0.04)	0.00 (0.01)	0.00 (003)
Bank length ratio	0.02 (0.10)	0.02 (0.04)	-0.02 (0.06)	0.02 (0.01)
Multithread index	0.18 (0.19)	-0.01 (0.09)	0.00 (0.00)	0.00 (0.00)
Cross section chain & tape	0.07 (0.10)	-0.01 (0.01)	-0.01 (0.04)	0.13 (0.20)
Cross section depth CV	0.06 (0.12)	0.02 (0.08)	0.02 (0.02)	0.03 (0.07)
Thalweg sinuosity⁺	-0.05 (0.01)	-0.04 (0.02)	-0.02 (0.03)	0.01 (0.01)
Thalweg R-square⁺	-0.35 (0.18)	-0.05 (0.05)	0.11 (0.05)	0.06 (0.06)
Thalweg SSE⁺	1.01 (0.22)	0.48 (0.54)	-0.23 (0.33)	-0.33 (0.34)
Thalweg MSE⁺	0.02 (0.00)	0.01 (0.01)	0.00 (0.00)	0.00 (0.01)
Longitudinal SD⁺ (m)	0.19 (0.02)	0.04 (0.12)	-0.01 (0.02)	-0.03 (0.04)
Longitudinal roughness⁺	0.06 (0.00)	0.02 (0.02)	0.00 (0.00)	-0.01 (0.03)
Average thalweg concavity⁺	0.02 (0.02)	0.01 (0.03)	-0.02 (0.03)	-0.02 (0.01)

3.4 Influence of location relative to FHC

Relative to channel size, rivers above the FHC were widened and deepened more than those below (Table 7; Appendix 3). This resulted in a higher percentage increase in cross-sectional area above the FHC. Width complexity metrics do not show substantial differences between sites above and below the FHC (Figure A3.3). Width SD is similar between sites above and below the FHC, but width CV indicates a positive change above the FHC and a negative change below, explained by the greater width of channels below. No side channels were reconnected above the FHC (Figure A3.3vi). Changes to the longitudinal profile complexity are similar above and below the FHC during restoration (Figure A3.5). Similarly, mean velocity decreased and SD velocity increased in both locations (Figure A3.6). Instream wood was mainly added to sites below the FHC (Figure A3.7).

Of the eight channels surveyed, only two continued to increase in planform area post restoration and these were both situated above the FHC (LMA1 & LMA2; Figure A3.1). Depth also decreased above the FHC, resulting in a mean decrease in cross-sectional area (despite some sites increasing in width; Figure A3.2). Longitudinal profile complexity experienced more change below the FHC than above (A3.5). Thalweg SSE, MSE & SD remained similar post restoration above the FHC but decreased below. In contrast thalweg sinuosity increased by a greater degree below the FHC. There was little change to wood volume above the FHC and similar residency above and below the FHC (Figure A3.7).

Table 6. Change in (i) general characteristics and (ii) complexity characteristics during and post restoration across all surveyed rivers. Values reported are means with SD (population) in brackets. Shading indicates whether a positive (salmon) or negative (blue) change occurred. For each metric, the location relative to the FHC (above or below) which experienced the greatest change has a darker shade. +Thalweg statistics do not include sites LMB1 and LMB2.

	During Restoration		Post Restoration	
	Above FHC	Below FHC	Above FHC	Below FHC
(i) General characteristics				
Average planform width (%)	46 (30)	22 (12)	0 (8)	-3 (3)
Planform Area (%)	46 (30)	22 (12)	0 (8)	-3 (3)
Area of new channel (%)	46 (30)	24 (11)	5 (5)	2 (1)
Area of channel lost (%)	0 (0)	2 (1)	46 (24)	544 (606)
Average cross section area (%)	72 (68)	14 (20)	-10 (10)	3 (18)
Average max depth (m)	0.25 (0.23)	0.02 (0.11)	-0.08 (0.08)	0.06 (0.15)
Mean DA velocity (m s^{-1})	-0.06 (0.17)	-0.01 (0.20)	-0.06 (0.05)	-0.02 (0.05)
SD DA velocity (m s^{-1})	0.02 (0.06)	0.02 (0.02)	-0.02 (0.02)	0.01 (0.03)
CV DA velocity	0.04 (0.23)	-0.01 (0.23)	0.10 (0.09)	-0.01 (0.09)
Total wood volume (m^3)	0.41 (0.28)	9.79 (6.88)	-0.06 (0.47)	-0.81 (0.23)
Wood density (# m^{-2})	0.003 (0.004)	0.046 (0.071)	0.001 (0.004)	0.007 (0.012)
Number of wood clusters (# 100 m^{-1})	0.00 (0.00)	8.00 (7.00)	0.50 (0.50)	0.00 (1.22)
(ii) Complexity characteristics				
Width SD (m)	0.61 (0.42)	0.42 (1.03)	-0.17 (0.32)	-0.47 (0.45)
Width CV	0.01 (0.02)	-0.02 (0.04)	-0.02 (0.02)	-0.01 (0.01)
Width residual (m)	0.01 (0.02)	-0.03 (0.03)	-0.02 (0.02)	-0.01 (0.01)
Average width concavity	0.02 (0.02)	0.03 (0.04)	0.01 (0.02)	-0.01 (0.03)
Bank length ratio	0.03 (0.04)	0.01 (0.10)	0.02 (0.02)	-0.02 (0.05)
Multithread index	0.00 (0.00)	0.16 (0.22)	0.00 (0.00)	0.00 (0.00)
Cross section chain & tape	0.07 (0.10)	-0.01 (0.02)	0.10 (0.21)	0.02 (0.03)
Cross section depth CV	-0.02 (0.09)	0.09 (0.09)	0.04 (0.06)	0.01 (0.04)
Thalweg sinuosity+	-0.04 (0.02)	-0.04 (0.01)	0.00 (0.03)	0.02 (0.01)
Thalweg R-square+	-0.18 (0.21)	-0.08 (0.04)	0.06 (0.07)	0.07 (0.03)
Thalweg SSE+	0.54 (0.57)	0.09 (0.26)	-0.15 (0.31)	-0.60 (0.08)
Thalweg MSE+	0.01 (0.01)	0.02 (0.00)	0.00 (0.00)	-0.01 (0.00)
Longitudinal SD+ (m)	0.07 (0.15)	0.12 (0.01)	0.00 (0.02)	-0.07 (0.00)
Longitudinal roughness+	0.04 (0.03)	0.03 (0.02)	0.00 (0.02)	-0.03 (0.01)
Average thalweg concavity+	0.01 (0.03)	0.03 (0.01)	-0.02 (0.02)	-0.01 (0.01)

4. Discussion

4.1 General conclusions from results

4.1.1 Modifications during restoration

Restoration successfully modified river planforms by increasing channel width and opening up numerous side channels. As northern Swedish rivers were typically narrowed to facilitate timber floating, this increase in width indicates progress towards a pre-disturbance state. Furthermore, the area of river habitat was increased at all sites (at LMA1 river habitat area doubled). An increased area of habitat should support a greater density of fish and other taxa, although this will also depend on habitat quality and complexity.

The reconnection of side channels appears to be successful and is likely a positive influence on habitat and biodiversity. Side channels were added at three sites and lost at one site during restoration. Observations in the field indicate that side channels are providing different hydraulic and sedimentological habitats to those in the main channel (Figure 10). Side channels likely provide slower flowing, depositional habitats (ideal for small fish) under low to medium flows and may provide refugia for fish from high flows during floods. The additional islands are also likely to be beneficial for terrestrial animals.

Channel depth was not decreased during restoration, and therefore, channel capacity (cross-sectional area) increased overall. This will allow restored channels to contain a greater discharge and probably reduce overbank flooding. This in turn will reduce the connectivity of the channel with the floodplain which is likely to have negative implications for aquatic and terrestrial biodiversity. For example, frequent overbank flows maintain hydraulic disturbance regimes for riparian vegetation and seed dispersal promoting a more diverse community of plants.

Because width CV is calculated by dividing the SD by mean width, the discrepancy between an increase in width SD during restoration but no change in width CV is probably due to an increase in mean width. In other words, more complex width variation is required to maintain the same width CV post restoration. However, many channels were widened by a similar amount along their length or were widened predominantly at their narrowest sections, resulting in a decrease in width complexity at some sites.

Hydraulics show high variability between sites but no clear differences in flow velocity or turbulence (i.e., variation in velocity) following restoration. Because velocity is dependent on temporal variations in discharge, it can be difficult to compare results between years or even between sites during the same year. Some sites showed large decreases in mean velocity and increases in standard deviations, as would be expected with an increase in roughness (i.e., friction) as a result of restored geomorphic complexity. However, other sites showed only marginal changes in velocities. Following restoration, there was very little change in velocity parameters while geomorphic changes were more significant. This suggests that velocity may not be sensitive to subtle changes in geomorphology occurring post-restoration.

Figure 10. Restoration of side channels (A) Side channel at LMB2 was dry during the survey in 2021. The lack of riparian vegetation indicates that the side channel is maintained at higher discharges and likely provides important ephemeral habitats and refugia. However, it is possible that over longer time periods the channel will become disconnected from the main channel again. (B) Fine sediment and organic material build up in side channels (also LMB2) shows that side channels are providing different habitats to the main channel (mostly clean scoured cobbles), increasing overall habitat heterogeneity within the site.

4.1.2 Post-restoration adjustments

Little hydromorphological monitoring of restoration has been undertaken in rivers with a legacy glacial geological history such as those in northern Sweden. Due to the constraints of glacial sediments, especially boulders, the magnitude of channel response following restoration was expected to be less than in alluvial rivers. However, this project indicates that channels change substantially following restoration but that this was variable between surveyed sites (up to 10 % increase and 8% decrease in channel planform area). The average decrease in channel width post restoration may indicate rivers adjusting to the changes and settling into a new equilibrium state. The increase in width will result in shallower flows and less concentrated hydraulic energy at the banks, which may explain the reduction in channel width following restoration. It is likely that vegetation growth is an important biogeomorphic player in the morphology of these streams because once established it can trap fine sediment along the banks and reduce channel width, as well as promoting the formation of islands and side channels.

It is interesting that one site (LMA2; Figure A1.8) experienced considerable erosion post restoration. It is evident that adjustment varies between sites. LMA2 site is directly downstream of a slow flowing reach and therefore has substantial fine sediment (Figure 11) which may explain the continued erosion.

Figure 11. LMA2 continued to erode following restoration. (i) looking downstream prior to restoration (ii) same location 3 years post restoration. New area of channel is the muddy area just above water level.

4.1.3 Further adjustments with time

In this monitoring project, we analyzed channels only one and up to three years after restoration, providing us with two points in time to attempt to draw conclusions from on channel adjustment to restoration. From these two data points we can start to infer the potential for, and directions of, channel adjustment to restoration. Ideally, we would require up to 10 years of data to draw concrete conclusions of how these channels respond and if there are differences between sites above and below the FHC and based on channel size. However, monitoring projects seldom allow for the luxury of multiple years of data before drawing conclusions. And in most studies, only case studies are examined, drawing conclusions from changes at a single site. The conclusions that we are able to draw from this monitoring study are thus more robust as they are based on trends and patterns from eight sites.

The longer-term changes to channel morphology following restoration are unknown. There is a risk that rivers may return to a pre-restoration planform state if side channels are filled with sediment and channel banks continue to move inwards. The addition of boulders and large wood will hopefully prevent this by deflecting flow and maintaining more complex channel planforms. Furthermore, if the increased depth that resulted from timber-floating modifications remains unchanged, there is a risk that side channels, which have not been deepened, will be too high relative to the main channel and are more likely to become disconnected in the future.

Most of the channels in this study exhibited the formation of an inset bankfull channel due to the overdimensioned cross-sectional area. By increasing width during restoration without a corresponding decrease in depth, the channel area is larger than required to convey flows. Therefore, a narrower bankfull channel started forming below and within the channel banks that were formed manually during restoration. However, at three years post-restoration, the inset banks were still diffuse due to the slow rate of vegetation establishment at this latitude. The formation of channel banks is a trade-off between fluvial erosional processes and the formation of vegetation and soil, and previous studies have found that post-restoration establishment of riparian vegetation can take over a decade in northern Sweden (Hasselquist et al. 2015). Therefore, the equilibrium channel banks will likely take at least a decade to form after the effect of several high flows is balanced by fully established riparian vegetation that can stabilize streambanks.

4.1.4 Instream wood

Woody material is an important natural part of river systems, both ecologically and geomorphologically. Wood addition during restoration was very variable between sites. Only a few sites had clusters of large wood but where present these are successful in trapping both sediment and smaller organic particles (e.g. timber chewed by beavers; Figure 12). Our measure of wood residency suggests that 32% of wood on average remained stable and the rest was transported post restoration. However, the wood only has to move marginally or there be some error in the operator surveys for the wood pieces not to overlap. Nevertheless, this suggests that much wood is mobile but wood volume and density show little change post restoration and therefore mobilised wood either is not transported out of the reach or is replaced by upstream wood.

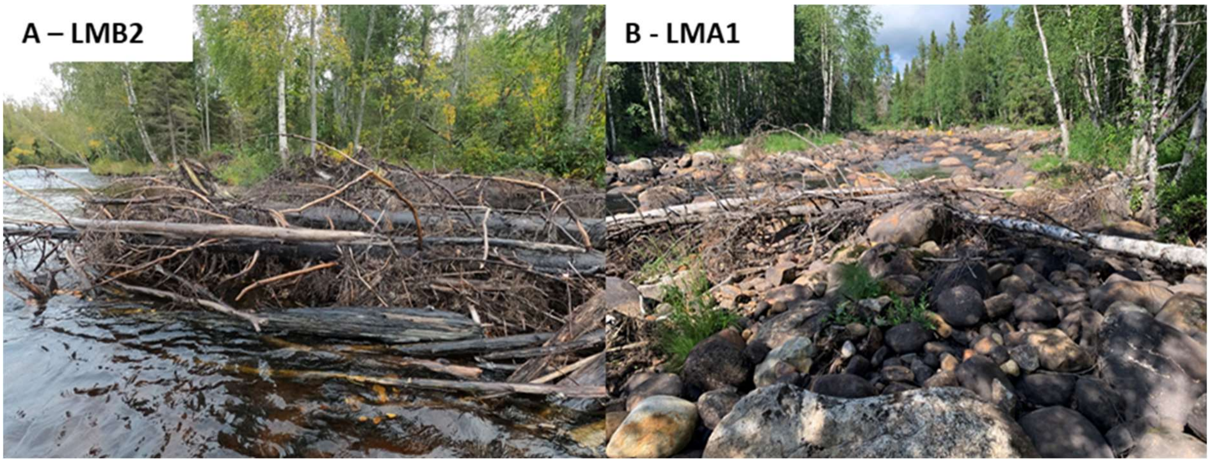

Figure 12. Examples of instream wood at two mainstem sites.

4.1.5 Differences between main channels and tributaries

Mainstem rivers typically have greater discharge and finer bed sediments, allowing them to have more control over their morphology than tributaries. The difference in channel size between mainstem channels above and below the FHC should be noted, especially as these sites responded very differently post restoration. Both mainstem sites above the FHC (LMA1 & LMA2) eroded post restoration unlike the two sites lower down the mainstem Lögde River and all of the tributary sites. Therefore, we conclude that dividing sites into either mainstem or tributary is less useful than considering their erosive power.

4.1.6 Differences between channels above and below FHC

Surficial geology varies relative to the FHC with implications for channel geomorphology (Polvi, 2021). Above the FHC channels typically exhibit very coarse boulders whilst below there is a greater amount of sand and gravel substrates. During restoration, no side channels were reconnected above the FHC; whereas side channels were connected in three out of four of the channels below the FHC. There were likely side channels in reaches above the FHC prior to timber-floating but they are more difficult to detect than those below the

FHC. Side channels above the FHC may be more diffuse, where water flowed between boulders in the floodplain and there was not enough transport capacity to create distinct side channels.

We hypothesized that, due to more erodible sediments, rivers below the FHC would adjust their bed and banks to a greater degree following restoration. In contrast, the only sites that increased in planform area after restoration were above the FHC. Longitudinal profile complexity experienced more change below the FHC. We suggest that channels below the FHC have greater ability to shape their bed sediments, but due to the oversized channels, they did not experience much lateral erosion. There was also less wood added to sites above the FHC during restoration and little wood recruitment occurred in the three years following restoration.

4.2 Suggestions for future restoration

River planform complexity was not increased with restoration. Therefore, to maintain river bank and channel complexity, future restoration should consider varying the degree to which width is increased along the channel length. However, ideally this variability should reflect natural processes (e.g. local surficial geology, topography, hydraulics of local erosion). If restoration promotes natural rates of bank erosion, then a natural variation in width will naturally occur after a few years.

Vertical complexity was increased during restoration, perhaps through addition of boulder clusters, riffles, or small steps. However, the reduction in thalweg lateral complexity during restoration suggests that future restoration might want to consider restoring a more sinuous thalweg, rather than promoting the main water flow to be in the center of the channel. If a greater density of boulders and large wood are placed on the sides of the channel, then water flow will be mainly in the channel center. Instead the boulder density should be mostly evenly spread out in the channel with occasional boulder clusters in varying placements within the channel.

Increasingly river restoration is moving towards thinking beyond the river channel and considering restoration of connected channel and floodplain systems (e.g. Stage Zero restoration; Wohl et al., 2021). There is a risk with restoration of channelized streams that the restoration is focused on habitat creation within the channel without consideration of connecting the channel to the floodplain. At the studied sites, there were several instances with large sediment piles placed in the riparian zones, which can hinder channel-floodplain connectivity. Another risk to channel-floodplain connectivity is if the channel adjusts to create an inset channel. Our results showed that channel width increased with restoration but depth was unchanged. This results in an over-dimensioned channel where the cross-sectional area increases, meaning that the same flows that previously filled the bankfull channel will no longer reach the channel edge and top of the channel banks. At most of the sites, we observed inset bankfull channels forming three years post-restoration (Figure 13). When inset channels form, then it is more difficult for high flows to cause overbank flooding. Whereas this can be a positive aspect in urban settings, if the goal is to increase habitat heterogeneity, biodiversity, and nutrient exchange between the channel and floodplain, then channel-floodplain connectivity should be promoted where landuse permits.

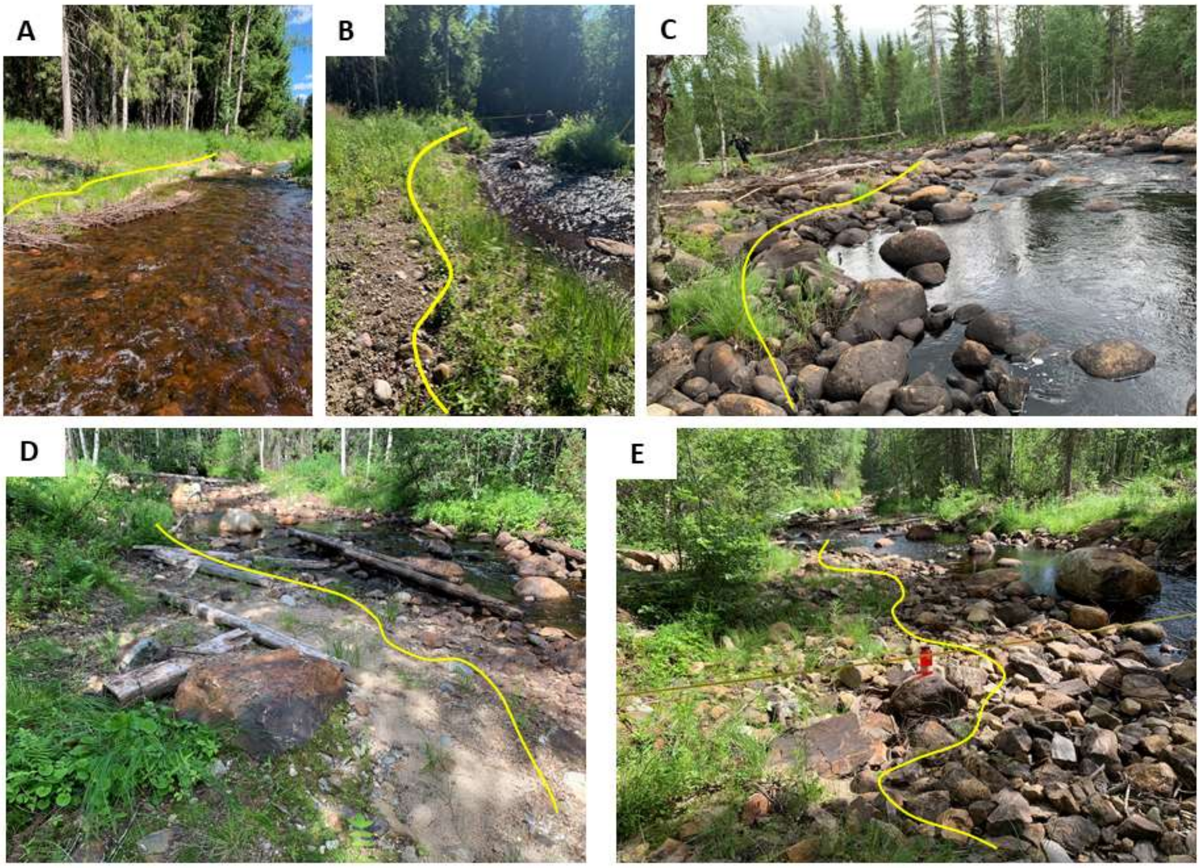

Figure 13. Examples of inset bankfull forming in three years following restoration. Yellow lines show the newly formed bankfull which is below that formed during restoration. The formation of an inset bankfull indicates the potential for post-restoration adjustment of channel above and below the FHC; however, an inset bankfull can decrease channel-floodplain connectivity. Photos (a) & (b) are from LTB1 in 2021; (c) is from LMA1 in 2021 and photos (d) & (e) are from LTB2 in 2021.

5. Conclusions

In this study, we examined the hydromorphological changes during restoration of formerly timber-floated channels. Restoration had a clear effect on channel geomorphology by widening the channel and increasing several aspects of geomorphic complexity. Whilst geomorphic complexity is only one aspect of stream restoration important for successful ecological recovery, it is the primary impact of the timber floating industry (which had little impact on water quality etc.). Therefore, improvements in hydromorphological complexity would be expected to promote biodiversity improvements.

Restoration was successful in removing lateral constraints imposed during timber floating. River width increased at all sites. Only two sites experienced less than the target of 0.126 ha km^{-1} additional channel area and on average the increase was 2 ha km^{-1}. Side channels and islands were reconnected and maintained in the 3 years following restoration. These reconnected side channels increase habitat diversity and likely provide important refugia for fish.

Geomorphic complexity typically increased during restoration. However, increases in the variability of channel width were minimal, because width was increased by a similar amount along both banks at many sites. Similarly, lateral variability in the location of the deepest part of the channel (thalweg) decreased with restoration. Future restoration should consider increasing complexity in these dimensions. Hydraulics show high variability between sites and no clear differences in flow velocity or turbulence (i.e., variation in velocity) following restoration.

Following restoration, rivers continued to adjust morphologically. Across most sites, there was a net decrease in river width (two sites had net increase in channel width and area). During restoration rivers were widened but there was no reduction in depth, meaning that river capacity was probably oversized. Field observations indicated the formation of an inset bankfull channel; this risks reducing connectivity between the river and the floodplain/riparian areas (contrary to aims of restoration) by reducing frequency of overbank flooding. We suggest that more sediment should be added to the channel beds to decrease channel depth and thus mitigate this potential loss of channel-floodplain connectivity.

Following restoration, there was a slight decrease in geomorphic complexity, indicating that channel form smoothed out, channel sediment settled causing grain interlocking, which is common after a series of low to medium flows. Inter-site variability was high and no large (or statistically significant) differences were found between main channel and tributary sites or sites above or below the FHC. It is evident that even rivers flowing over legacy glacial sediments adapt following restoration. The direction of this change varied between sites, where most rivers experienced a decrease in channel size whilst two sites had net erosion. Future restoration should ensure that rivers are not overly deep and ensure that channels are laterally connected with the floodplain. However, it is important to keep in mind that rivers respond differently - whilst most reduced in width following restoration, two increased in width.

In order to further improve the physical restoration of timber-floated streams, we recommend increasing variation in planform by varying the degree of increased width. Although width significantly increased during restoration, the width complexity did not increase due to a constant increase in width throughout each reach. There could also be a greater focus on channel-floodplain connectivity. First, restoration practices should be sure to respect the channel’s ability for overbank flooding by taking care when placing excavated sediment on the floodplain. Second, restoration should minimize the risk of creating inset bankfull channels by adding sediment to the channels to reduce the channel depth, with the added benefit of restoring potential spawning gravels.

Continued restoration of previously timber-floated channels in northern Sweden show great promise of increasing geomorphic complexity and increasing channel dynamics, both above and below the FHC. Stream restoration is an evolving practice where future projects can continue to learn from previous results. Therefore, post-restoration monitoring of both biota and hydromorphology is important to prioritize.

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7. Appendix

7.1 Appendix 1: Channel maps

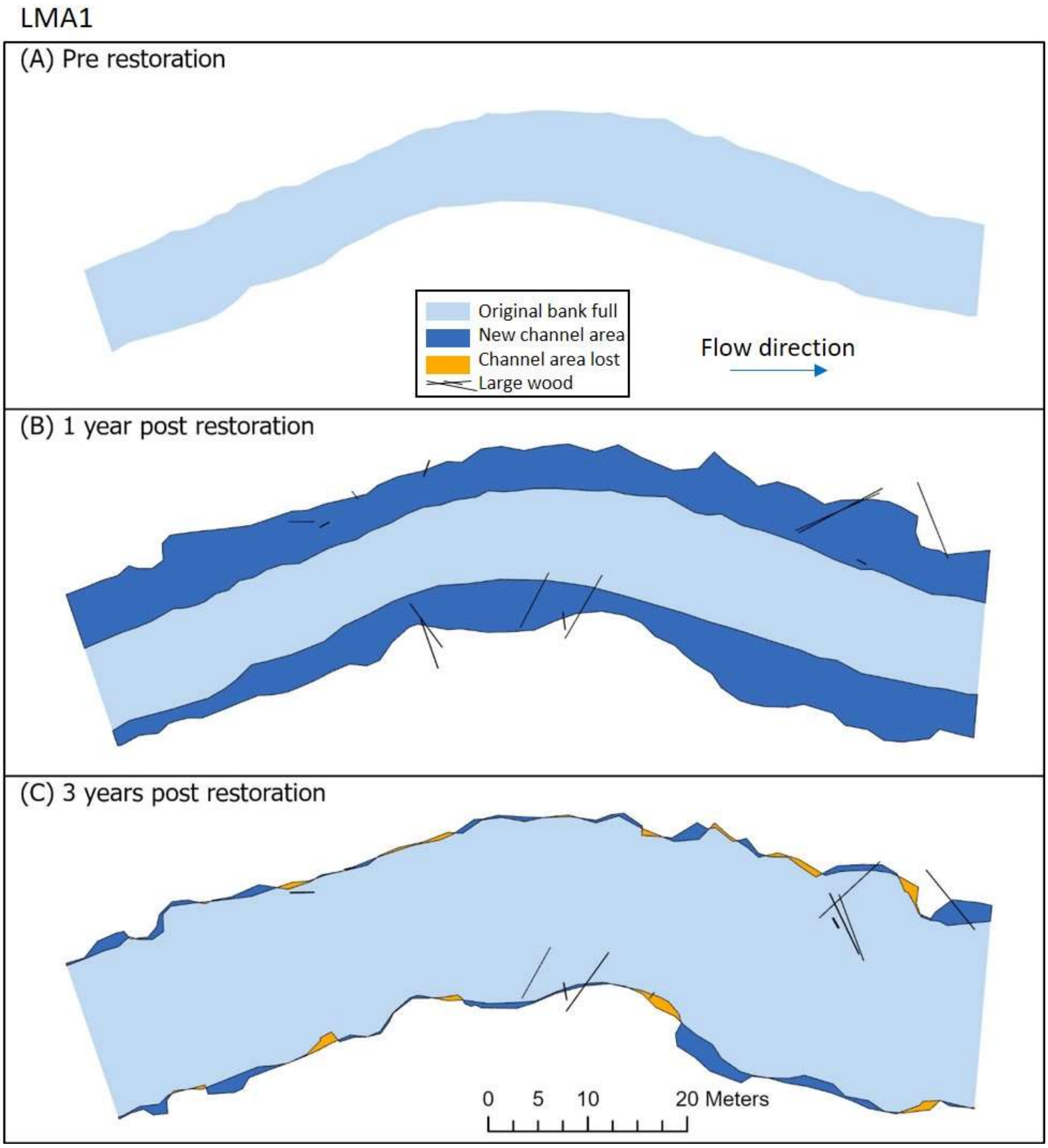

Figure A1.1. LMA1 planform map. During restoration channel was widened and maintains this width post restoration.

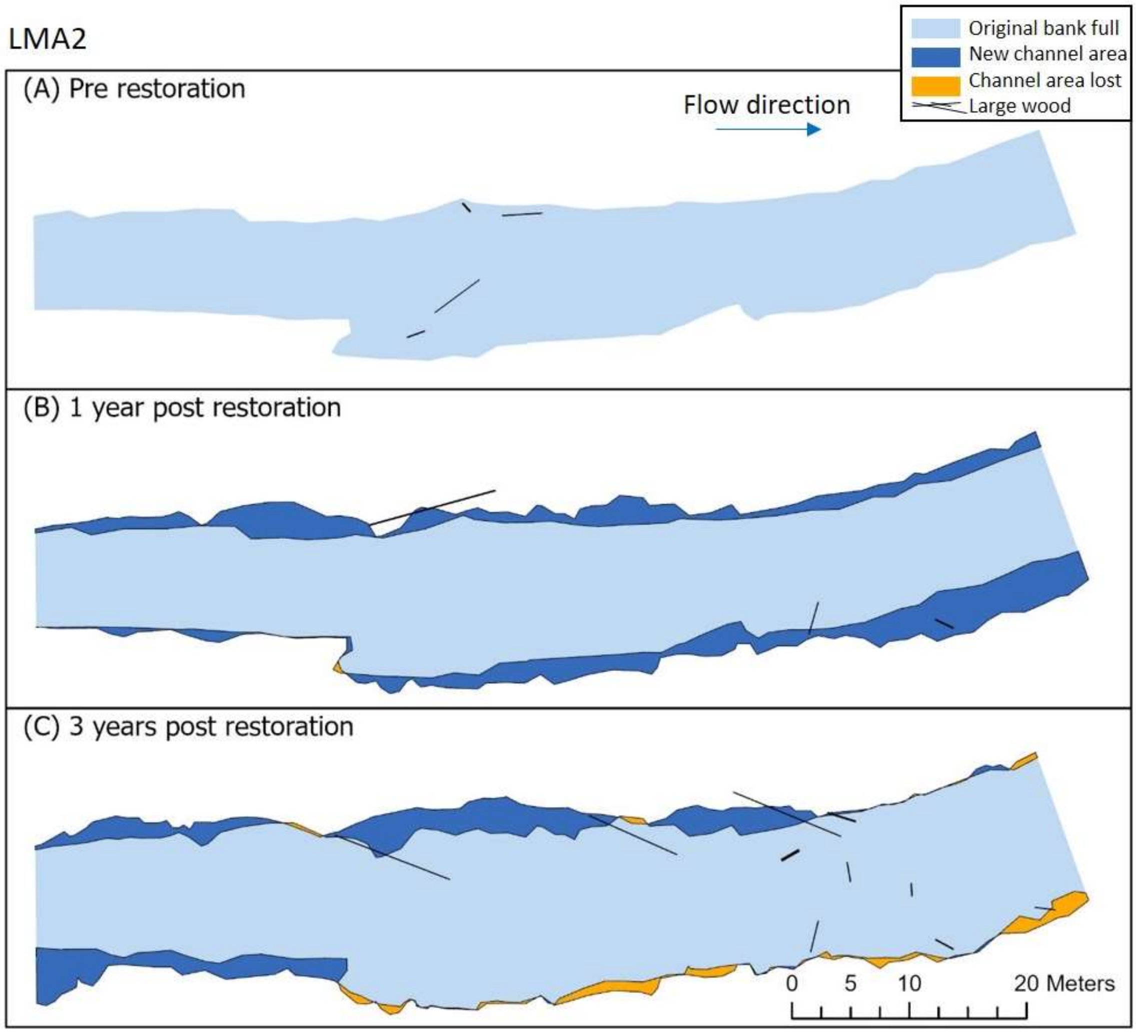

Figure A1.2. LMA2 planform map. During restoration the channel was widened. Interestingly, the channel widens considerably post restoration as well.

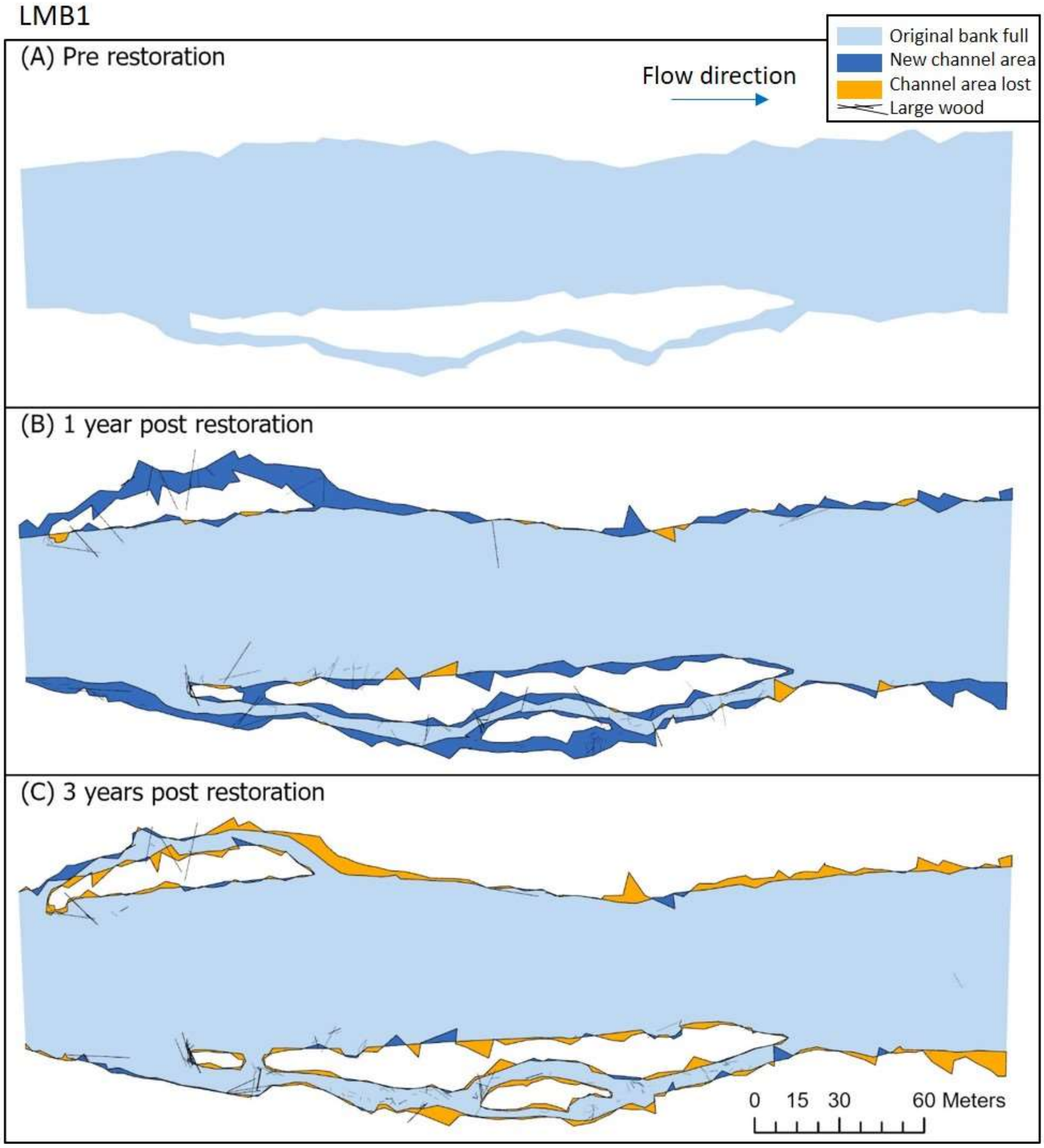

Figure A1.3. LMB1 planform map. During restoration two side channels were opened and lots of wood added. Both side channels and the wood remain post restoration.

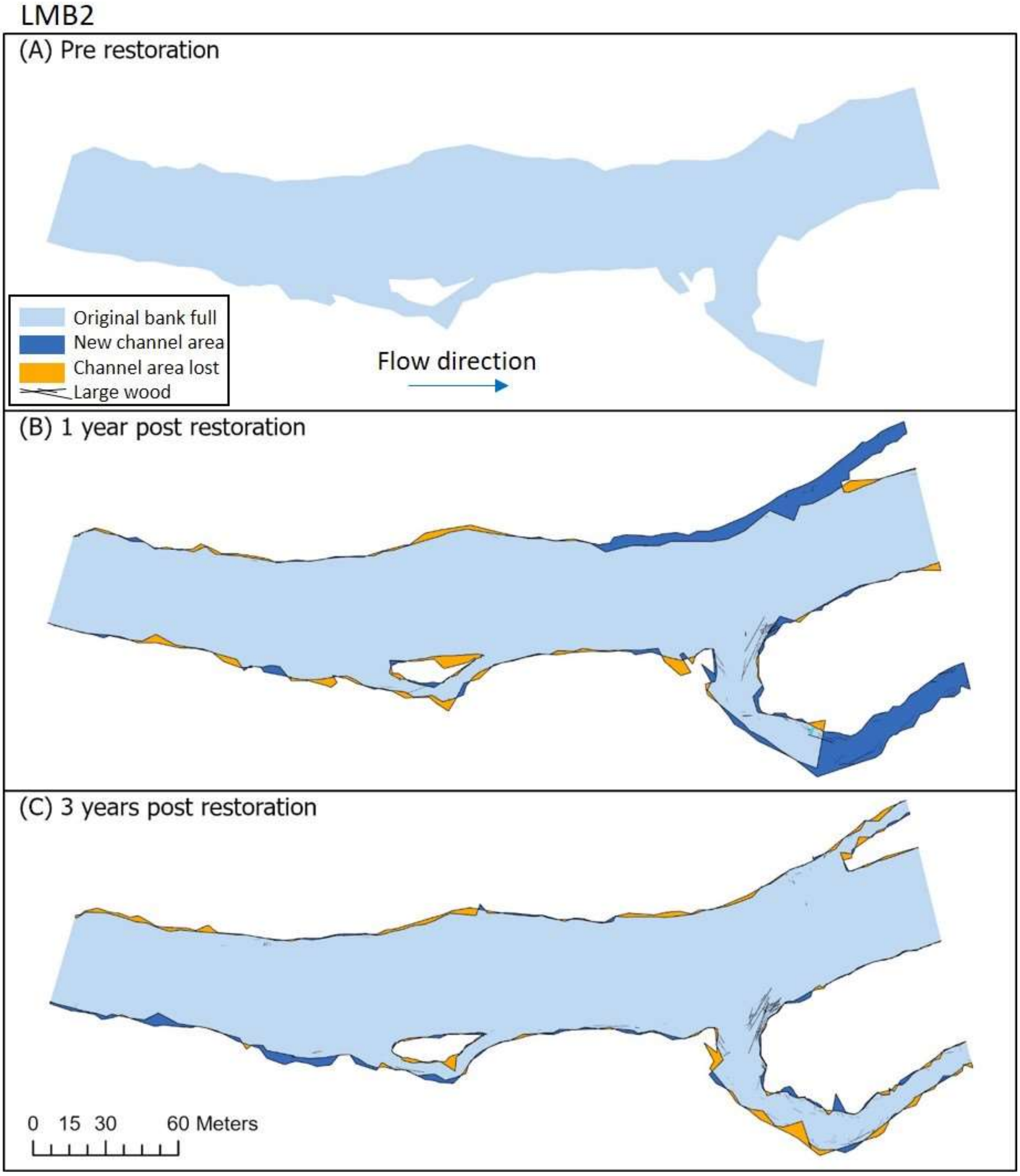

Figure A1.4. LMB2 planform map. During restoration one side channel was opened up and a back water was extended back into the main channel forming an island. Otherwise little change to overall planform during restoration. Post restoration there is some deposition and erosion but not clear trend.

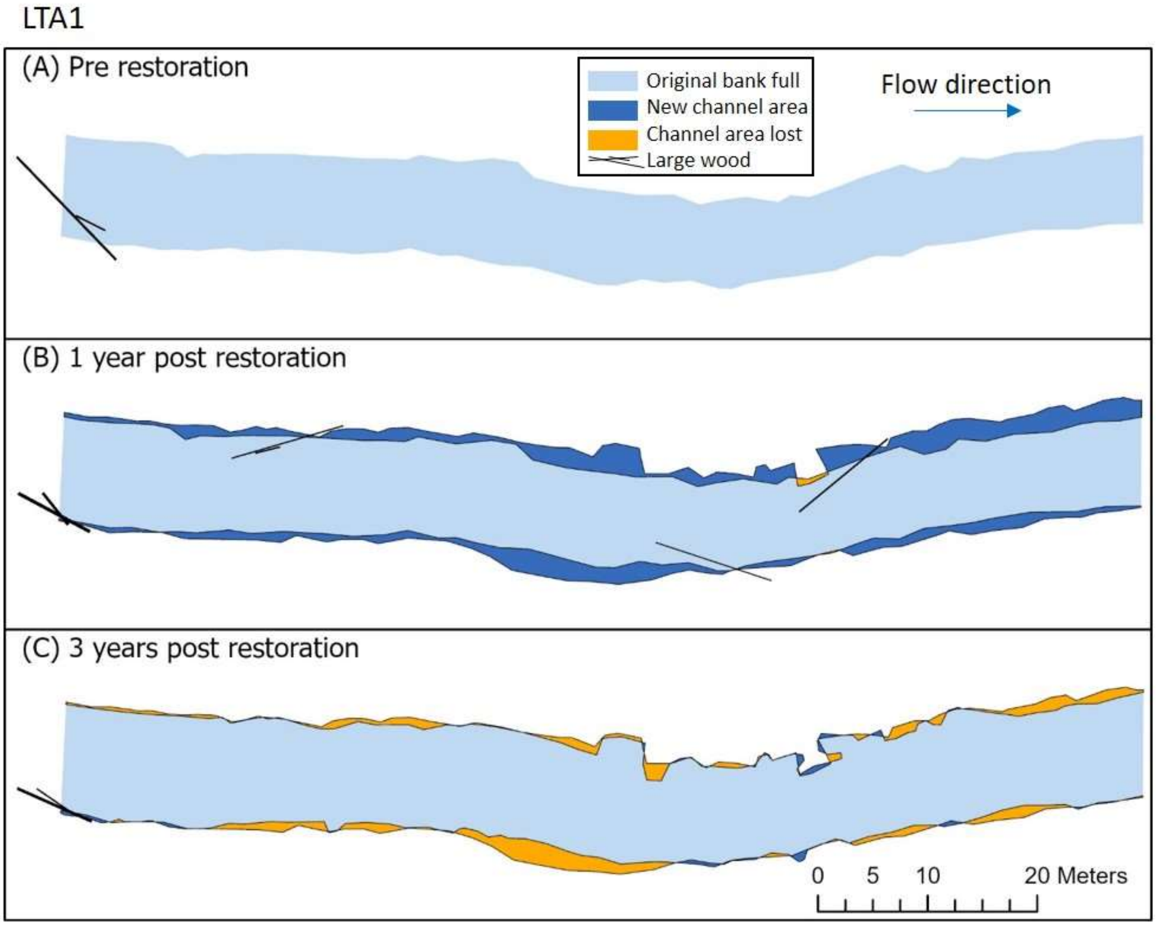

Figure A1.5. LTA1 planform map. During restoration channel was widened considerably and some wood added. Post restoration much of the widened channel is lost and wood has gone.

LTA2

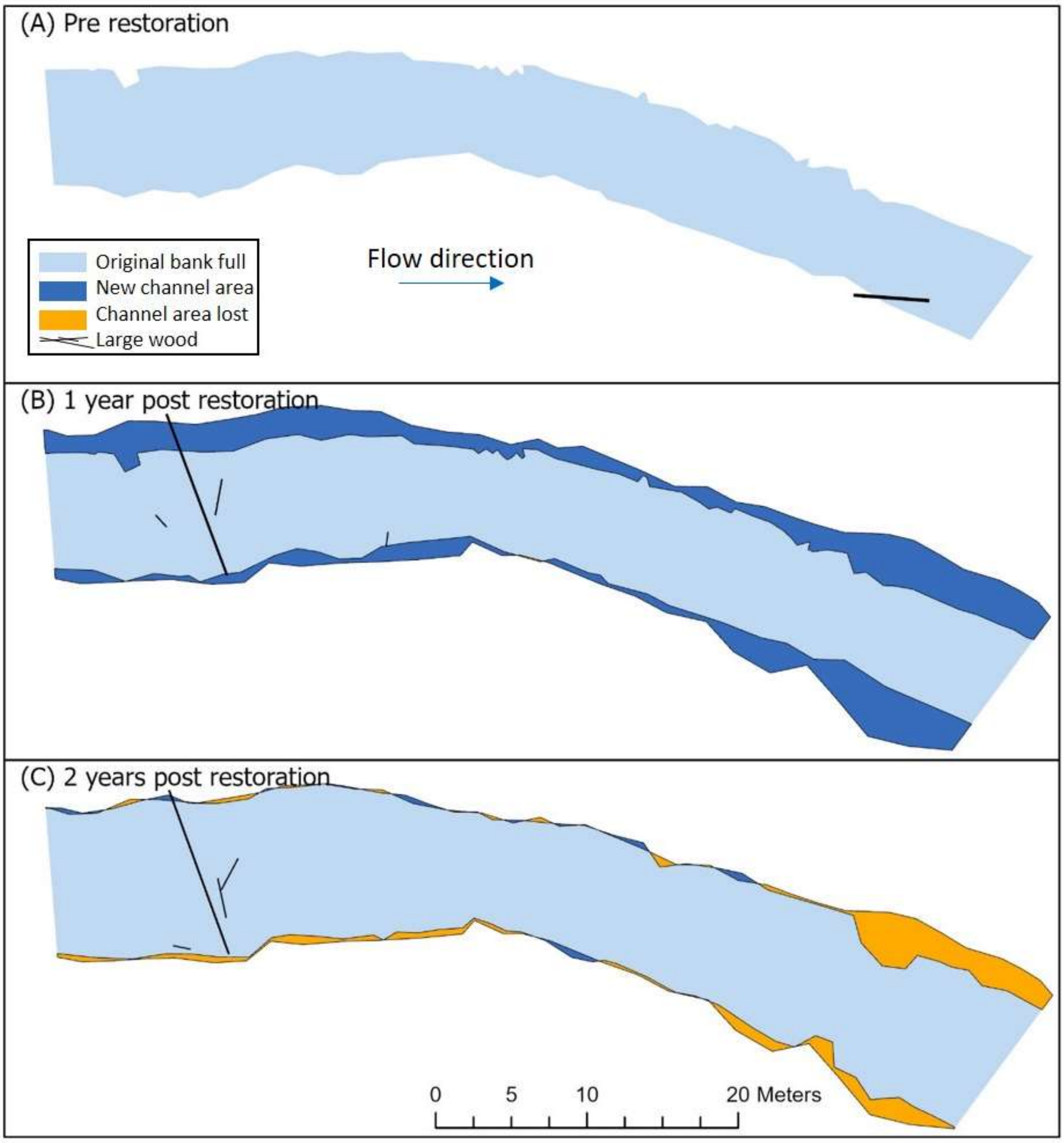

Figure A1.6. LTA2 planform map. Channel widened considerably during restoration. Downstream end of the surveyed reach narrows in the 2 years following restoration.

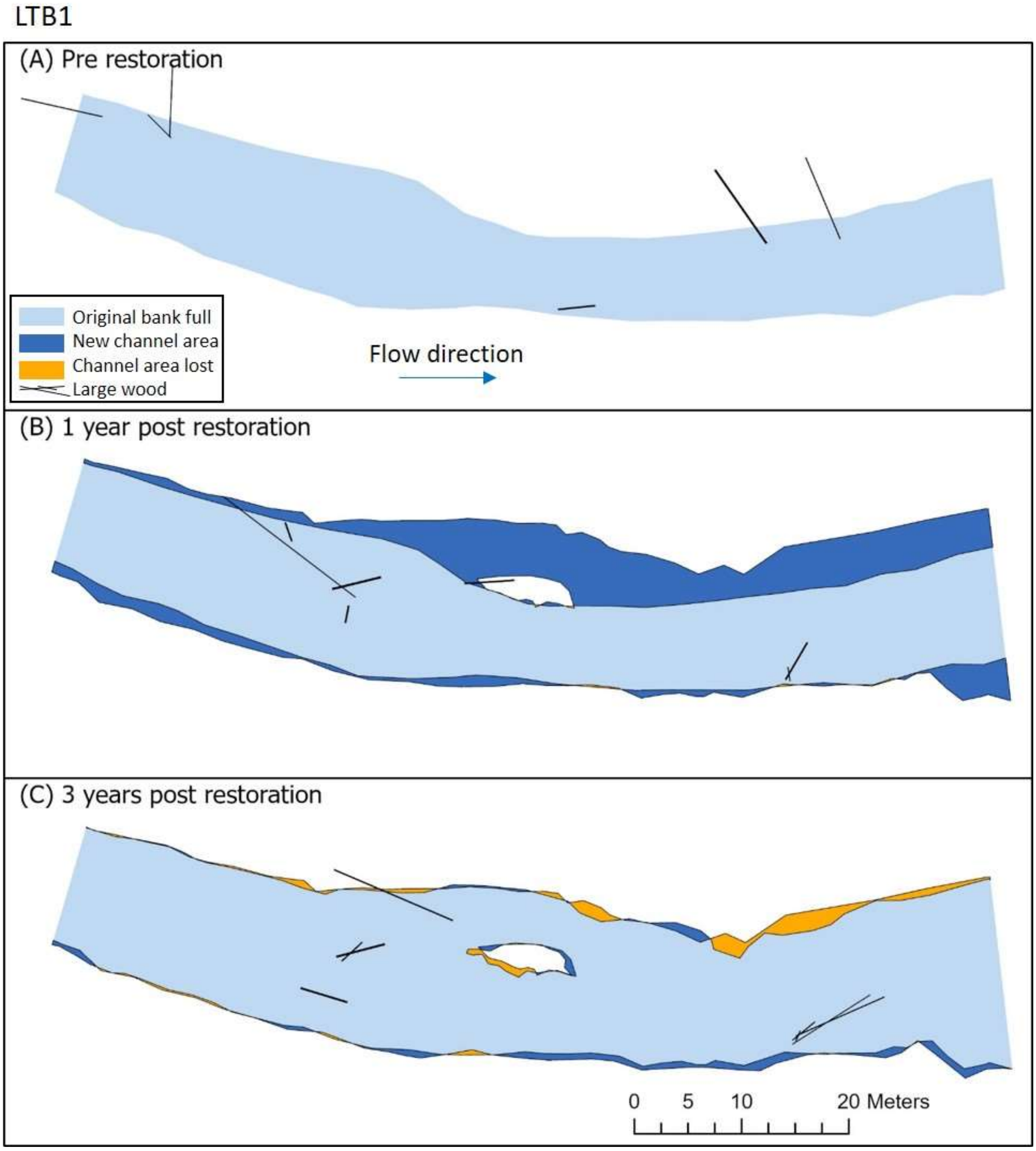

Figure A1.7. LTB1 planform map. During restoration channel was widened considerably and a side channel opened. Post restoration there has been some deposition but also some bank erosion.

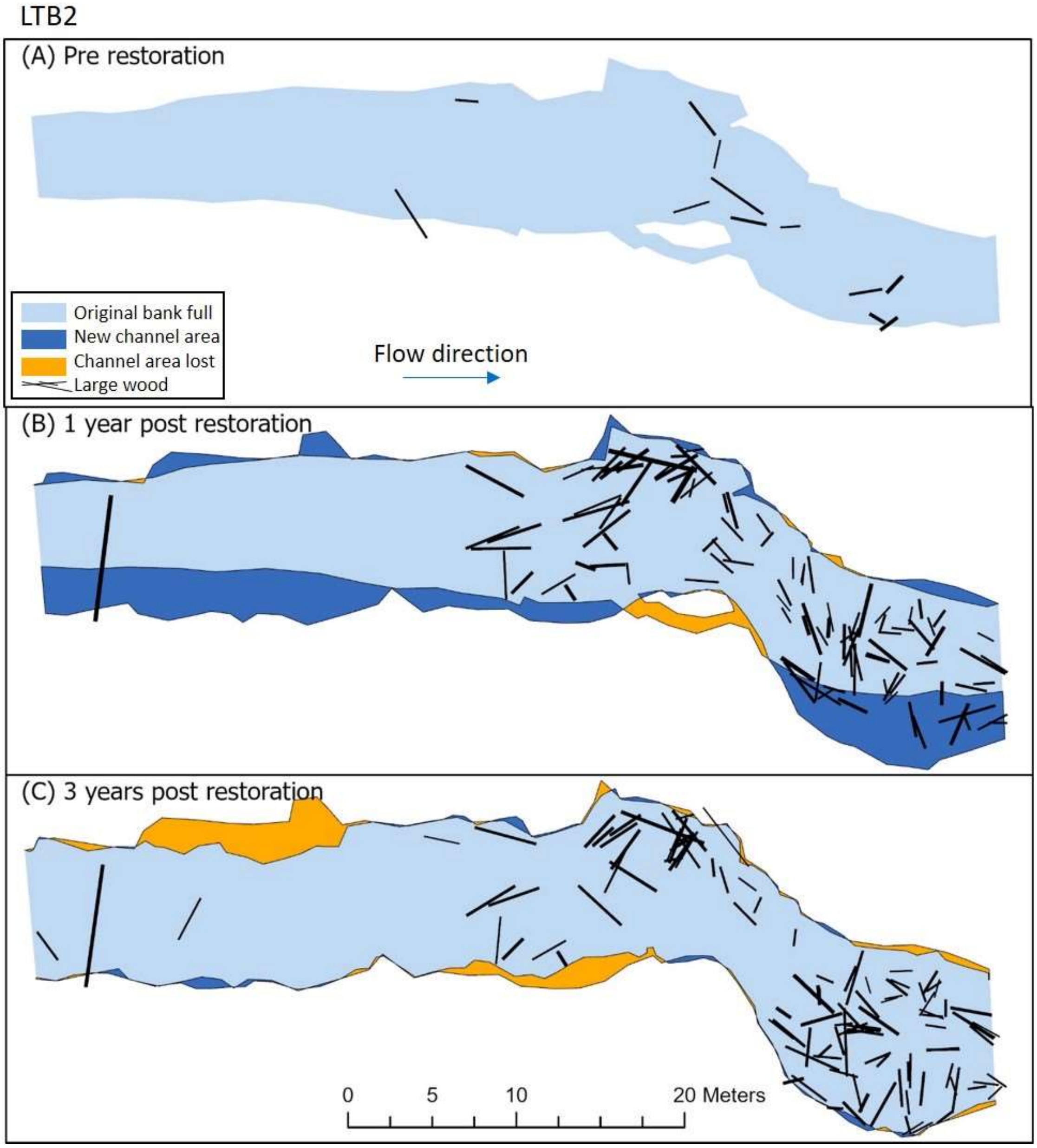

Figure A1.8. LTB2 planform map. During restoration the channel was widened and a considerable amount of wood added. A small side channel was lost. Post restoration there is deposition in two areas.

7.2 Appendix 2: Mainstem and tributary boxplots

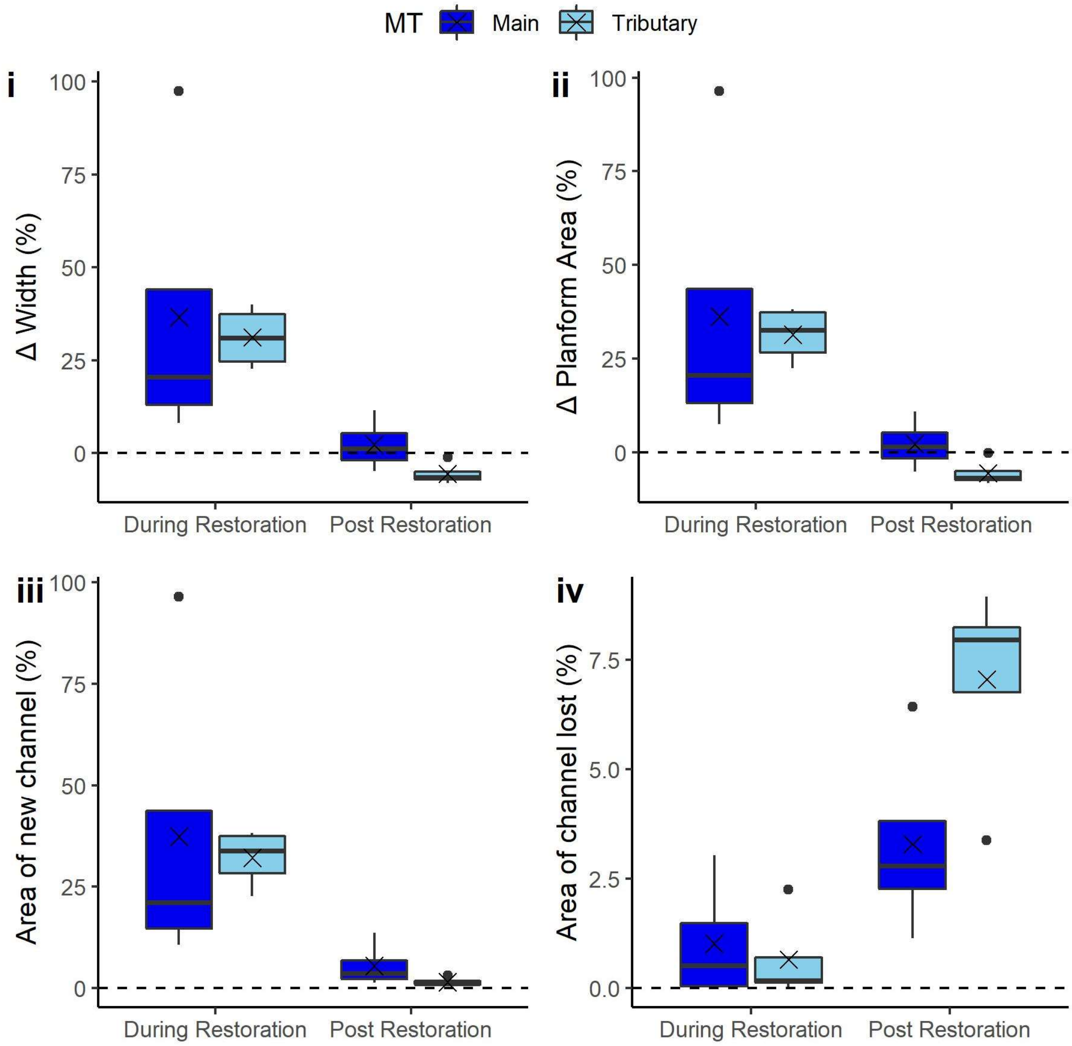

Figure A2.1. Boxplots of change in general geomorphic parameters describing planform during and post restoration comparing sites on mainstem and tributaries.

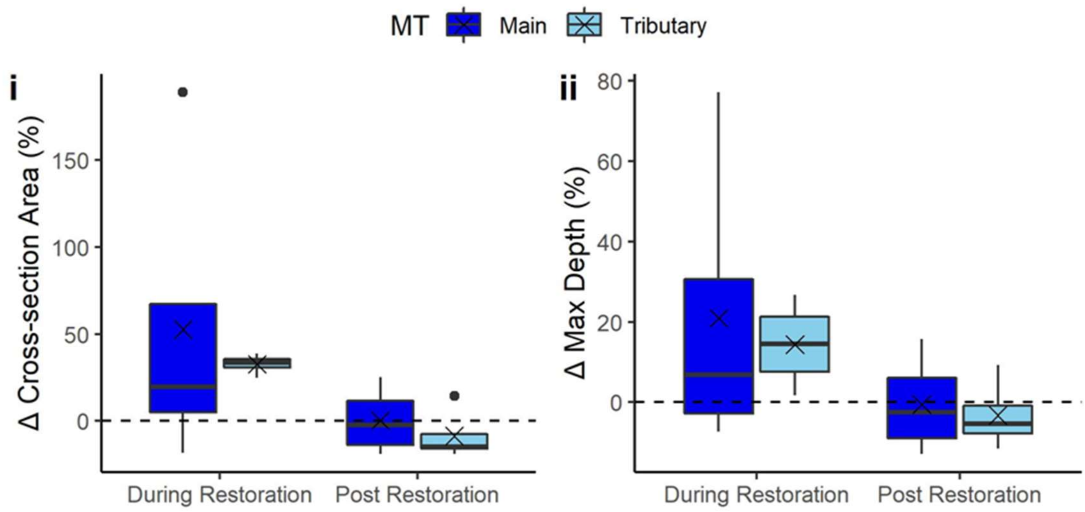

Figure A2.2. Boxplots of change in general geomorphic parameters describing cross-section transects during and post restoration comparing sites on mainstem and tributaries.

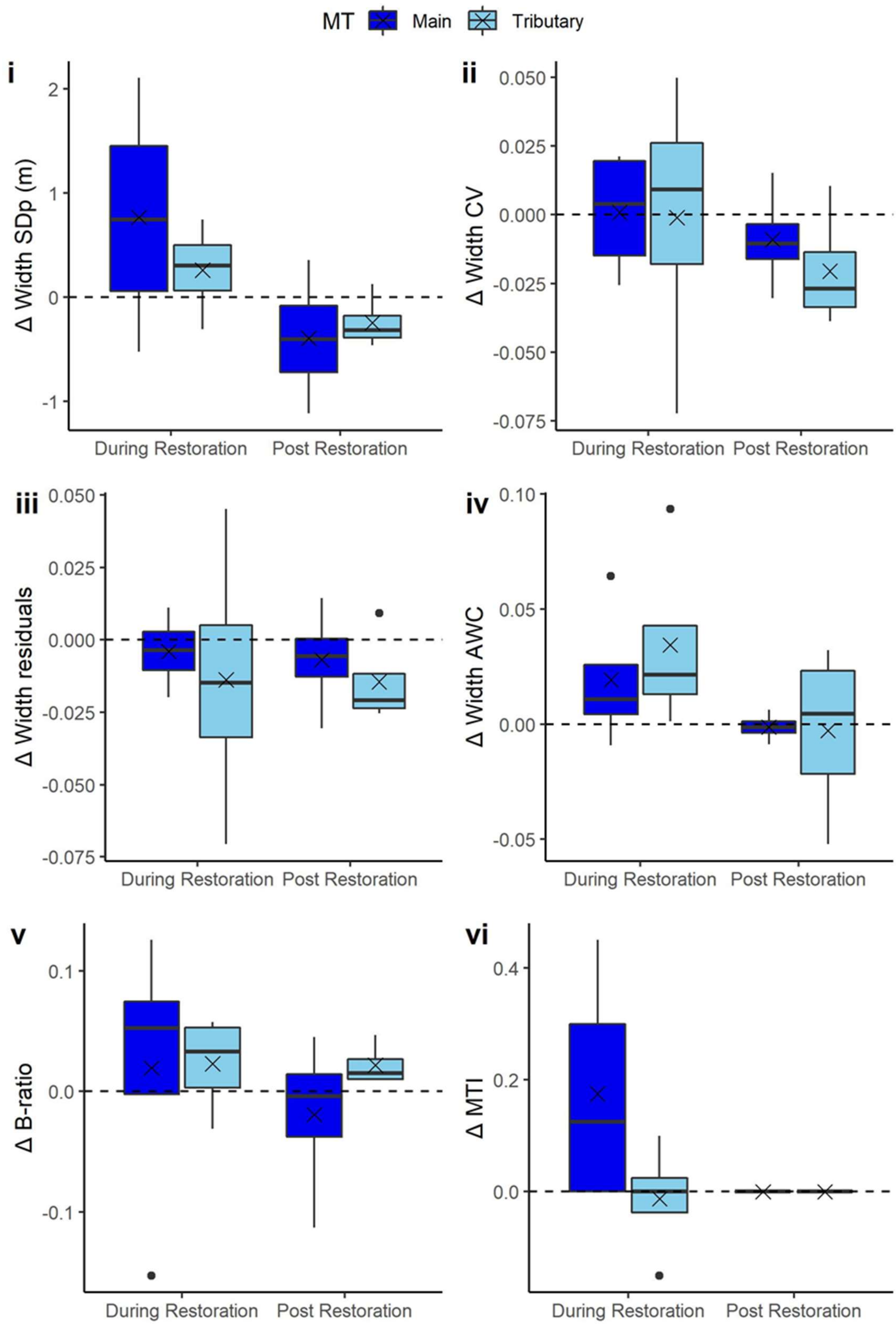

Figure A2.3. Boxplots of change in geomorphic complexity parameters of planform during and post restoration comparing sites on mainstem and tributaries.

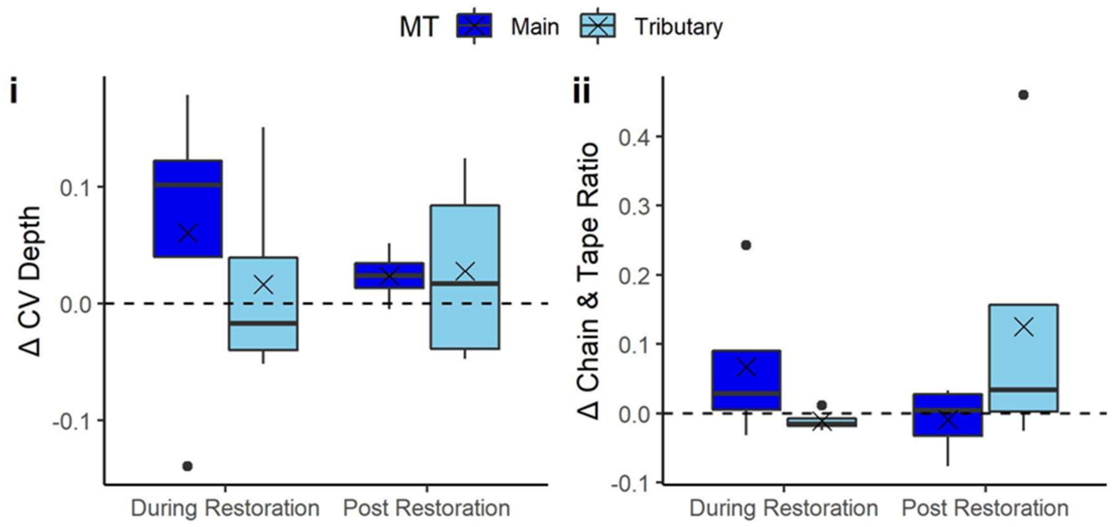

Figure A2.4. Boxplots of change in geomorphic complexity parameters describing cross-section transects during and post restoration comparing sites on mainstem and tributaries.

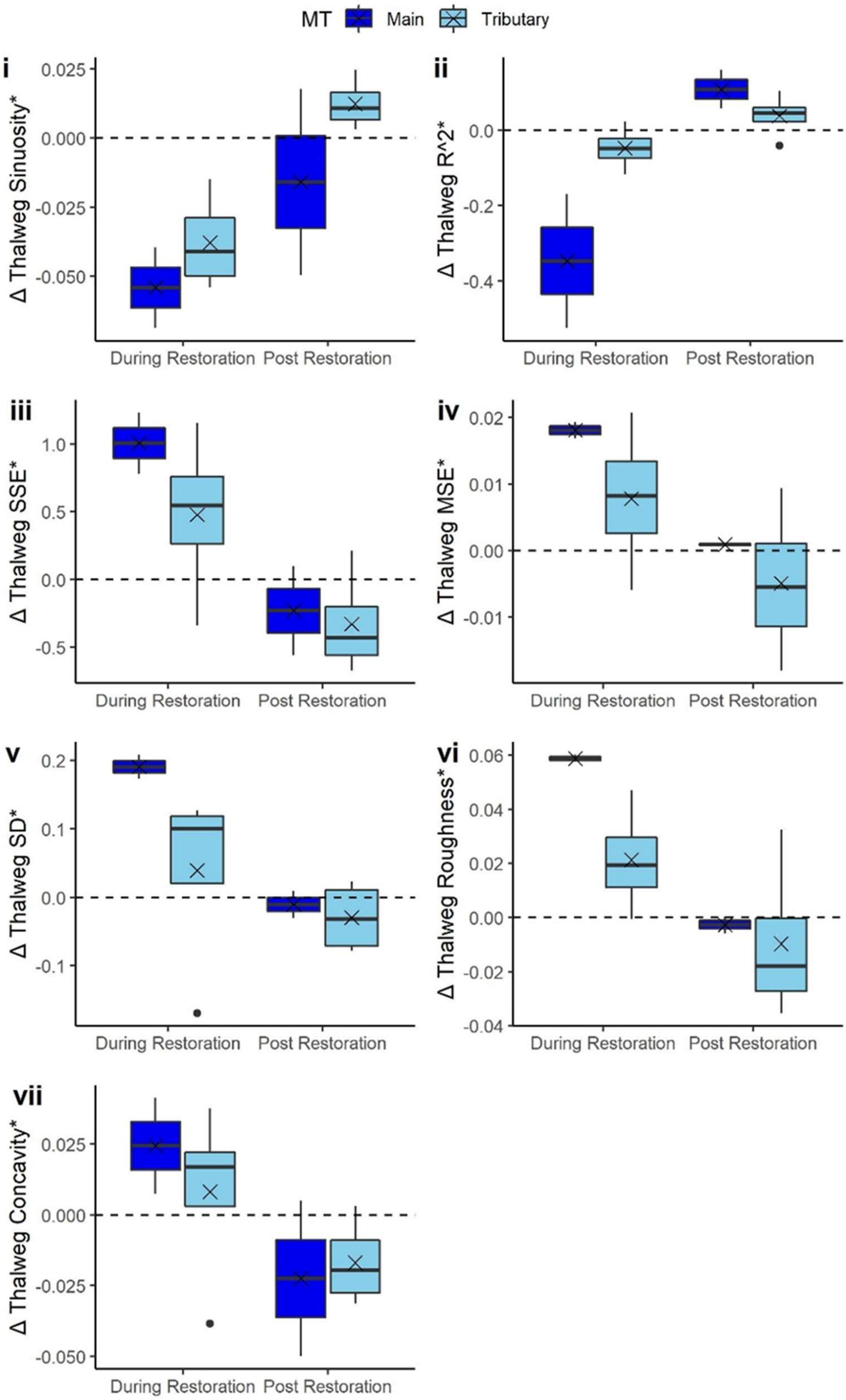

Figure A2.5. *Boxplots of change in geomorphic complexity parameters describing the thalweg and longitudinal profiles during and post restoration comparing sites on mainstem and tributaries.*

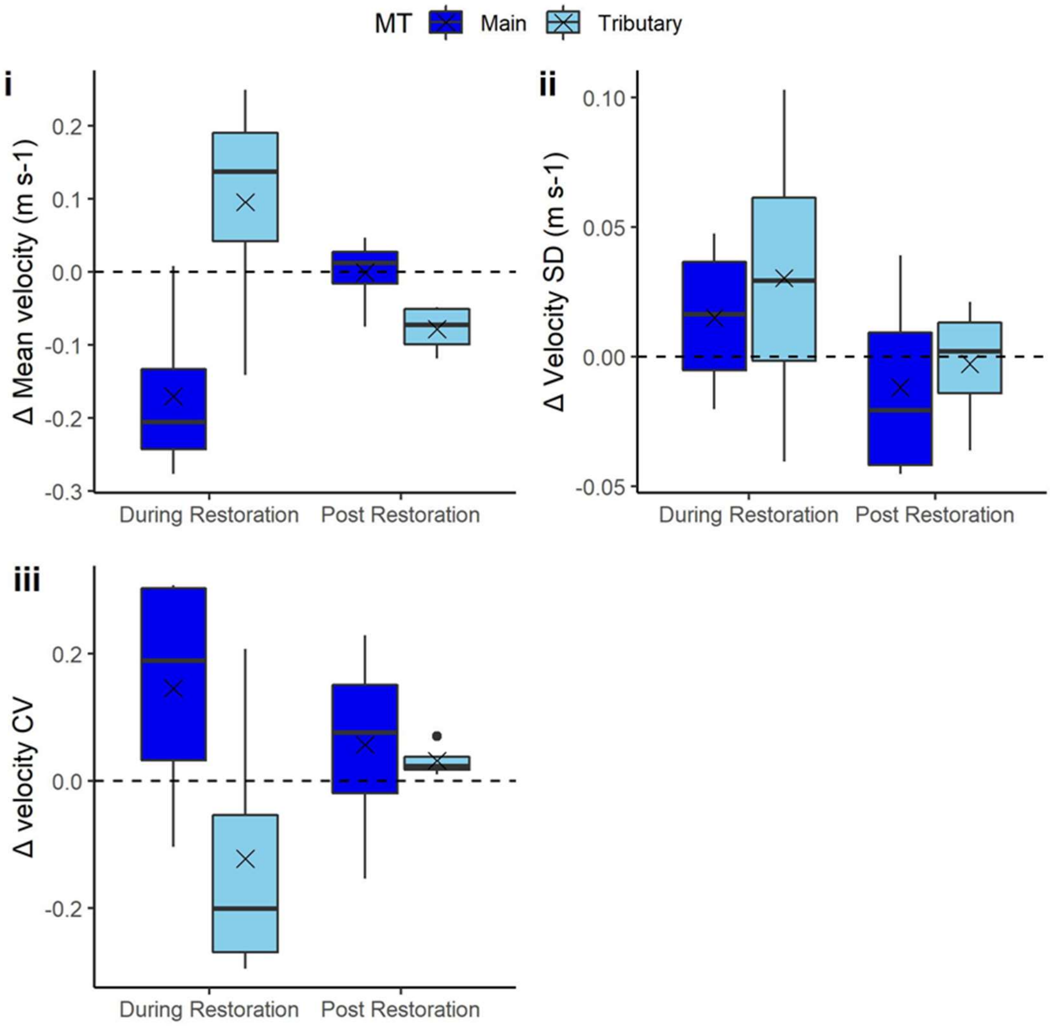

Figure A2.6. *Boxplots of change in hydraulic parameters during and post restoration comparing sites on mainstem and tributaries.*

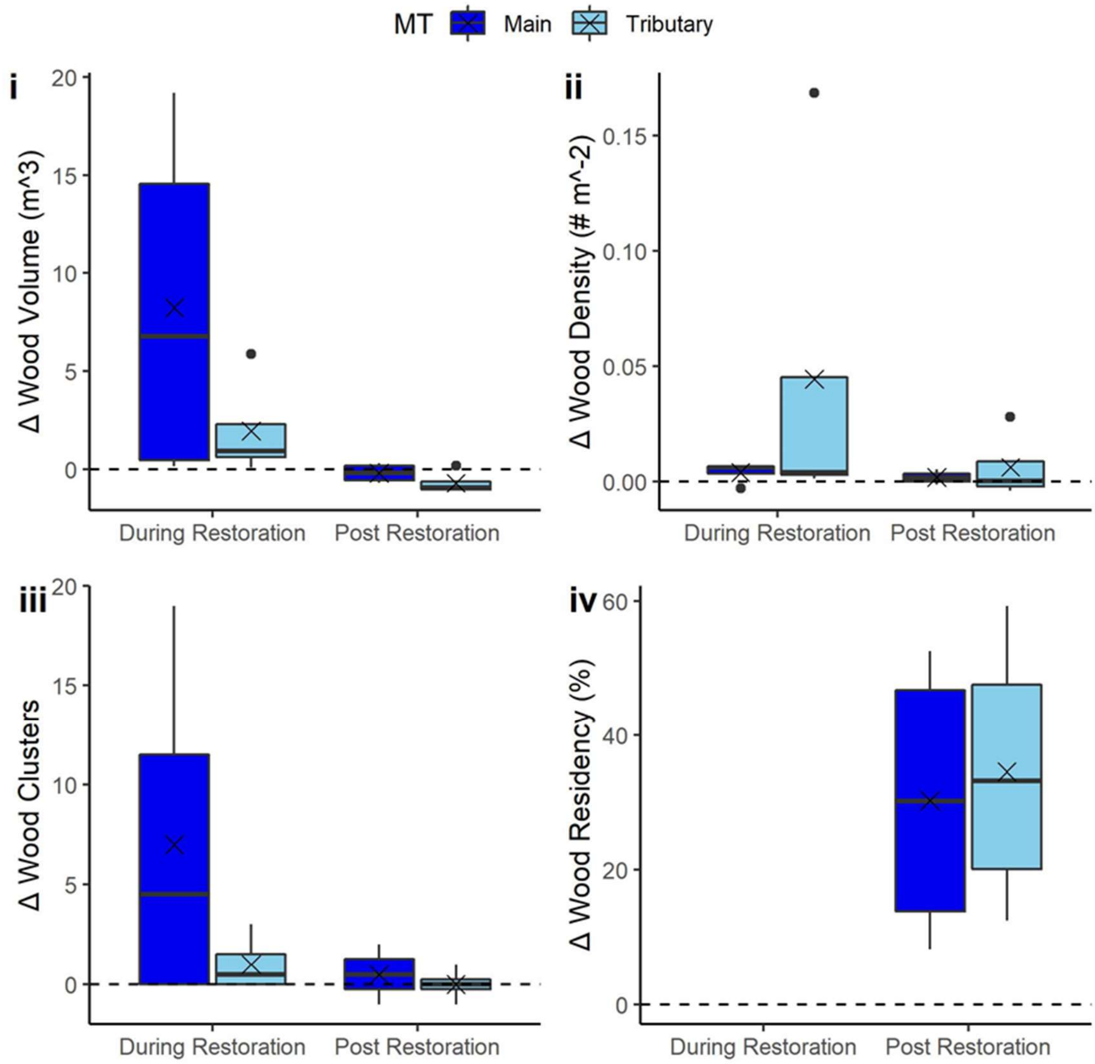

Figure A2.7. Boxplots of change in instream wood during and post restoration comparing sites on mainstem and tributaries.

7.3 Appendix 3: Above and below the FHC boxplots

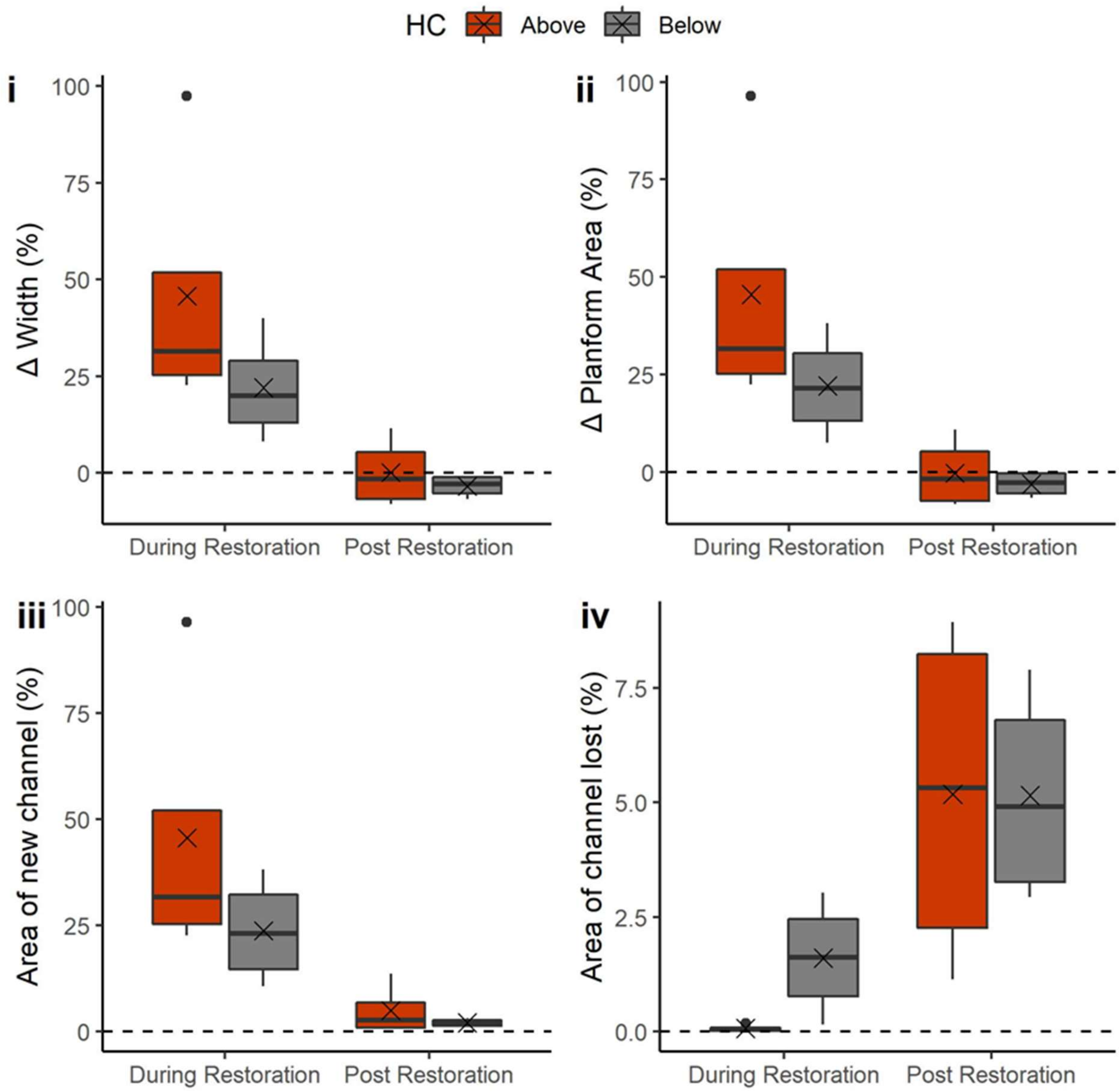

Figure A3.1. Boxplots of change in general geomorphic parameters describing planform during and post restoration comparing sites above and below the FHC.

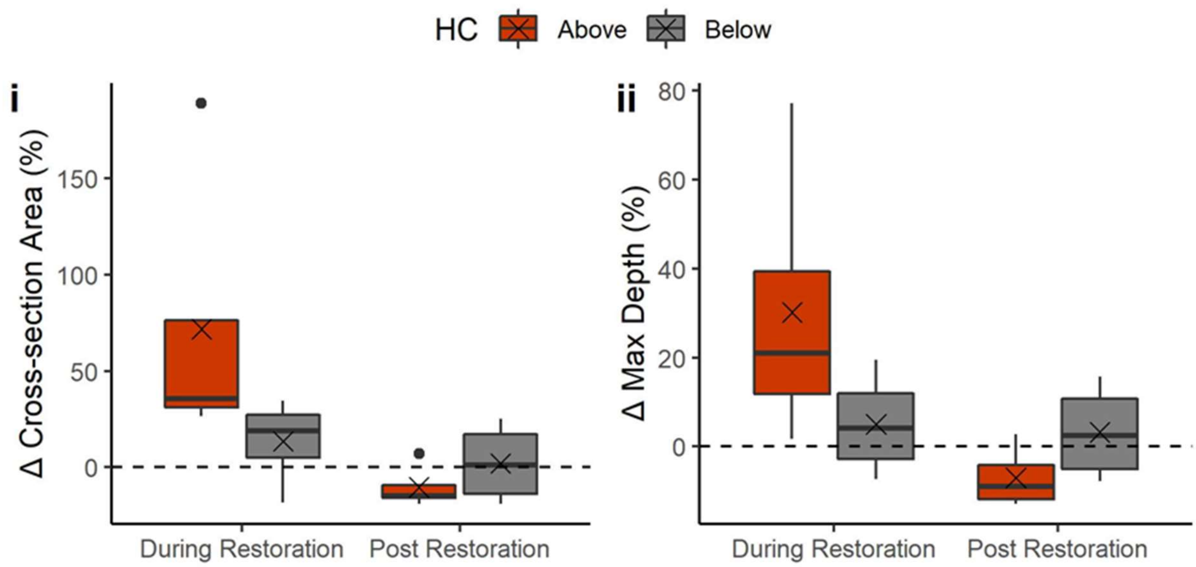

Figure A3.2. Boxplots of change in general geomorphic parameters describing cross-section transects during and post restoration comparing sites above and below the FHC.

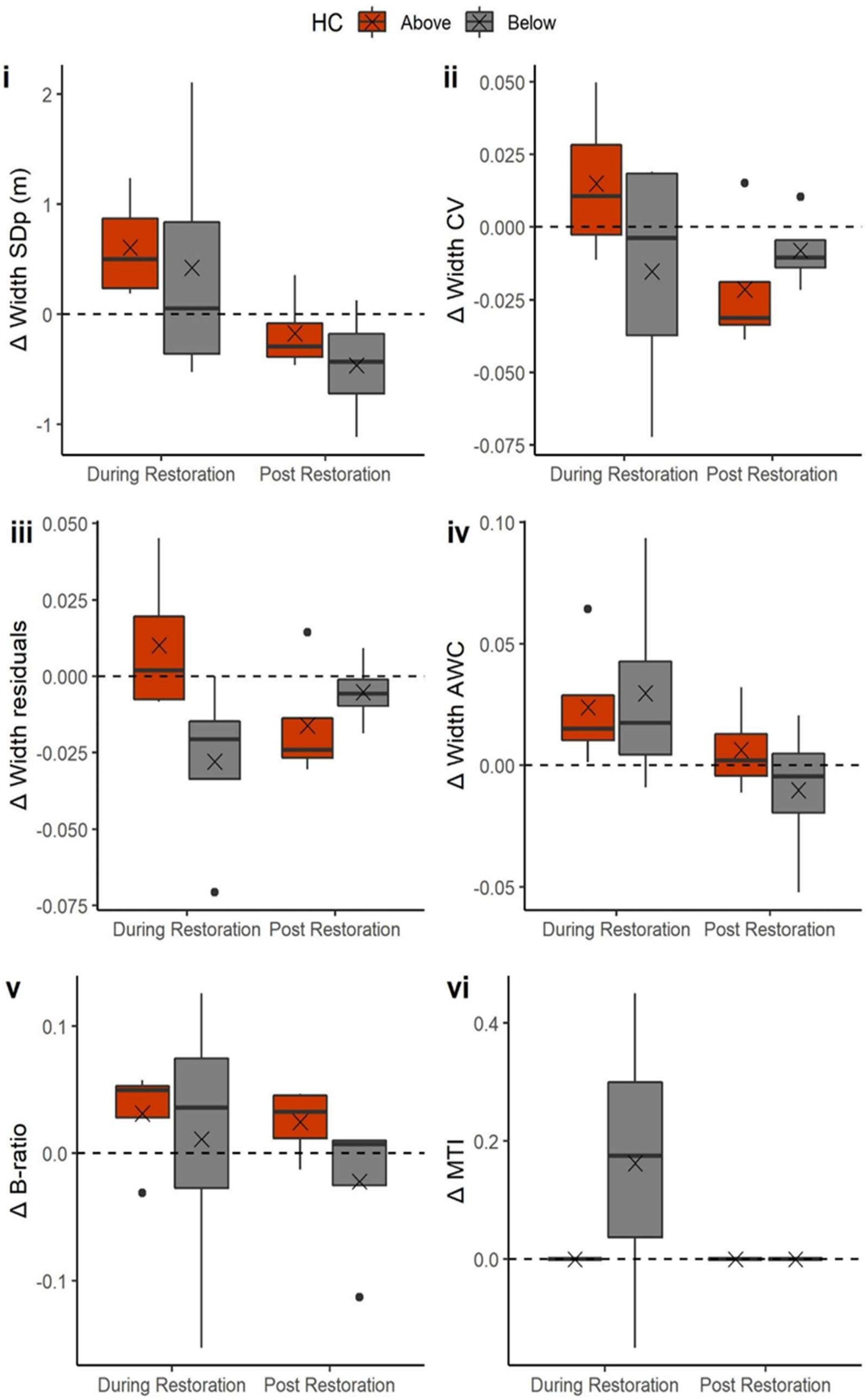

Figure A3.3. Boxplots of change in geomorphic complexity parameters describing planform during and post restoration comparing sites above and below the FHC.

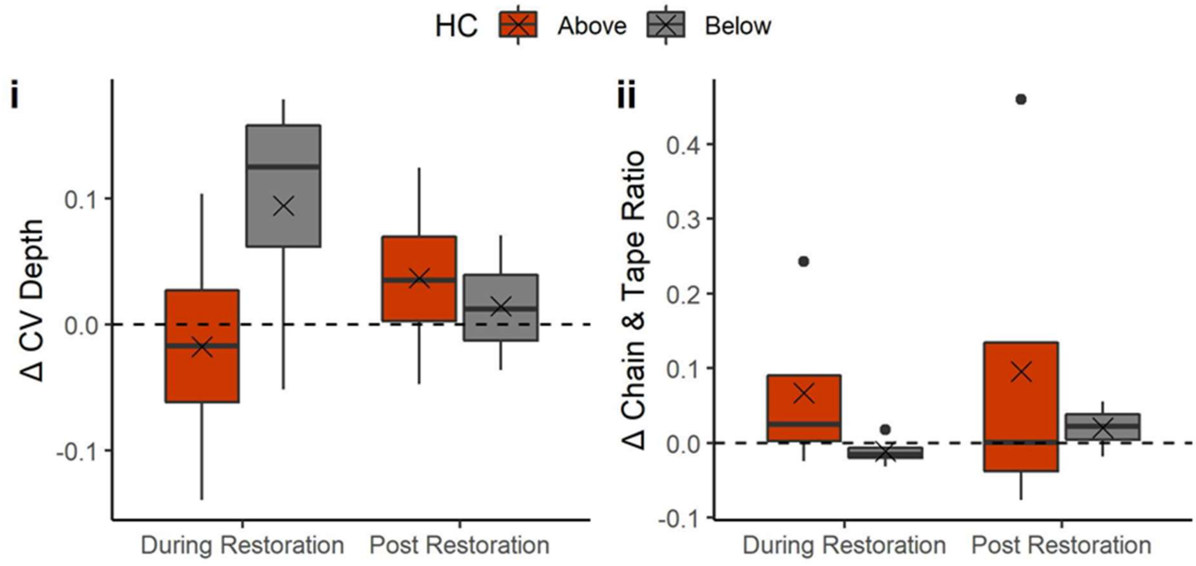

Figure A3.4. Boxplots of change in geomorphic complexity parameters describing cross-section transects during and post restoration comparing sites above and below the FHC.

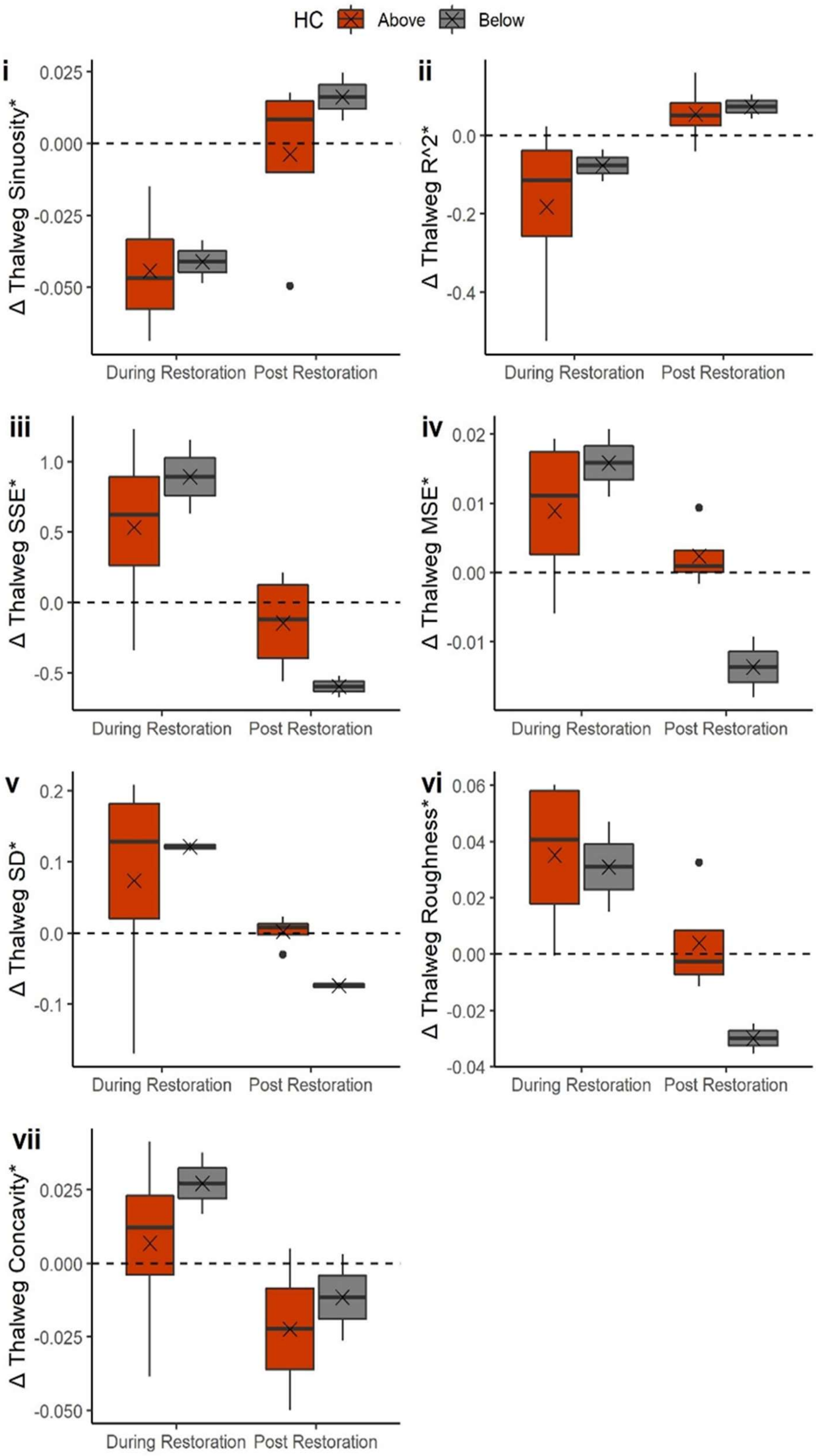

Figure A3.5. Boxplots of change in geomorphic complexity parameters describing thalweg and longitudinal profiles during and post restoration comparing sites above and below the FHC.

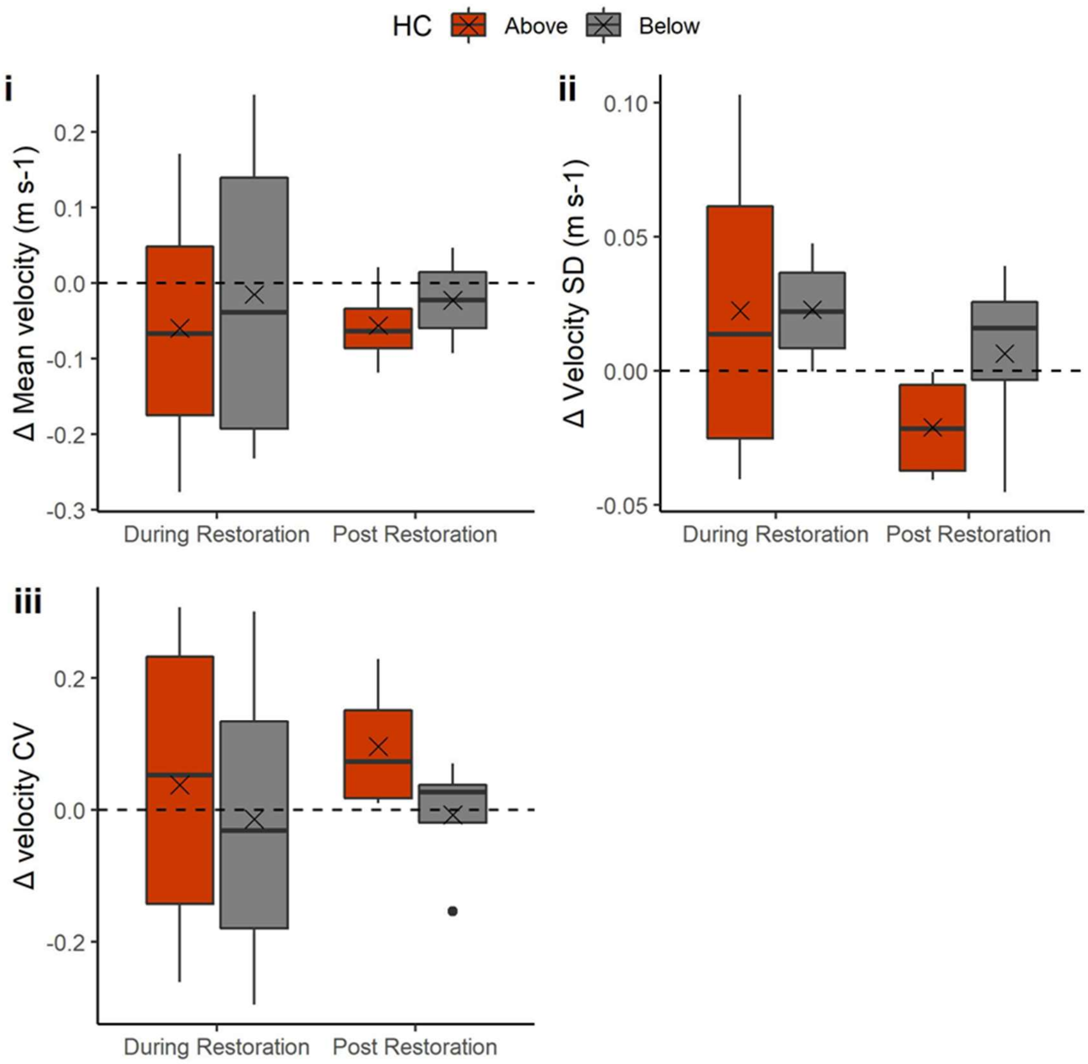

Figure A3.6. Boxplots of change in hydraulic parameters during and post restoration comparing sites above and below the FHC.

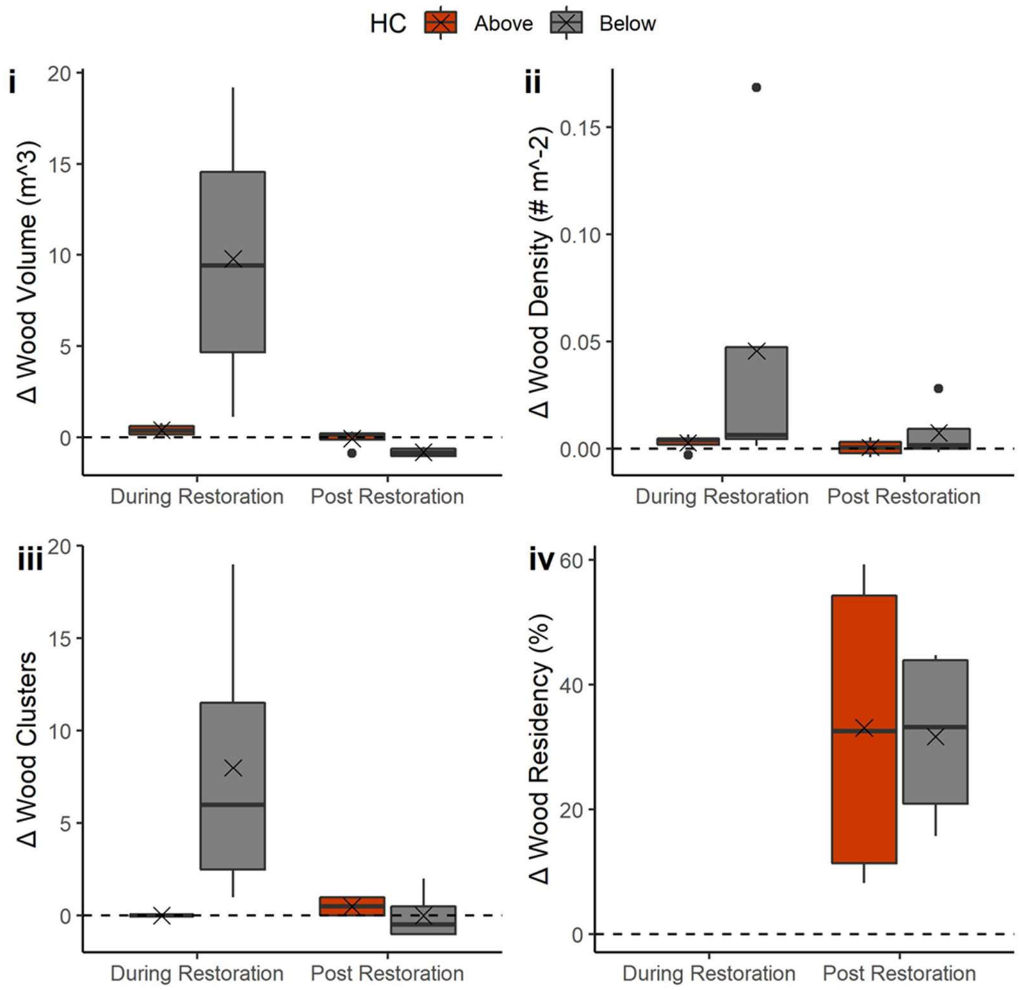

Figure A3.7. Boxplots of change in instream wood parameters during and post restoration comparing sites above and below the FHC.