A nine year assessment of the Logie Burn reach scale restoration project

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Abstract

Long term (≥10 years) assessments of river restoration projects remain rare but are needed to provide a robust evaluation of the success of restoration schemes. Moreover studies of low energy, sand-bedded restoration projects remain rare in contrast to higher energy gravel bed rivers. In such environments morphological degradation is often high due to channel straightening, dredging and fine sediment input (< 2 mm particle diameter). Questions remain over the nature of physical habitat changes (e.g. distribution of geomorphic units and changes in sediment texture) and whether or not there is an improvement. A 240 m long reach of the Logie Burn (catchment area: 25 km^2) in north-east Scotland was restored in 2011 through the reconnection of its meanders resulting in the formation of two backwaters. A monitoring project measured geomorphic, nutrient storage and sedimentary changes over time to evaluate the success of the project. Nine years after restoration, the reach appears to be still adjusting morphologically to the prevailing sediment supply and flow regimes as well as inputs of large wood. In common with other case studies of higher energy streams, diversity of in-channel geomorphic units improved over time and thalweg sinuosity increased indicating greater geomorphic complexity. However, sediment texture and total phosphorous (TP) within the active riverbed area appear to have largely stabilised to levels observed prior to restoration suggesting complete adjustment of these aspects to the flow and sediment supply regimes. In contrast the backwaters functioned as sinks where net fining and increased TP levels occurred.

Contents

1. Introduction

Long term (≥10 years) assessments of river restoration projects remain rare but are needed to provide a more robust evaluation of the sustainability and success of restoration schemes (Erwin et al., 2016). Often studies are short term (2-4 years; e.g. Addy and Wilkinson, 2019; Eekhout et al., 2015; Williams et al., 2020) in nature which may provide a limited insight into the success of restoration schemes as they may only quantify part of the adjustment phase following restoration. The magnitude and cumulative number of geomorphically significant floods are likely to be very important for the style and rate of adjusment. Moreover studies of low energy, sand-bedded restoration projects remain rare in contrast to higher energy gravel bed rivers. In such environments morphological degradation is often high due to channel straightening, dredging and fine sediment runoff (< 2 mm particle diameter). Due to land use, the extent and types of restoration may be constrained in some situations thus limiting the restoration of characterisic forms and processes. Questions remain over the nature of physical habitat changes (e.g. distribution of geomorphic units and changes in sediment texture) in such schemes and whether or not there is an improvement. It would be expected that restoring complex meandering channel planforms and, or reconnecting floodplains where possible would result in an improvement in the diversity or patchiness of sediment and geomorphic units (e.g. extent of pools, riffles and bars) within the active river channel. Also such channel restoration may have the effect of reducing velocities and encouraging the deposition of more fine sediment, organic material and nutrients.

Thus long term studies of these changes in processes and forms in restoration schemes are needed to help inform restoration projects in future. Whilst all projects are unique in terms of controlling conditions and findings are not necessarily transferable, such information could help inform:

(1) The optimal types of channel and catchment locations to target restoration efforts;
(2) Give an idea of levels of beneficial return and any negative side effects to be aware of and plan mitigation for and;
(3) Give information on the optimal channel planforms and levels of floodplain connectivity that restoration projects should strive for.

A 240 m long reach of the Logie Burn (catchment area: 25 km^2) in north-east Scotland (Figure 1) was restored in October 2011 through the reconnection of its meanders resulting in the formation of two backwaters (Figure 2). The Logie Burn flows through a catchment with a significant area of farmland and feeds into Loch Davan in the Muir of Dinnet National Nature Reserve (Figure 1). Further details on the Logie Burn and the nature of the restoration project are given in Addy and Wilkinson (2019).

The aims of the restoration project were to:

(1) Restore channel morphology, improve river and river bank (riparian) habitat;

(2) Reduce fine sediment and nutrient transfer into Loch Davan and;

(3) Act as a demonstration site for stakeholders to learn about restoration techniques and responses.

A monitoring project commenced in 2011 to quantify geomorphic, nutrient storage and sedimentary changes over time to evaluate the success of the project. The monitoring involved surveys of the restored reach immediately before and after restoration in 2011 and an upstream control reach from 2012. The control reach in contrast to the restored reach is slightly steeper, straighter and with poorer connection to the floodplain due to historical dredging and straightening. Thus it represented a degraded river reach (Figure 2). Both reaches were surveyed annually up until 2014.

Thereafter, surveys were carried out every two years up until 2020 when the monitoring ended. This provided a nine year record of changes since restoration.

This report builds on a previous report (Addy et al., 2022) by presenting new findings on the adjustment of bed sediment texture, nutrient storage, channel morphology and distribution of geomorphic units (e.g. extent of pools, riffles and bars). In this assessment, a distinction is made between the active riverbed areas of the control reach and the restored reach and the connected backwaters of the restored reach. The active riverbed areas are characterised by higher water velocities whilst the backwaters are charactersied by stagnant water under most flow conditions. It was hypothesised that restoring the meandering planform and processes compared to the control reach and pre-restoration, would result in:

(1) A reduction of median bed sediment size due to increased deposition of fine (<2 mm) sediment (H1) but an increase in the diversity of sediment patchiness measured by reduced sediment sorting in the active riverbed area (H2) and backwaters (H3);
(2) An increase in nutrient storage (measured by organic material mass and total phosphourous mass) within the active riverbed area (H4) and backwaters (H5);
(3) A reduction in channel adjustment over time in the active riverbed areas following the intial disturbance period and progression towards a dynamic-equilibrium state (i.e. erosion processes equalling deposition processes) (H6);
(4) A higher diversity of geomorphic units compared to pre-restoration and increase in the overall diversity of geomorphic units over time with an increase in the proportional extent of pools, riffles and bar features within the active river channel (H7).

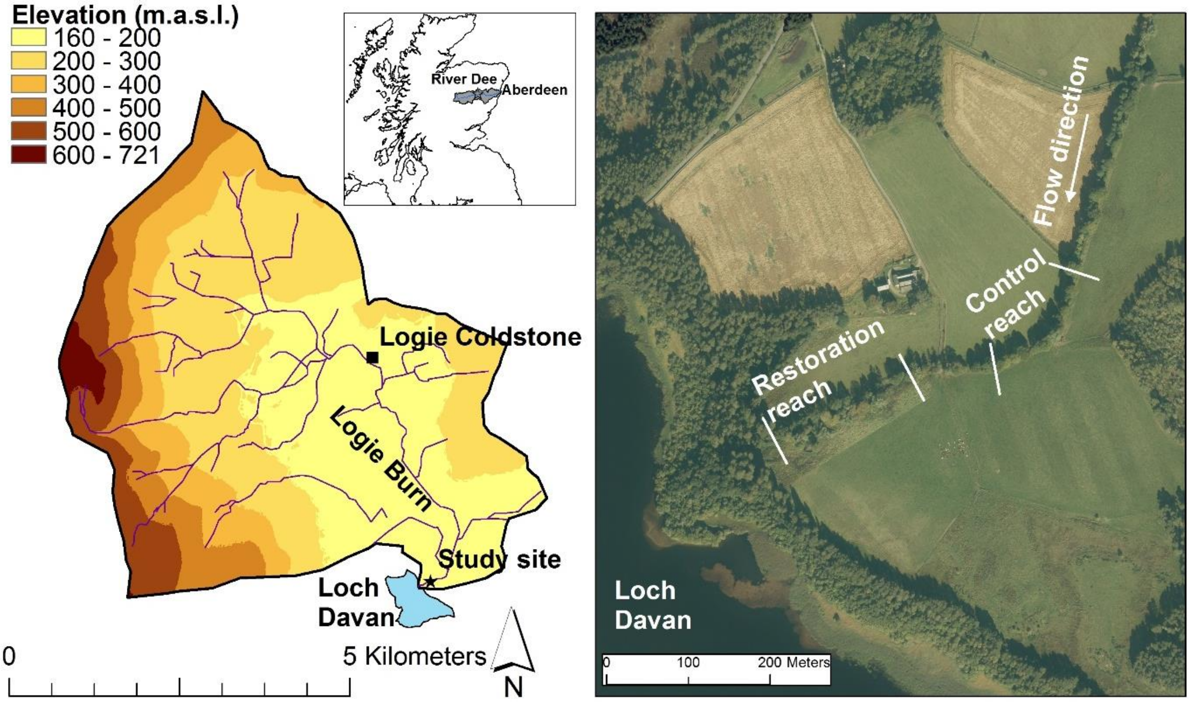

Figure 1 Location of the Logie Burn catchment, the restored reach and the control reach.

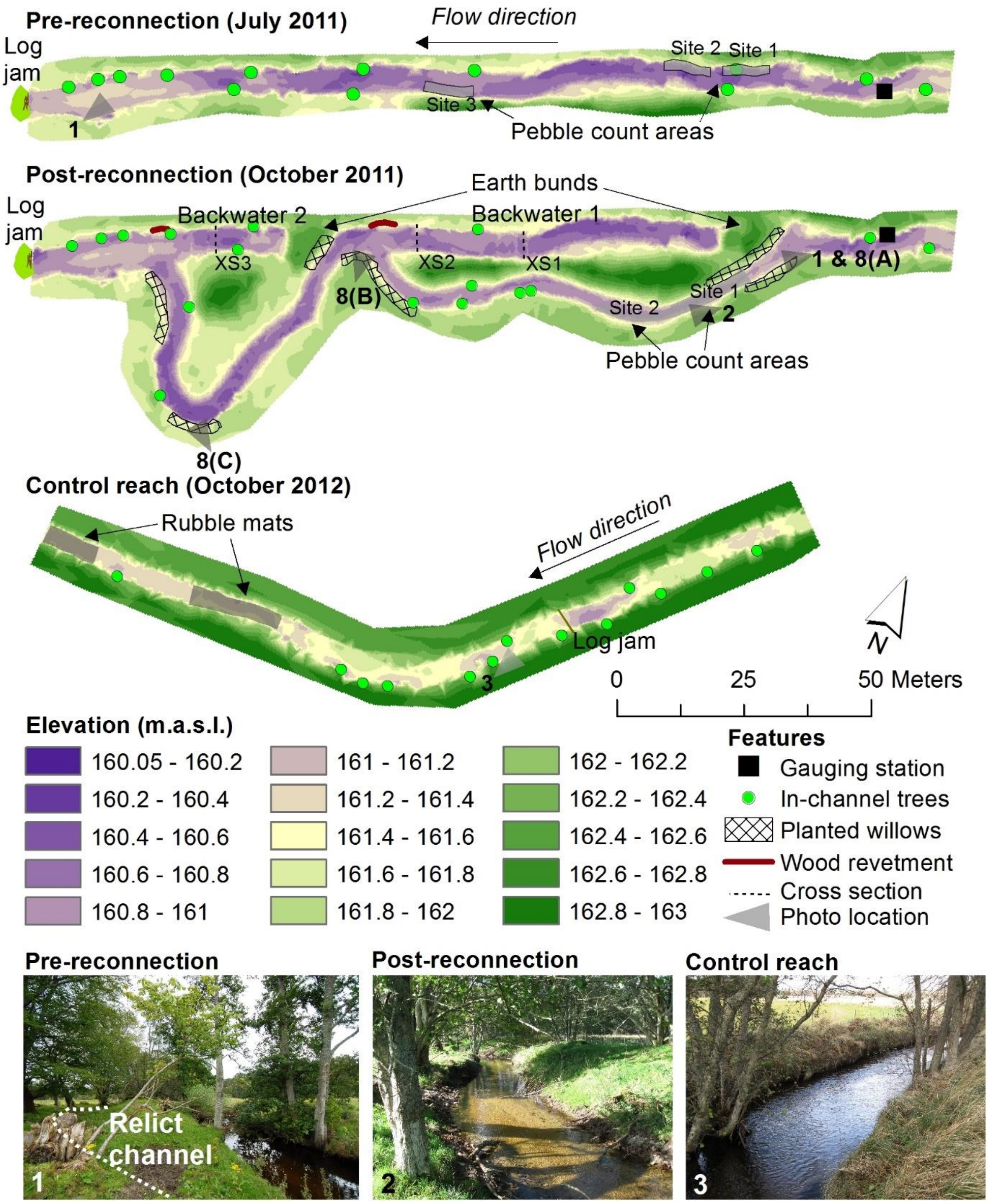

Figure 2 Pre- and post-restoration morphology of the restored reach and control reach.

2. Methods

Further details on the topographical survey, sediment survey and morphological change assessment methods are given in Addy and Wilkinson (2019) so only a brief overview of these methods is given here.

Topographical surveys

Ground based surveys were undertaken at ~0.5-1 m intervals using a total station to determine the stream bed and bank topography. Survey points were referenced to the British National Grid and coded according to the visually idenfied substrate type (e.g. gravel, sand or grass). Each survey was undertaken in low flow conditions during the October or November months.

Sediment surveys

The riverbed surface was spot sampled using 7.5 cm diameter metal ring cores over the extent of the active channel area in the restored and control reaches. Sediment samples were oven dried and sieved in a lab to determine grain size distribitution by mass. From the grain size distribution data, metrics of median grain size and % of fine sediment (particles < 2 mm diameter) for the total sample mass for each reach were derived. Organic material content by mass for each sample was determined by loss on ignition (LOI) testing and the storage of total phosphorous was measured by the sodium hydroxide fustion method.

Morphological change assessment

The topographical survey point data for each survey was imported into ArcGIS and converted into a Triangular Integrated Network (TIN) model. Each TIN was then converted into a 0.25 m resolution Digital Elevation Model (DEM) through direct interpolation. To quantify morphological changes (i.e. changes in channel shape due to erosion or deposition) and the net sediment volumetric change (i.e. gain or loss of sediment at the reach scale), the Geomorphic Change Detection (GCD; Riverscapes · GitHub) tool was used. The GCD tool accounted for the uncertainy in the DEMs using a Fuzzy Inference System (FIS) that incuded survey point density and slope to account for the spatial variability in the quality of both the DEM and the survey points. The GCD tool subtracted the changes in elevation between the old and new DEMs to produce a sequence of elevation change maps at 95% confidence interval and net volumatric change statistics over time that accounted for uncertainty in the source data. To capture changes in the bed longitudinal profile and sinuosity of the channel, thalwegs (deepest flow path of the river channel) were manually digitised in each DEM.

GUT (geomorphic unit tool) identification of geomorphic features

The Geomorphic Unit Toolbox (GUT; Riverscapes · GitHub) extension for ArcGIS was used to automatically and consistently define the extents of geomorphic features at the sub-reach scale (2-30 m) based on the shape of the togography. The tool has been applied succefully in a variety of stream restoration assesments in the UK where high resolution topography datasets are available (Williams et al., 2020; Maniatas et al., 2020; Costaz, 2022; Blackburn et al., 2022). DEMs, wetted area extent, banfull channel extent and thalwegs for each survey were used as the inputs to run GUT. The default rules for defining the geomorphic units were left unchanged. In all runs, the outputs were checked and compared to qualiative interpretation of geomorphic units in each DEM and with field observations. Areas of steeper planar areas of riverbed topography, were falsely defined as a rapids more commonly associated with cobble-boulder riverbeds in steep channels. These units instead were reclassified as runs. To quantify the changing diversity of geomorphic features in a single metric, the Shannon-Weiner diversity index was applied to each output of GUT.

3. Results and discussion

3.1 Sediment texture changes

Following restoration, the median bed sediment was variable in the first three years of adjustment within the restored reach (Figure 3A) but over the nine year period showed a small declining trend of from fine gravel (3.4 mm) to sand (1.9 mm) but slightly coarser than prior to restoration (1.6 mm). This was mirrored by the fining trend in the backwaters which was more marked (Figure 3B). In contrast the control reach showed greater variation but overall no trend in grainsize. Sediment sorting varied over time but exhibited no overall change over time in the control reach and restored reach (Figure 3C). In contrast the sediment sorting was more variable within the backwaters and showed a decline over time.

In summary the active riverbed sediment texture was essentially similar to pre-restoration but with a lower fines content (50% fines in 2020 compared to 60% fines in 2011 pre-restoration) thus hypothesis H1 is rejected. Sediment sorting reached a level similar prior to restoration and the control reach rejecting hypothesis H2 that restoration would increase the hetereogeneity of the bed sediment particle sizes in the active riverbed area. These obervations suggest that despite creating a meandering planform expected to be characeterised by increased complexity of hydraulic conditions and sediment transport, the active riverbed sediment texture is similar reflecting an ongoing, similar sediment supply regime. In contrast in support of hypothesis H3, the backwaters showed a marked gain of fine sediment and poorer sorting over time reflecting their roles as sinks for fine sediment deposition. The backwaters may have helped to reduce fine sediment deposition over the active riverbed area leading to the slighly lower fines content.

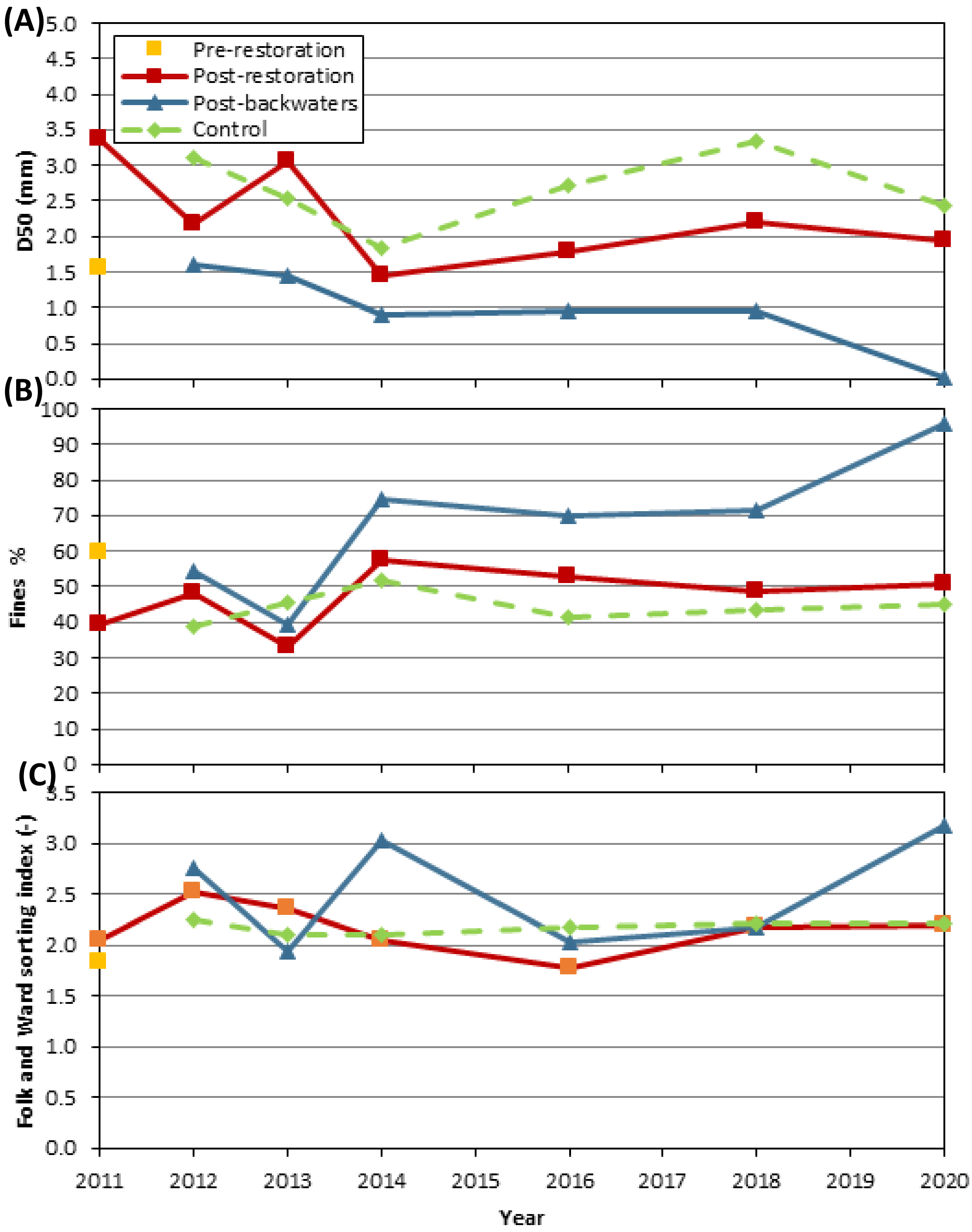

Figure 3(A) Median bed sediment size variation between 2011 and 2020, **(B)** fine sediment (<2 mm particle diameter) percentage of total sediment sample mass and **(C)** sediment sorting index.

3.2 Nutrient storage changes

Organic matter content was high within the restored active riverbed immediatley following reconnection reflecting the residual deposits of organic matter (Figure 4). These deposits were rich in TP with higher levels than prior to restoration but were soon eroded away within a year and organic matter and TP levels settled down to levels similar to pre-restoration and the control reach. Over time levels changed little and by 2020, the active riverbed levels were basically unchanged. In contrast, the backwaters accumulated organic matter and TP levels over the nine years with final levels of both markedley higher than the control and restored reach active riverbeds.

In summary, the restoration of a meandering planform did not increase nutrient storage within the active riverbed area (rejection of H4) but did within the backwaters reflecting their sediment sink function (acceptance of H5). The finding that the backwaters trap a large amount of fine sediment and nutrients suggests that the restored reach has more capacity to reduce and delay the movement of nutrient rich sediment into Loch Davan thus satisfying the second goal of the restoration project. However such levels could lead to nutrification and ecologial degradation within the backwaters depedning on the rates of nutrient uptake and mobilisation (Ballantine et al., 2009).

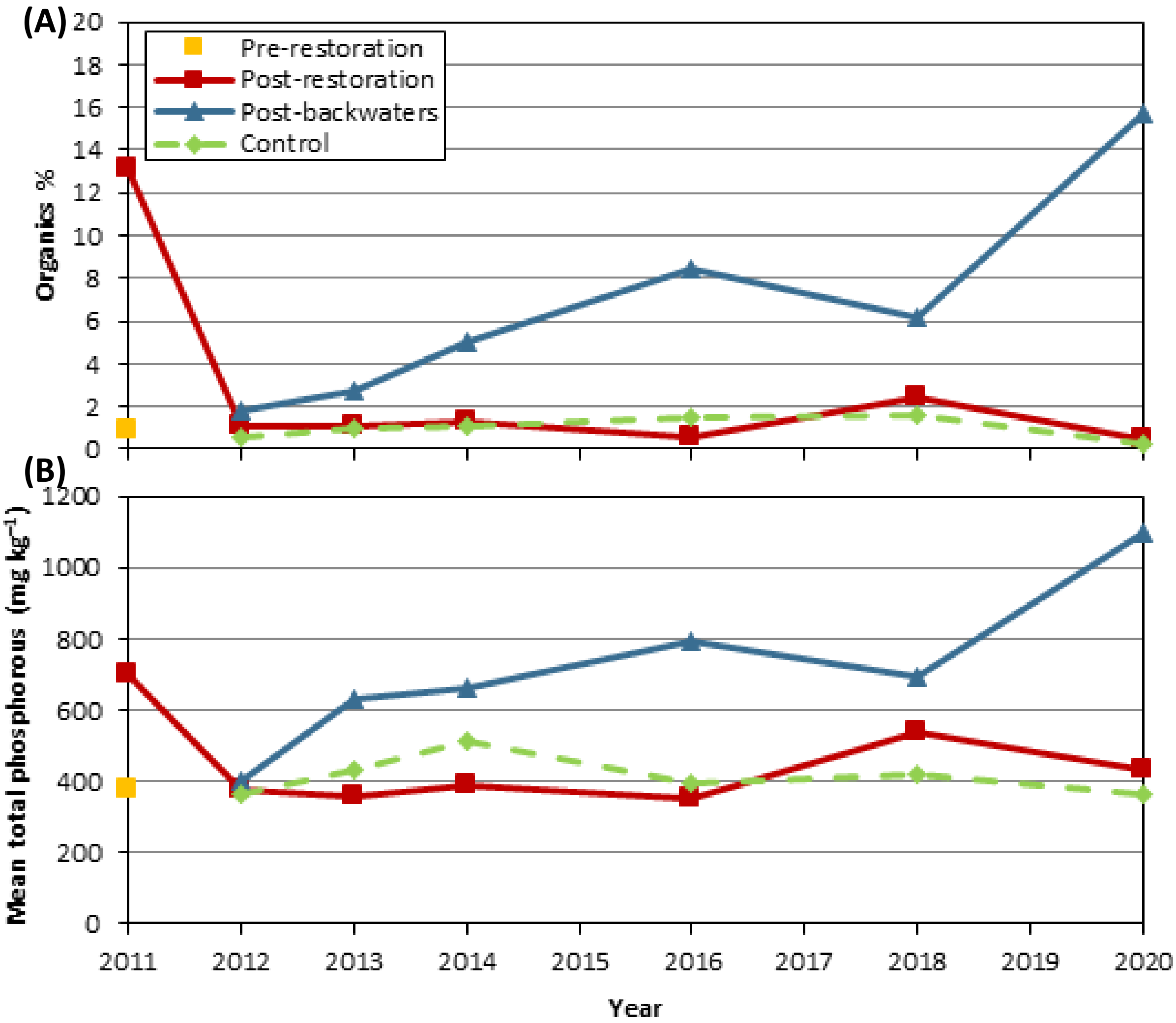

Figure 4(A) Variation of organic percentage by sediment sample mass (based on loss on ignition testing) and **(B)** mean bed sediment total phosphorous storage.

3.3 Morphological change

Over time, the riverbed profile of the restored reach rose in elevation reflecting the net aggradation response (Addy et al., 2021) following restoration (Figure 5). Much of this adjustment was complete within the first 5 years following restoration with less adjustment observed between 2016 and 2020. The input of large wood and subsequent formation of log jams, resulted in localised upstream deposition. Further local variability in the bed elevation profile occurred due to the formation of the pool (topographical lows) and riffle (topographical highs) sequence characteristic of meandering channels. Channel thalweg sinuosity showed a gradual increase over time to a level in 2020 that was slightly higher than the control reach and the pre-restoration reach (Figure 6).

The control reach showed less change in thalweg bed elevations over 2012 to 2020 indicating a stable morphology adjusted to its banks, flows and sediment supply (Figure 5). Over this period the sequence and shape of topographical highs and lows remained essentially unchanged although there was aggradation towards the end of the reach associated with the occurance of an in-stream rubble mat. Furthermore, channel thalweg sinuosity remained essentially the same over the period again indicating stability.

The lack of thalweg bed elevation and sinusoity change within the control reach indicates that the marked changes within the restored reach were due to its inherent adjustment to long term average, natural flow and sediment supply regimes rather than a marked catchment wide disturbance (e.g. marked increase in flooding or sedimemt supply). If a such a disturbance occurred, it would be expected to also be reflected by large changes in both reaches (e.g. consistent and marked net depositional or erosional responses).

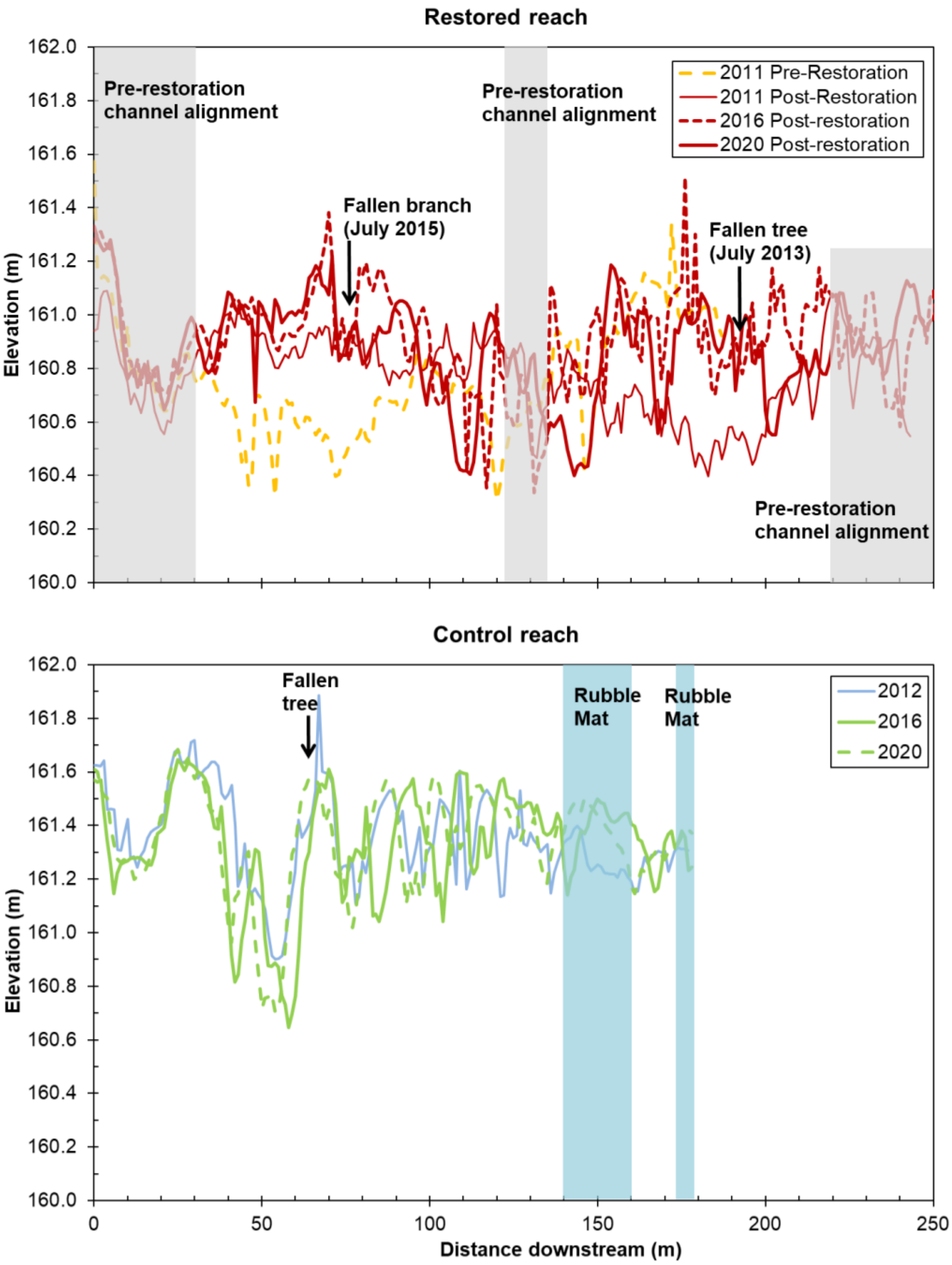

Figure 5 Variation of riverbed thalweg (deepest flow paths) elevations over time. Locations of large wood input (due to natural tree and branch fall) and rubble mat structures deliberately placed in 2007 by the Dee Fishery Board to improve habitat for fish shown.

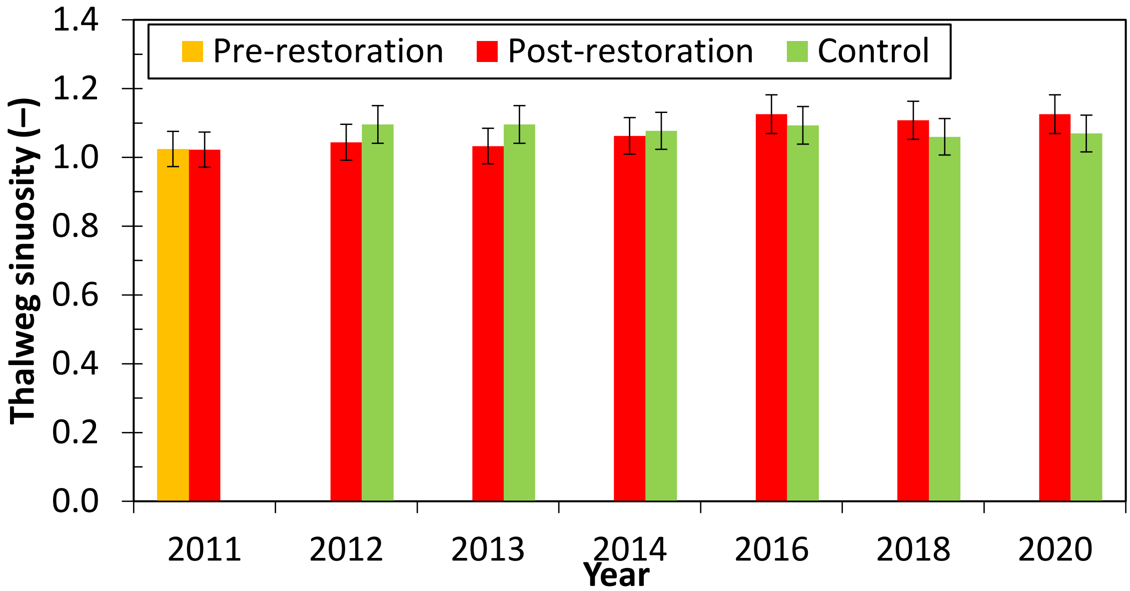

Figure 6 Variation of thalweg sinuosity over time. Assumed +/- 5% error bars shown.

Net volumetric changes over time at annual and biennial temporal scales, were higher within the restored reach compared to the control reach and for most sub-periods (5 out 6), depositional in nature (Figure 7). The depositional response reflects in part the low energy, meandering morphology of the restored reach making it a more effective sediment trap compared to the higher energy, straight control reach. It also likely reflects the continued sensitive and adjusting nature of the restored reach combined with the input of large wood that both liberated locally sourced sediment through scour and trap sediment from these sources and further upstream. However closer scrutiny of the sub-periods shows changing morphological behaviour over time. After a marked post-restoration response of deposition that lasted 5 years, notably during the 2016-2018 period, the net deposition response was much lower indicating a progression towards a dynamic-equlibrium state (Figure 7). However this behaviour suddenly shifted to a signiciant net erosional response over 2018-2020 indicating that the restored reach was still in a sensitive state. It is likely that this response at least partly reflects the 'Storm Alex' flood event on the 4th October 2020, possibly largest flood on record, that occurred shortly before the survey was undertaken (Figure 8). The erosion occurred in the form of locally significant bank erosion alongside bed erosion. In contrast, a net erosional response was observed within the control reach but it was much smaller and confined to the bed. These observations suggest that the restored reach after nine years has not fully adjusted to the prevailing flow and sediment regimes thus hypothesis H6 can be rejected.

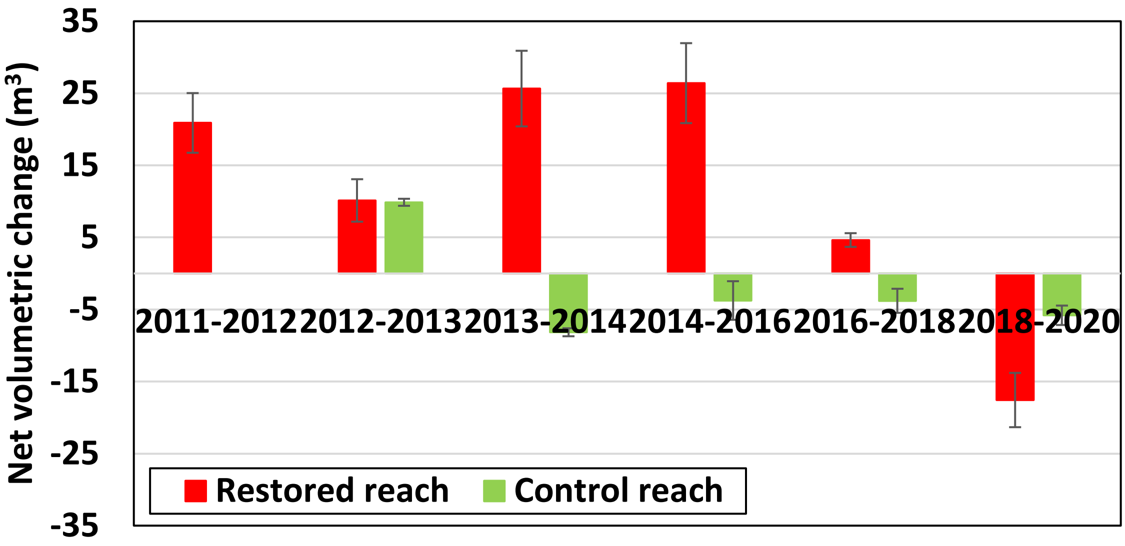

Figure 7 Annual net volumetric changes over time based on DEM differencing. Error bars based on DEM error dervied from the FIS error maps.

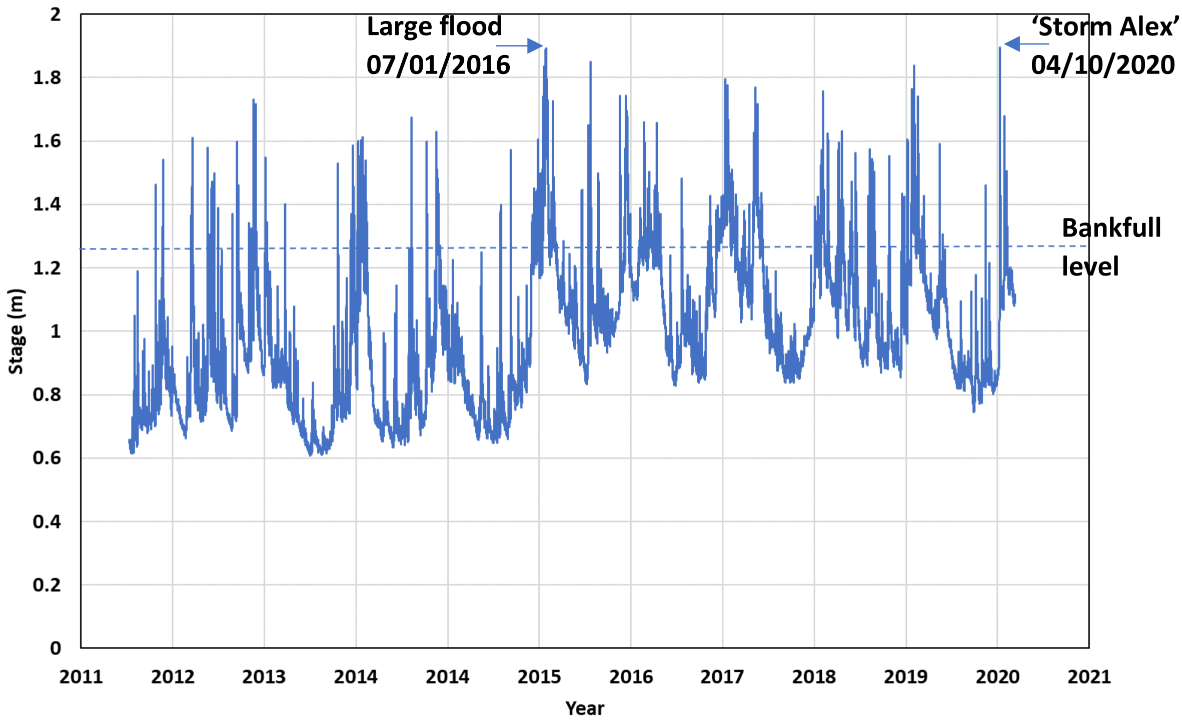

Figure 8 Stage hydrograph (see Figure 2 for station location). Note stage is predicted and therefore uncertain from early 2016 onwards (based on a relationship with the upstream gauging station as the original station was moved). Stage from 2016 onwards also influenced by formation of a log jam that led to backwater effects (higher stages).

3.4 Development of geomorphic units

Mapping of geomorphic units with GUT showed changes in the spatial distribution of units over time both within the restored reach and the control reach (Figure 9). To begin with following restoration, pool units were distributed almost continuously through the restored reach combined with extensive areas of glide-run and transition units. This simplified layout of units presumably reflects the recently excavated and unnatural channel geometry. This differed to the more patchy arrangement of units prior to restoration that was also dominated by pools, glide-runs and transition units. By 2020, a more complex mosaic of units emerged compared to immediately pre- and especially post-restoration, reflecting natural morphological adjustment associated with the newly created meandering planform. The reach was dominated by pool, glide-run and transition units. Localised patchiness of units also occurred through the input of large wood generating scour and erosion processes that in turn created units and widened the channel. The restored reach also gained bar features in the form of a mid-channel bar upstream of the lower log jam and margin attached bars throughout. These bar features were lacking prior to restoration.

Compared to the restored reach both pre- and post-restoration, the spatial and statistical distribution of geomorphic units was considerably simpler over time in the control reach with glide-runs and pools dominating (Figure 10). Over time, the diversity of units also steadily increased within the restored reach whereas it remained essentially static in the control reach following an initial increase then decrease between 2012 and 2014 (Figure 11). By 2020 the diversity within the restored reach was relatively higher than the pre-restoration state (increase in diversity of 13%) lending support to hypothesis H7 that restoration increases the diversity of geomorphic units. This suggests a small improvement in the range of habitats available compared to the degraded morphological state thus partially satisifying the first goal of the restoration project.

The observation of improved geomorphic diversity is similar to recent studies of restored reaches in higher energy rivers than the Logie Burn that applied GUT over < 10 year timescales (Williams et al., 2020; Spray et al., 2021; Blackburn et al., 2022). However given so far the lack of stabilisation of diversity and the continued morphological adjustment nine years on from restoration, there is potential for the diversity to increase or decrease beyond the period of monitoring undertaken. This contrasts to obervations from the Ben Gill, a steeper and coarser stream where dynamic-equilibrium was suggested to occur roughly 4.5 years following restoration (Blackburn et al., 2022).

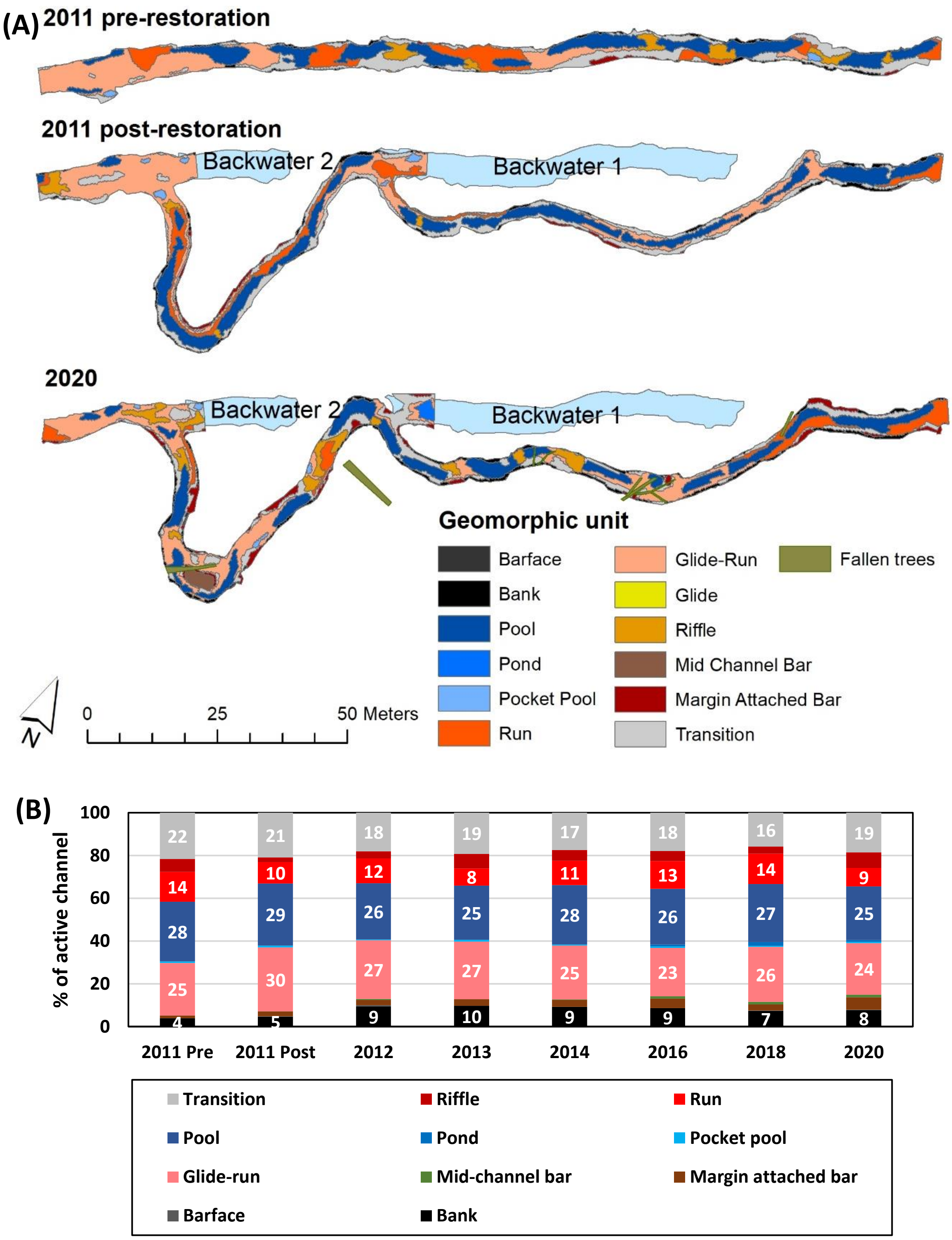

Figure 9(A) Distribution of geomorphic units in 2011 and 2020 within the restored reach identified using the GUT tool. **(B)** Proportions of geomorphic units over time.

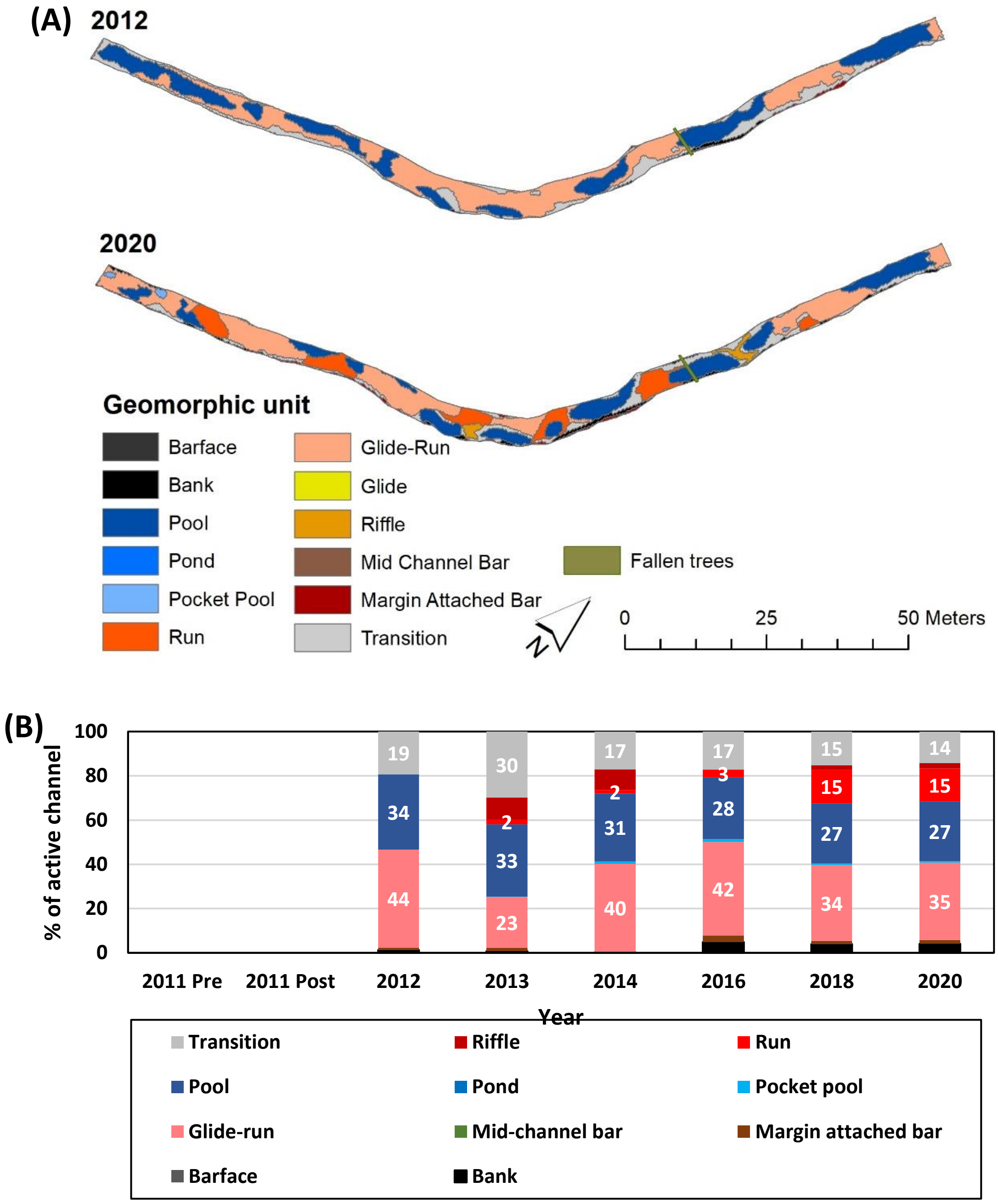

Figure 10(A) Distribution of geomorphic units in 2011 and 2020 within the control reach identified using the GUT tool. **(B)** Proportions of geomorphic units over time.

The overall heterogeneity of geomorphic units as meausured by the Shannon-Weiner diversity index, shows a clear difference between the restored reach and the control reach over time (Figure 11). This suggests differences in the inherent controls on the variability of morphology between the two reaches. The control reach is straighter, more entrenched, slightly steeper with well vegetated, steep and high banks. These conditions result in deeper water and higher water velocities. This favours either onward transport of sediment or adjustment through vertical erosion or deposition over the bed rather than lateral adjustment through bank erosion. In contrast the restored reach is lower in gradient and less entrenched, conditions that favour lower water depths and velocities, and in turn riverbed deposition as observed through most of the monitoring period. However, the potential for channel adjustment through lateral movement via bank erosion as compensation for riverbed deposition reducing channel capacity, is likely to be higher than the control reach due to the lower banks and sinuous planform. This has had the effect of both generating greater inputs of sediment from the banks that in turn leads to an increase in thalweg sinuosity and generatation of geomorphic units such as bars. The bank erosion also creates more space for new geomorphic units thus further bolstering overall diversity. These explanations were given for the increasing diversity of units observed on the higher energy gravel-bed Allt Lorgy in Highland region (Williams et al., 2020). Following the removal of riverbank protection in 2012 that opened up eroding bank sediment supply sources and created accomodation space, a greater diversity of geomorphic units were generated in the 4 years of adjustment that followed (increase from 1.40 to 2.05) Williams et al., 2020).

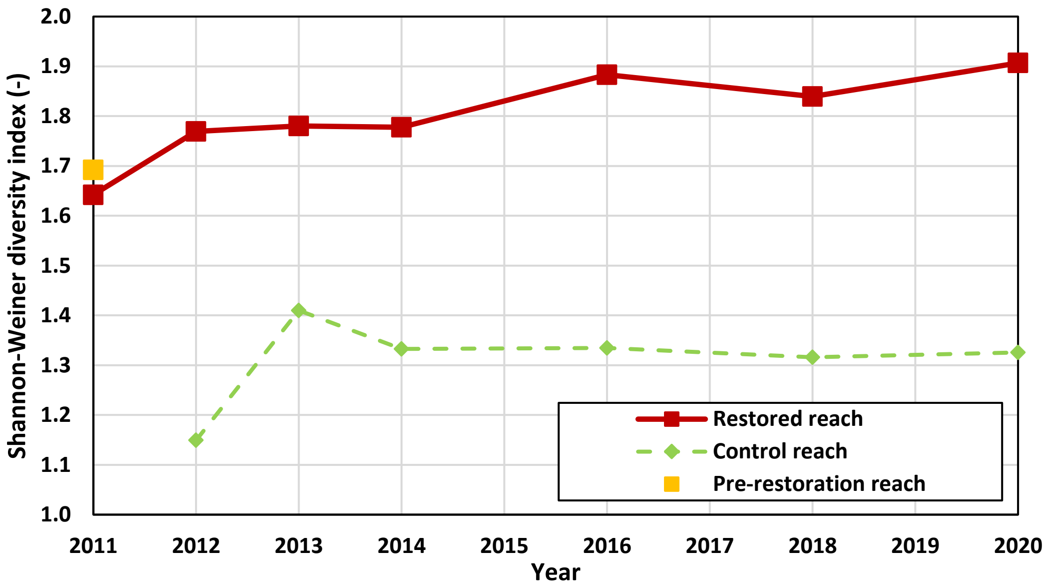

Figure 11 Change in the diversity of geomorphic units over time.

4. Conclusions

Nine years of monitoring adjustments of channel geomorphology, nutrient storage and sediment texture on the restored reach of the Logie Burn gives a near long term case study of a restoration project in a straightened, low energy stream. In summary, the monitoring showed that the reach appears to be still adjusting morphologically to the prevailing sediment supply and flow regimes as well as inputs of large wood (Figure 12). However, sediment texture and nutrient storage within the active riverbed area appear to have largely stabilised to levels observed prior to restoration suggesting adjustment to the flow and sediment supply regimes within the nine-year period. The continued morphological adjustment suggests that a longer period of monitoring may be required to assess the restoration project following further flood events. Although the findings in this study may be unique and site specific, the study further underlines the need to monitor beyond 2-4 years and perhaps even longer than 10 years to reliably capture the full range of changes in similar low energy, streams elsewhere.

In evaluating the success of the project after nine years of adjustment the responses were mixed. In common with other case studies of higher energy streams, diversity of in-channel geomorphic units improved and thalweg sinuosity increased reflecting steady morphological adjustment throughout the period. However, sediment texture did not show an improvement in variability with a slightly lower but still high fine bed sediment content (50% compared to 60% pre-restoration) that may be ecologically detrimental. Monitoring of nutrients (organic matter and total phosphorous) showed levels of storage in the active riverbed of the restored reach were similar to pre-restoration. In contrast within the backwaters, nutrient storage was higher within these sink areas suggesting an improvement in the retention capacity of the reach that satisfies one of the goals of the project.

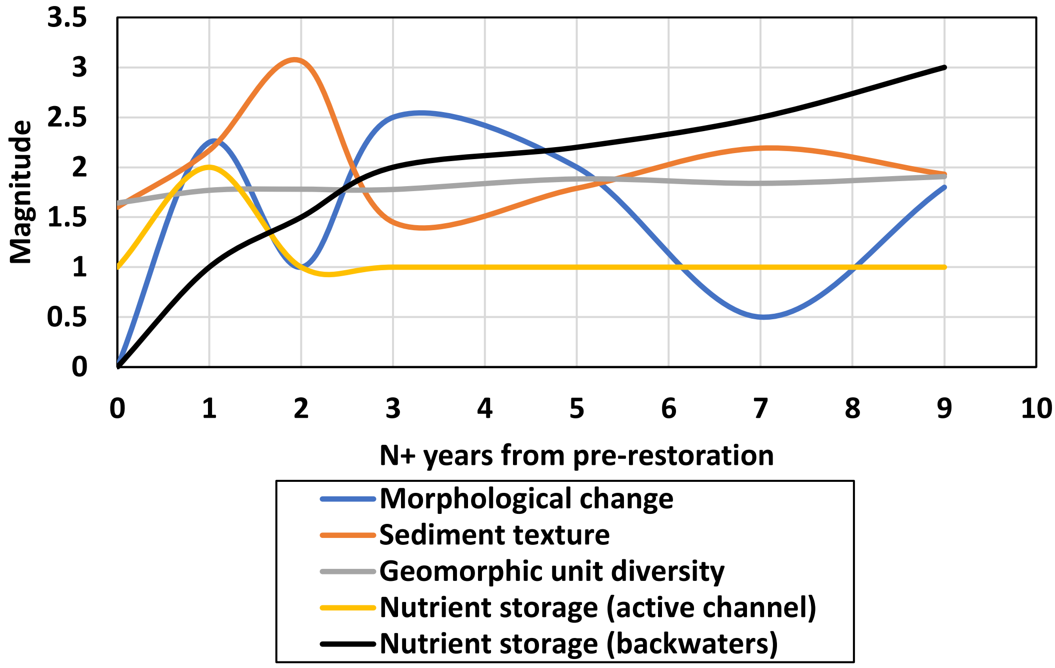

Figure 12 Conceptual overview of geomorphic, sedimentary and nutrient storage changes in the restored reach of the Logie Burn. Qualitative levels given for morphological and nutrient storage changes. Sediment texture based on median bed sediment sizes and geomorphic unity diversity based on Shannon-Weiner index.

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Acknowledgments

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