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## Abstract

River restoration practice frequently employs conservative designs that create and maintain prescribed, static morphology. Such approaches ignore an emerging understanding of resilient river systems that typically adjust their morphology in response to hydrologic, vegetative and sediment supply changes. As such, using increased dynamism as a restoration design objective will arguably yield more diverse and productive habitats, better managed expectations, and more self-sustaining outcomes. Here, we answer the following question: does restoring lateral migration in a channelised river that was once a wandering gravel-bed river, result in more diverse in-channel geomorphology? We acquired pre- and post-restoration topographic surveys on a segment of the Allt Lorgy, Scotland to quantify morphodynamics and systematically map geomorphic units, using Geomorphic Unit Tool (GUT) software. GUT implements topographic definitions to discriminate between a taxonomy of fluvial landforms that have been developed from an extension of the River Styles framework, using 3-tiered hierarchy: (1) differentiation based on stage or elevation relative to channel; (2) classification of form based on shape (mound, bowl, trough, saddle, plane, wall); and (3) mapping geomorphic units based on attributes (e.g., position and orientation). Results showed restoration increased geomorphic unit diversity, with the Shannon Diversity Index increasing from 1.40 pre-restoration (2012) to 2.04 (2014) and 2.05 (2016) after restoration. Channel widening, due to bank erosion, caused aerial coverage of in-channel geomorphic units to increase 23% after restoration and 6% further in the two-years following restoration. Once bank protection was removed, allowing bank erosion yieled a local supply of sediment to enable the formation and maintenance of lateral and point bars, riffles and diagonal bar complexes, and instream wood created structurally-forced pools and riffles. The methodology used systematically quantifies how geomorphic unit diversity increases when a river is given back its freedom space. The framework allows for testing restoration design hypotheses in post-project appraisal.

## Keyworks (6)

River restoration, geomorphic unit classification, high resolution topography, fluvial geomorphology, lateral migration, freedom space

## 1 Introduction

Traditional river restoration practice, which seeks to improve the form of channels predominantly does so by grading with large construction equipment (i.e. diesel power). That grading is recognition that changes in topography are necessary to improve conditions, but the vast majority of such projects do not design to promote adjustment of topography (i.e. via fluvial processes of erosion, deposition and change in storage). This is in despite of calls for more process-based approaches (Beechie et al., 2010) that might allow fluvial and biological (Castro and Thorne, 2019; Johnson et al., 2019) processes to drive such topographic change. Put another way, we expect our rivers to have chiselled, toned and muscular bodies, but we fail to recognize the roll exercise and diet play in shaping that form, and instead rely solely on reconstructive surgery (Wheaton et al. 2019). Indeed, resilient river systems typically adjust their morphology to yield more spatially and temporally diverse and productive habitats that are often the aim of restoration interventions (Ward, 1998). However, restoration practitioners and managers often fail to include increased dynamism as a design objective and rarely "*let the water do the work*" as coined by Zeedyk and Clothier (2014), trusting instead in our ability to grade channels with diesel power instead of removing constraints and allowing rivers to create their own forms through time with stream power. Broadly, there is irrational fear of channel adjustment and a misunderstanding of the role that bank erosion, as part of lateral migration, plays in both providing important local sediment supply and building diverse instream habitat (Florsheim et al., 2008). Such fear has been accentuated by a lack of objective approaches to systematically quantify river morphology and physical habitat to provide a necessary evidence base. The proliferation of high resolution topographic (HRT; Passalacqua et al., 2015) surveys that capture river morphology before and after restoration will at least enable mapping and quantification of patterns of erosion and deposition (Marteau et al., 2016).

Field-based approaches to classifying morphology and habitat units have long been the standard in river science (e.g. Hawkins et al., 1993; Moir and Pasternack, 2008; Raven et al., 1998), but involve subjective interpretation of unit type and unit boundaries. This subjectivity along with a high potential for individual surveyor and/or inter-protocol variance has led some to conclude that field-based repeat surveys of channel units are unreliable for use in quantitative analyses (Roper et al., 2010). However, topographic surveys have been shown to reliably reproduce the morphology of riverscapes (e.g. Bangen et al., 2014; Williams et al., 2014; Williams et al., 2019) and can be used for a variety of classification approaches. Morphological units (Wyrick et al., 2014) provide a more consistent lens but also require hydraulic modelling which is, by definition, stage-dependent so a user must decide what flow(s) to model (Wheaton et al. 2015). *Belletti et al.'s* (2017) Geomorphic Unit Survey and classification system (GUS) offers a framework for mapping geomorphic units and is generally either field-based or derived from remotely sensed imagery. At coarser scales, fluvial unit mapping has been demonstrated using data from remote sensing (Bizzi and Lerner, 2012; Roux et al., 2015) but these do not resolve finer-scale in-channel units.

In response to the problems associated with consistently mapping geomorphic units from the aforementioned approaches, a fluvial taxonomy (Wheaton et al., 2015) was developed that builds upon the River Styles Framework (Brierley and Fryirs, 2000) and provides explicit topographic definitions for geomorphic units. The Geomorphic Unit Tool (GUT; http://gut.riverscapes.xyz) is currently an open-source set of research-grade GIS scripts with ArcPy dependcies, which applies the definitions from the fluvial taxonomy of *Wheaton et al* [2015] to objectively and consistently delineate units from topographic data (Bangen et al., 2017). This more consistent approach to mapping geomorphic units has potential for assessing changes in geomorphic units as part of quantitative river restoration monitoring.

This paper focuses upon using consistent Geomorphic Unit (GU) mapping for the post-project appraisal (Downs and Kondolf, 2002) of a process-based restoration design for a wandering gravel-bed river. Process based restoration (Beechie et al., 2010) of riverscapes is gaining momentum (Wohl et al., 2015; Powers et al, 2018; Wheaton et al. 2019). One important component of this has been giving rivers space, allowing rivers to be more dynamic by removing constraints to lateral migrationacross their own valley bottoms (e.g. Freedom Space; Biron et al. 2014; Buffin-Belnager et al. 2015). This paper addresses the question: does allowing the process of bank erosion to take place and reclaim some its former active channel spacein a river that was artificially straightened but was historically a dynamic, wandering gravel-bed river, result in more diverse in-channel habitat? We use a series of pre- and post-restoration high resolution topographic surveys of the Allt Lorgy river restoration project in Scotland to systematically map changes in geomorphic unit (GU) mosaics using GUT. We then interpret the findings in the context of common applied river management objectives. The discussion focuses upon the utility of a repeatable and objective mapping approaches for interepreting changes, as well as  a recasting of Allt Lorgy's adjustemnt in the context of *Cluer and Thorne's* (2014) stream evolution model and the relationships between geomorphic units, physical habitat and ecology.

## 2 Methods

### 2.1 Site Description and Restoration

Allt Lorgy is a tributary of the River Dulnain, within the Spey catchment, Scotland (Figure 1). At the downstream end of the study reach the catchment area is 21.6 km$^2$. The bankfull discharge, estimated using the ReFH 2 model (Kjeldsen, 2007) is 8.17 $m^3s^{-1}$. The 50 year flood, estimated using the same method, has a peak discharge of 21.9 $m^3s^{-1}$. Based on area-scaled discharge statistics area from the nearest downstream flow gauge (Balnaan Bridge on the River Dulnain; catchment area 272 $km^2$), the mean daily flow is 0.42 $m^3s^{-1}$. The 10%, 50% and 95% exceedance flows are 0.82, 0.30 and 0.11 $m^3s^{-1}$ respectively. Analysis of historic maps from 1875 and 1982 (Figure 1c) show that the river was characterised by geoindicators that are characteristic of a wandering gravel-bed river (i.e., the presence of active bank erosion and islands, braiding index fluctuating between 1 and 2, and moderate sinuosity). Moreover, evidence from the historic mapped planform indicates the presence of diagonal bar complexes and wood accumulations. Manual, categorical, expert-derived analysis of confinement (Fryirs et al., 2016) show that in 1875 the study reach was in a partly confined, margin-controlled setting (Figure 2a). In 1982 the study reach had a lower confinement ratio but the setting remained the same as in 1975 (Figure 2b). In the mid-1980s, a c. 500 m long reach of the river was altered to convert the floodplain to agricultural land. Alterations included channel realignment (i.e. straightening), extensive raised embankments, dredging and boulder bank toe protection. Combined, these interventions caused increased channel confinement relative to 1982, resulting in an anthropogenic partly confined setting (Figure 2c), and associated incision of the channel bed, disconnection of high-flows from the floodplain and impacted sediment transport processes.  These impacts subsequently led to a decrease in geomorphic unit heterogeneity and associated habitat diversity. Prior to restoration, the study reach exhibited a generally plane bed morphology at its upstream extents, transitioning to a constrained pool-riffle morphology with some gravel bars as the valley width increases and the bed slope decreases in the downstream direction.

Approximately 500 m of the 720 m long study reach was restored in August-September 2012 using a process-based (Beechie et al., 2010) approach to design. The design hypothesis was that if artificial constraints to the lateral migration of the channel were removed then accommodation space would be generated by bank erosion, which creates a local supply of sediment, which can help develop bar and more diverse geomorphic units in that accommodation space. Restoration components that were undertaken in August-September 2012 included (Figure 1d): removing or lowering of protected embankments to enable the initiation of lateral erosion and the creation of diagonal bar complexes; gravel augmentation (injection) to initiate the development of bars; wood placement on bar apexes to initiate mid- or lateral bar development; and cross-channel wood placement to create plunge pools and riffles. This intervention removed most constraints to natural bank erosion although in places, as a result of channel incision, the bank tops may be higher than they were prior to channelisation. Gravel augmentation was undertaken at two locations (Figure 1d), one near the upstream limit of the site and the other just downstream of the major migrating meander bend. Material was piled adjacent to the channel and was entrained during moderate flows. Sediment augmentation was repeated in October 2015. During the August-September 2012 construction phase, turf from lowered or removed embankments was put back ("re-thatched") onto the exposed surface underneath. Lowered or removed embankments were planted with tree saplings but they largely didn't establish. However, by the time of the 2016 survey, natural pine saplings had started to establish although their distribution was sparse. Analysis of valley confinement (Figure 2d) shows that restoration measures removed anthropogenic confinement measures, resulting in a partially confined, margin-controlled setting with the same margin types as in 1982.

### 2.2 Topographic surveys and geomorphic change

Topographic surveys were acquired before restoration, in 2012, and post-restoration in September 2014 and October 2016 (Figure 3). The September 2014 survey was acquired in the aftermath of ex-Hurricane Bertha in August 2014, which caused flooding in northeast Scotland (National Climate Information Centre, 2015). The 2016 survey was a repeat monitoring survey. Each survey was undertaken using a combination of total station and Real Time Kinematic (RTK) GNSS. We used the same topographically stratified sampling strategy (Brasington et al., 2000; Fuller et al., 2003) for each survey whereby survey point density was increased in areas with high geomorphic complexity and breaklines were surveyed along linear features such as bank tops and toes. Mean point densities for the 2012, 2014 and 2016 surveys were 0.1, 0.4 and 0.8 points/m$^2$ respectively. The topography surveyed in 2012 was more topographically simple that that surveyed in 2014 and 2016 hence the application of a topographically stratified sampling strategy resulted in a lower point density for the 2012 survey. Digital Elevation Models (DEMs) were generated by interpolating a triangular irregular network (TIN) from point data using a Delaunay triangulation in AutoCAD software. Breaklines were used to constrain the TIN and ensure a realistic geometry (Lane et al., 1994). The TIN was subsequently converted into a 0.2 m resolution DEM using linear interpolation.

To provide context for the analysis of temporal changes in geomorphic units, geomorphic change was mapped using a probabilistic thresholding approach (Brasington et al., 2003), using Geomorphic Change Detection software (GCD v7.10; Wheaton et al., 2010). To calculate the propagated error in the DEM of Difference (DoD) a spatially constant Standard Deviation Error (SDE) of 0.100 m was assumed. This value was taken from *Bangen et al.'s* (2014) extensive assessment of uncertainty in DEMs of wadeable rivers; it is equal to the maximum SDE value obtained for RTK-GNSS and TS surveys, of wet and dry areas. Geomorphic change was mapped at the 80% confidence interval (Vericat et al., 2017).

To investigate the hypothesis that restoration enabled bank erosion to supply sediment that was subsequently reworked to create a variety of geomorphic units, mutually exclusive polygons were digitised around individual erosional and depositions units on the thresholded DoDs. These polygons were then classified manually to interpret the mechanism of geomorphic adjustment (Wheaton et al., 2013). The following morphodynamic signatures classes were used: channel lowering; bar sculpting; bank erosion; head cut; pool scour; structurally-forced plunge pool scour; structurally-forced riffle development; bank-attached bar development; diagonal bar development; channel filling; and bench development. Since these signatures are clearly discerned from before and after comparisons of geomorphic units, they can be objectively mapped.

### 2.2 Geomorphic Unit Tool

We used GUT (Bangen et al., 2017; available from http://gut.riverscapes.xyz) to automatically map geomorphic units for each of the three topographic surveys. GUT was developed from a desire to leverage high resolution topographic data and a need to delineate geomorphic units in a consistent, objective manner. The algorithms apply a three-tiered hierarchical classification framework that was adapted from *Wheaton et al.* (2015; Figure 3) whereby each subsequent tier provides greater detail. In addition to a high resolution topographic DEM, the following inputs are required to run the tool and were prepared for each survey: low flow and bankfull extent polygons; a bankfull centreline; a thalweg polyline (Figure 5b). Low flow extent polygons were digitised from topographic survey data. Bankfull extent polygons were derived by detrending each DEM of its longitudinal slope, then using the Bankfull Tool in the River Bathymetry Toolkit (McKean et al., 2009) to determine the water elevation where the channel is filled. The bankfull extent polygon and bankfull centreline are used to calculate an average bankfull width for the site. The latter is used as a scalar for unit size thresholding.

The tier 1 step classifies the valley unit and flow unit using the bankfull and low flow extent polygons (Figure 5c). Valley units are the coarsest GUT designation with areas classified as either in-channel (within the bankfull extent) or out-of-channel (outside the bankfull extent). Flow units incorporate the low flow extent polygon with areas classified as either submerged (within the wetted and bankfull extents), emergent (within bankfull extent but not wetted), or high (outside both extents). The version of GUT applied here (pyGUT 2.2.1) only supports classifying beyond the tier 1 step for the in-channel portion of a reach.

The tier 2 step classifies topographic unit shape and form (Figure 5d, Figure 6). Tier 2 unit shape (concavity, planar, convexity) and form (bowl, trough, planes, wall, saddle, mounds, transition zones) are delineated using a variety of evidence layers. These include: DEM slope; DEM contours; the channel margin (approximately the region between the bankfull and wetted extent); residual topography (approximation of local relief calculated by subtracting a smoothed DEM, from the original DEM (Sofia et al., 2014)); and residual pool depth (difference between the filled DEM and the DEM). Transition zones represent areas with greater ambiguity, specifically in the residual topography thresholds used by GUT. Saddles are delineated using DEM contours and the thalweg polyline as these features are often subtle and not always captured using the residual topography evidence layer.

The tier 3 step classifies geomorphic units and sub-geomorphic units (Figure 5e and f). During this step, each tier 2 form unit was classified into tier 3 geomorphic units using attributes such as, unit position (margin attached, mid-channel or channel spanning), orientation (longitudinal, diagonal, transverse), bankfull water surface slope, ratio of unit width to bankfull width, channel type (main, cut-off, return) and elongation ratio. These tier 3 units were further split into sub-geomorphic units using attributes such as the number of thalwegs intersecting a unit, the meander bend (inside, straight, outside), bed slope, relief and a user defined forcing element (plunge of grade control). Tier 3 geomorphic unit maps were reviewed and, where necessary, attribute data and contextual information from oblique ground-based images were used to manually edit geomorphic unit classifications (2.6% of number of units; 2.6% of area). Subsequently, all margin attached and mid channel bar units (10% of units) were further classified into point, diagonal, eddy, forced and lateral bar types.

### 2.3 Abundance and diversity

The Shannon Diversity Index (Shannon, 1948) can be used to quantify habitat heterogeneity and spatial complexity but it has also been used to quantify morphological unit abundance and diversity (Maddock et al., 2008; Wyrick and Pasternack, 2014). The metric can be used to assess whether a river is dominated by a small number of geomorphic units or whether geomorphic unit distribution is more spatially even. Diversity (H), evenness (J) and dominance (D) of total geomorphic unit areas, within the in-channel area mapped from each survey, were calculated using:

$$H = -\Sigma(p_i \times \ln p_i) \qquad (1)$$

$$J = H / \ln (N) \qquad (2)$$

$$D = \ln (N) - H \qquad (3)$$

where $p_i$ is fraction of total wetted area of the *i-th* geomorphic unit type and $N$ is the number of geomorphic unit types. Fourteen geomorphic units were identified within the study area. Full diversity across the geomorphic units that were mapped would result in a diversity index (H) of 2.64, evenness (J) of 1.00 and dominance (D) of 0.00. Whilst full geomorphic unit diversity is unlikely to be either physically plausible or an outcome for successful restoration, changes in assessments of diversity, evenness and dominance from each survey can be used to indicate the evolutionary trajectory of the restoration project.

## 3 Results and Interpretation

### 3.1 Reach-scale channel adjustment and geomorphic unit development

An example of the GUT data processing workflow is shown in Figure 5. Figure 7 shows geomorphic unit maps for 2012, 2014 and 2016, and geomorphic change maps for 2012 to 2014 and 2014 to 2016. Table 1 summarises the sediment budget for the study area. The total area covered by in-channel geomorphic units increased by 23% between the pre- and post-restoration surveys and increased by a further 6% between 2014 and 2016 (Table 2; Figure 8). This increase is associated with an expansion in the width of the active channel. Thus, the restoration principle of *letting the river do the work* yielded a significant overall increase in physical habitat. Analysis of changes in the area and proportion of tier 2 topographic units sheds light on how the topographic shape and form of the reach changed (Figure 8; Figure 9). Notable changes between pre- and post-restoration analyses were that bowls and saddles more than doubled in total area between 2012 and 2016, and there was a substantial increase in the area and proportion of walls between the pre- and post-restoration surveys. The increases in bowls and riffles show the study area evolved towards being characterised by greater morphological complexity. The substantial increase in walls was a result of steep, erodible banks being identified in the 2014 and 2016 surveys. Bank profiles in 2012 were less steep and most bank areas were therefore classified as mounds. The proportion of mounds stayed similar between 2012 and 2014 and decreased in area between 2014 and 2016. Interpreting these changes alongside the geomorphic unit (Tier 3) classification, showed that in 2012 mounds were predominantly convex features along channel banks and some bars, whereas in 2014 and 2016 mounds were more likely to be convex features associated with bars.

#### 3.1.1 Geomorphic Unit Assemblages

Analysis of geomorphic unit total area and proportion reveal the overall change in the geomorphology of the study area due to restoration (Table 2; Figure 8; Figure 9). Prior to restoration, glide-run and transition geomorphic units covered 42% and 38% of the study reach area respectively. The next most abundant units were diagonal bars (5%), pools (5%) and riffles (4%). The diversity index was 1.40, evenness was 0.53 and dominance was 1.23. Together, these indices indicate that prior to restoration there was poor diversity in geomorphic units due to the dominance of glide-run and transition geomorphic units. Following restoration, in 2014, the diversity index increased to 2.04 towards the value for full diversity (2.64). The evenness (0.77) and dominance (0.60) metrics indicate evolution towards more even and less dominant geomorphic units. Glide-run and transition units decrease to covering 30% and 21% of the study area respectively. Diagonal bar, riffle, bank, lateral bar and point bar geomorphic units all increased in their spatial coverage between 2012 and 2014 (Figure 8). In 2016 the metrics for diversity (2.05), evenness (0.78) and dominance (0.58) show that sediment reworking resulted in the study area's geomorphic unit diversity slightly increasing. Notably, the proportion of glide-run and transition geomorphic units decreased further, in line with the changes between 2012 and 2014. Overall, the similar diversity metrics for 2014 and 2016 indicate that the restoration project has an evolution trajectory that is maintaining geomorphic unit diversity and in-channel geomorphic unit total area through the sequence of different magnitude high-flow events that are causing sediment transport and morphological change. Overall, the study area evolved from a plane-bed to a riffle-pool dominated morphology.

### 3.1.2 Mechanisms of Geomorphic Adjustment

Overall, bank erosion dominates as the single most important mechanism in both the initial adjustment (2012 to 2014) and the subsequent time period (2014 to 2016). From 2012 to 2014, 52% of the volumetric change (692 ± 157 m$^3$) was bank erosion, whereas between 2014 and 2016, 46% was bank erosion (180 ± 51 m$^3$). This dominance of bank erosion explains the potentially degradational signal in both time periods (-344 ± 333 m$^3$ and -89 ± 125 m$^3$; Table 1), as well as the primary response to the restoration treatment of removal of protected embankments. This net, reach-averaged channel widening of approximately 1.4 m between 2012 and 2014, and a further 0.7 m between 2014 and 2016, created an additional 23% of bankfull area (0.11 hectares) from 2012 to 2014, and an additional 6% (0.04 hectares) from 2014 to 2016. In that new bankfull accommodation space, a variety of mechanisms reshaped topography at high flows. The most important mechanism (by volume and areal change) was development of diagonal bar complexes followed by bank-attached bar development. From 2012 to 2014, 24% of the volumetric change (310 ± 139 m$^3$) was diagonal bar development, whereas between 2014 and 2016, 16% was diagonal bar development (64 ± 33 m$^3$). From 2012 to 2014, 9% of the volumetric change (116 ± 59 m$^3$) was bank-attached bar development, whereas between 2014 and 2016, 13% was bank-attached bar development (50 ± 26 m$^3$). While a host of other mechanisms are present and critical to creating diverse geomorphic unit assemblages (Table 3), the trio of bank erosion, diagonal bar development and bank-attached bar development dominate the sediment budget and are consistently first, second and third largest respectively by area and volume.

### 3.2 Sub-reach-Scale channel adjustment and geomorphic unit development

To analyse the geomorphological evolution of the restoration project in detail, the study area was divided into four reaches (Figure 7a): the most upstream reach where gravel supply was augmented

(Sub-reach 1); a reach where bank protection was removed and wood installed at the head of two bars (Sub-reach 2); a reach where cross-stream wood was installed and bank protection was removed (Sub-reach 3); a high sinuosity reach towards the downstream end of the project where embankments were removed in the upper section of the reach but no interventions were made in the lower section of the reach (Sub-reach 4).

### 3.2.1 Longitudinally segmented sediment budget

Table 4 shows a sediment budget that was longitudinally segmented by sub-reach. Between 2012 and 2014 the upper three sub-reaches (1-3) were degradational and the downstream sub-reach (4) was aggradational. Net-degradation in Sub-reach 1 (-90 $m^3$) was due to the dominance of bank erosion on the true left of the reach. Net-degradation in Sub-reaches 2 (-161 $m^3$) and 3 (-172 $m^3$), where embankments and bank protection were removed, shows the dominance of bank erosion as a mechanism of geomorphic adjustment in these sub-reaches and is consistent with channel widening where constraints to bank erosion were removed. Net-aggradation in sub-reach 4 (92 $m^3$) indicates that material from upstream bank erosion and sediment augmentation is being deposited in this reach. However, aggradation in this reach does not account for all material that is eroded from the reaches upstream and there is a net sediment volume export of 331 $m^3$ from the downstream end of the study reach.

During the period 2014-2016, the Sub-reach that had the greatest proportion of geomorphic activity compared to other Sub-reaches was Sub-reach 2. This is in common with the period 2012-2016 and is in the reach where several diagonal bar complexes were evolving. Between 2014-2016, Sub-reach 1 was marginally degradational (-3 $m^3$), Sub-reach 2 was aggradational (25 $m^3$), and Sub-reaches 3 and 4 were degradational (-39 $m^3$ and -45 $m^3$ respectively). Since Sub-reach 1 was net-degradational and Sub-reach 2 was net-aggradational, sediment to account for aggradation in Sub-reach 2 must either have come from sediment supply from further upstream than the study area or from the gravel augmentation point in Sub-reach 1. The net sediment volume export from the downstream end of the study reach was 62 $m^3$. This net export is common with the 2012-2014 period and is due to net channel widening. The topography of the reaches downstream from the study area was not monitored. Anecdotal observations, however, indicate that these reaches were always quite dynamic and physically diverse as they were largely unimpacted by previous human intervention. There has been continued morphological change in the section of channel extending c. 200 m downstream from the downstream limit of the study area since the works were undertaken but it is no possible to determine whether this has been any less or more than prior to restoration.

### 3.2.1 Sub-Reach 1

Prior to restoration, this upper sub-reach was dominated by a glide-run geomorphic unit (Figure 7b). The only restoration measure within this reach was the injection of gravel at the upstream boundary (Figure 1d). Following restoration, ex-Hurricane Bertha delivered exceptionally heavy rain to the Allt Lorgy catchment in August 2014, causing considerable post-restoration geomorphic change (Table 1). In the upper reach, bank erosion was longitudinally continuous along the true left of the river and sediment, most likely from gravel augmentation, formed a new point bar on the true right of the reach (Figure 7d). Downstream of the meander, the development of pools, a riffle and a lateral bar increased the geomorphic unit diversity of the reach (Figure 7d). Between 2014 and 2016, high flows caused further geomorphic change along Reach 1; bank erosion occurred along the outer bank of the meander bend, scour changed the position of the pool at the meander bend; and sediment was deposited in-channel in the downstream part of the reach to form a second riffle (Figure 7e and f).

### 3.2.2 Sub-Reach 2

Prior to restoration, the upper part of Sub-reach 2 featured a diagonal bar complex followed by a spatially continuous glide-run unit, with several pools, that extended through the rest of the reach to its downstream end, where there was a chute on the true right of the main channel. Restoration measures within this reach included the replacement of cross-channel and bar apex boulders with large wood, and the removal of an embankment on the true right of the river. With the removal of these physical constraints, the sinuosity of the reach increased, as shown by extensive bank erosion that was detected between 2012 and 2014 (Figure 7c). However, outer bank erosion did reveal granite boulders that may have previously been placed to prevent the river re-occupying its pre-straightened course. These may have constrained the rate of erosion that occurred post-restoration. Erosion also contributed to the formation of a number of pools. Sediment deposition, sourced from upstream and bank erosion within the reach, resulted in the evolution of the upstream diagonal bar complex, the return of active gravel bar reworking to a downstream diagonal bar complex, and the development of a number of riffles (Figure 7d). The overall pattern of geomorphic change that was identified between 2012 and 2014 continues between 2014 and 2016 (Figure 7e), with bank erosion along the banks of the channel’s outer bends and the evolution of the two bar complexes through the deposition and reworking of diagonal bars.

### 3.2.3 Sub-Reach 3

Prior to restoration this Sub-reach was dominated by a run-glide morphology with three riffles, a few pools and hydraulically forced plunge pools downstream of the boulder and wood cross-channel features (Figure 7b). Restoration measures along this low-sinuosity reach included the replacement of cross-channel boulders with cross-channel wood, and embankment removal towards the upstream and downstream ends of the reach (Figure 1d). Patterns of geomorphic change, and geomorphic unit development, from 2012 to 2014 are longitudinally distinct within the reach (Figures 6c and Figure 6d). Between the start of the reach and the cross-channel wood that was installed as part of restoration, bank erosion occurred along the true left and an associated lateral bar formed on the true right. This bar is most likely from the deposition of sediment transported downstream from the reworking of the Sub-reach 2 diagonal bar complex. There is considerable erosion downstream of the new cross-channel wood feature, resulting in a more diverse set of geomorphic units. In 2014, the second cross-channel wood feature is associated with the formation of a channel-spanning forced riffle upstream of the feature and, downstream, a channel-spanning plunge pool and bank-attached eddy bar. The downstream part of this reach is dominated by deposition, with the formation of lateral bars. Geomorphic change between 2014 and 2016 is more spatially discrete than in the period immediately after restoration (Figure 7e). The reworking of sediment causes various changes to the spatial extents of geomorphic units within the reach but the overall pattern is similar between 2014 and 2016.

### 3.2.4 Sub-Reach 4

Compared to the other reaches, Sub-Reach 4 showed a greater diversity of run-glide, riffle, pool and diagonal bar units before restoration (Figure 7b). This is due to the high sinuosity of this reach and the absence of any bank protection measures except along the outer bank of the first meander. This embankment was partially removed during restoration, resulting in bank erosion along the outer bank of this bend (Figure 7c and Figure 7e) and the development of a pool (Figure 7d and Figure 7f). Elsewhere along this reach, between 2012 and 2014, there was bank erosion along the channel’s outer meander bends and extensive erosion resulting in the formation of point bars and a diagonal bar complex. The reach was characterised by a more complex and diverse spatial pattern of geomorphic units in 2014 than 2012. Between 2014 and 2016 this reach remained geomorphologically active, with localised erosion and deposition reshaping geomorphic units.

## 4 Discussion

### 4.1 Methodological Development

The results from mapping geomorphic units from a three-dimensional topographic analysis clearly show changes in geomorphic unit diversity as a consequence of a river management intervention, namely the removal of unnecessary anthropogenic margins (i.e. stop banks and levees) which constrained important natural processes of bank erosion and lateral migration. GUT’s effectiveness at mapping geomorphic units purely from topography is significant because the methodology is characterised by less crew and operator variability than is associated with qualitative, user interpretive techniques (e.g. Hawkins et al., 1993; Moir and Pasternack, 2008; Raven et al., 1998). Moreover, it does not require the additional steps of a hydrological investigation to estimate a river's flows and hydrodynamic modelling to map depth and velocity patterns for the classification of units or using Froude number dependent depth-velocity classification tables with crisp, subjective boundaries (Maddock et al., 2013; Wyrick et al., 2014). Although GUT does require the input of channel thalweg and centerline polylines, and channel polygons these are all direct derivatives of the primary input of topography. The time taken for the step of manually editing and classifying tier 3 bars was also relatively minimal.

A wide variety of geomatics technologies have now been demonstrated to survey fluvial topography. Approaches that can map both wet and dry topography include rod-based surveys with RTK-GNSS or total station (Brasington et al., 2000; Fuller et al., 2003; Lane et al., 1994), topo-bathymetric airborne laser scanning (Mandlburger et al., 2015; Tonina et al., 2019) and Structure-from-Motion Multi-View Stereo (SfM MVS) photogrammetry with appropriate refraction corrections for wet areas (Dietrich, 2017; Woodget et al., 2015). A plethora of examples are also available of where topographic (e.g. airborne, terrestrial and mobile laser scanning) and bathymetric methods (e.g. echo-sounding, spectral mapping) have been fused together to provide complete mapping of fluvial morphology (Flener et al., 2013; Legleiter, 2012; Reid et al., 2019; Williams et al., 2014; Williams et al., 2015). The growing availability of high resolution topographic data (Passalacqua et al., 2015; Tarolli, 2014) will make multi-temporal mapping of geomorphic units increasingly viable, enabling the monitoring of fluvial system evolution. Specifically, the consistent geomorphological monitoring of river restoration outcomes which is widely called for (Addy et al., 2016; Wohl et al., 2015) is now viable and should be part of a holistic approach to designing a restoration monitoring plan (Podolak, 2014). Whilst our analysis has focused on the application of diversity, evenness and dominance metrics, which are suitable for answering our research question, a variety of other metrics (Wyrick and Pasternack, 2014) are available to characterise geomorphic unit assemblages when investigating other fluvial geomorphological hypotheses.

### 4.2 River Restoration by *letting the river do the work*

*Kondolf* (2011) argues that allowing a river to *self-heal* by designating space for channel migration is the most sustainable approach to river restoration. However, most degraded rivers in poor condition are unlikely to *self-heal* when the anthropogenic margins preventing their adjustment are not removed. The idea of giving rivers space to morphologically adjust has received considerable recent attention through notions of a channel migration zone (Rapp and Abbe, 2003), an erodible corridor

(Piégay et al., 2005), fluvial territory (Ollero, 2010), a river corridor (Kline and Cahoon, 2010) and freedom space (Biron et al., 2014; Buffin-Bélanger et al., 2015). Channels that have space to self-adjust are more likely to be characterised by channel migration, thus promoting active bank erosion which supplies sediment, and creating and maintaining diverse geomorphic units and physical habitat features (Florsheim et al., 2008). Whilst the Allt Lorgy restoration project involved minor earth works to remove most of the anthropogenic margins preventing lateral migration, the channel planform was not graded as part of the restoration. The overall river restoration design philosophy can be characterised as process-based once the constraints to it exercising its normal processes were removed in a manner that enabled the river to *self-heal* or *do the work* to recruit wood from channel banks, and set its own channel pattern and spatial distribution of geomorphic units. The maintenance of a high diversity of geomorphic units between the post-restoration survey in 2014 and the subsequent monitoring survey two years later, in 2016, suggests that the approach of *self-healing* is one that has maintained rich and resilient geomorphic unit diversity over a two-year post-restoration timescale. Moreover, the *letting the river do the work* approach provides the restored reaches with resilience to climate change or upstream land use change by providing space for future channel migration.

One approach to contextualising the geomorphic unit changes that were mapped at Allt Lorgy is to consider the response of the river reach as a change in condition. *Cluer and Thorne's* (2014) riverscape evolution model (Figure 10) can be invoked as a way of describing geomorphic condition. This model combines the stages of *Schumm et al.'s* (1984) and *Simon and Hupp's* (1987) channel evolution models, adds a precursor multi-thread stage, and links each stage as a cyclical evolution rather than a linear sequence. The addition of a pre-disturbance multi-threaded anastamosing stage (stage 0 in *Cluer and Thorne's* model) matches the pre-channelisation, multi-thread wandering gravel bed river channel pattern that was mapped at Allt Lorgy (Figure 1c). Stage 0 or 8 in the Allt Lorgy represents a healthy condition.  Channelisation of the Allt Lorgy study reach resulted in the stage 0 stream being degraded into an artificial stage 2 or channelised state, characterised by physical attributes that included reduced flood attenuation, relative uniformity in depth and velocity patterns, armoured bed substrate, reduced sediment patchiness through armouring, stable banks, reduced geomorphic diversity lowering the capacity of the channel to store sediment and wood, and stable banks. Geomorphic unit mapping shows that the removal of lateral constraints has enabled the study reach to evolve to a stage 4 stream, where widening through bank erosion is enabling greater channel-floodplain connectivity, an increased range of depth-velocity combinations, variable substrate sorting and different degrees of armouring. Compared to the stage 0 stream, the stage 4 stream is characterised by fewer side channels, confluences and diffluences, resulting in a lower capacity to store sediment and wood. It is likely that Allt Lorgy study reach may evolve towards a stage 0 channel with subsequent flood disturbances generating stream power to do the work. Given that historic mapping indicates that the study reach was multi-channel in 1980 and there is a plentiful supply of sediment from where the channel is connected to the valley sides (Figure 1c; Figure 2; Figure 7). However, at present, there are only a limited number of places where bank erosion may cause the recruitment of wood to the restored reaches. Although pine saplings have started to colonise some bank areas (Section 2.2), the reestablishment of a wooded riparian corridor is at an early stage. The biological role (Castro and Thorne, 2019; Johnson et al., 2019) of large wood in influencing river forms and processes is thus likely to be limited until pine saplings grow to large trees and collapse into the river channel as a result of bank erosion.

The restoration approach of *letting the river do the work* is suitable where there is sufficient lateral space to accommodate geomorphic dynamism and flooding without harming infrastructure or incompatible land uses, and a river has sufficient stream power to undertake lateral reworking of floodplain deposits or lateral erosion into active margins of hillslope, fans, terraces or moraines across the timescales through which stakeholders expect restoration benefits to emerge (Kondolf, 2011). The Allt Lorgy restoration project provided an upland, high energy site setting where most constraints to lateral adjustment were removed. The rapid increase in geomorphic unit diversity may partially have been a function of a large magnitude event occurring shortly after earth works were completed. The geomorphological effectiveness (Costa and O'Connor, 1995) of post-restoration high flows may therefore influence the timescale for rapid channel evolution at other restoration sites that apply a similar design philosophy. Space for channel migration is limited in many restoration settings due to constraints such as land-use practices, the presence of infrastructure and property, and difficulties in engineering connections between restored and unrestored reaches due to longitudinal patterns of land ownership. These challenges are exemplified by current natural flood risk management and river restoration practice in the UK (Gilvear et al., 2012; Smith et al., 2013; Waylen et al., 2018), which is typical of wider international practice. Whilst there is potential to give rivers full valley bottom width to migrate across in upland settings, in downstream settings reduced levels of freedom space may be necessary to compromise between land management, property and infrastructure issues and the need to restore fluvial and ecological functionality (Biron et al., 2014). In such anthropogenciallly constrained settings, stage 6, 7 and 8 targets may be appropriate. Information from the topographic monitoring of channel migration rates of river restoration projects that *let the river do the work* may prove invaluable in guiding river restoration planning efforts that seek to reclaim more “freedom space” and their former valley bottoms.

### 4.3 Geomorphic Units, Physical Habitat and Ecology

To infer that an increase in geomorphic unit diversity, or that an increase in the spatial area covered by submerged geomorphic units, is likely to be followed by an ecological improvement, it is necessary to assume that such changes are correlated with changes in physical habitat that ecology will respond to. Three recent meta-analyses have quantitatively reviewed data on river restoration measures and ecological response. First, with respect to macroinvertebrates, *Miller et al.* (2010) showed in a meta-analysis of 24 investigations that increasing habitat diversity had a significant positive effect on macroinvertebrate richness although the effect on macroinvertebrate density was negligible. Second, *Kail et al.* (2015) collated data from 91 restoration projects published in peer-reviewed literature and 64 unpublished studies to show that restoration had a significant effect on fish, macroinvertebrates and macrophytes, with especially clear effects of instream measures on fish and macroinvertebrates. However, one-third of restoration projects were found to have no or a negative effect and effects were smaller in agricultural catchments, illustrating the influence of catchment-wide pressures on in-stream restoration effectiveness. Third, *Muhar et al.* (2016) assessed 20 restoration sites in Europe using a paired comparison of restored and unrestored reaches, and concluded that restoration had positive effects across small and large projects. Although many of the restoration schemes that were included in these meta-analyses were graded with heavy construction equipment to create channel form rather than removing constraints to allow the stream to create its own forms through time , these meta-analyses indicate that it is likely that an increase in geomorphic unit diversity is likely to increase physical habitat diversity and thus macroinvertebrate, fish and macrophyte richness. An assemblage of individual geomorphic units make up reach-scale habitats which are at the scale that most ecological monitoring takes place. Links between ecological response to changes in geomorphic units must therefore be made by considering geomorphic unit assemblages. Results from studies that have mapped reach type and ecological response support the broader findings of the meta-analyses. For example, *Moir et al*. (2004) showed that, in two Scottish rivers, reach type could be used to predict Atlantic salmon spawning activity. Overall, geomorphic unit diversity can therefore be considered as a proxy for physical habitat diversity and thus ecological richness. Moreover, the principle of *letting the river do the work* is likely to produce physical habitat that is characterised by variability, that can adapt to changing catchment conditions and thus increase ecological resilience (Hiers et al., 2016). The increase in overall physical habitat area through restoration, as well as increasing diversity, is also important for conservation given declining trends in aquatic insects (although, in lowland areas, water quality issues must also be addressed (Bojková et al., 2014; Sánchez-Bayo and Wyckhuys, 2019)).

## 5 Conclusion

Consistent geomorphic unit mapping shows that restoration of Allt Lorgy increased the spatial extent of in-channel geomorphic units by 31% four years after restoration and has created a rich assemblage of geomorphic unit diversity. Once bank protection was removed, lateral channel migration/evolution and associated bank erosion enabled the formation of lateral and point bars, diagonal bar complexes, and instream wood created forced plunge pools and riffles. The analysis thus demonstrates that in river corridors where morphological change does not pose a risk to adjacent property or infrastructure, removing most constraints to letting a river undertake geomorphic work is an appropriate restoration option to deliver higher geomorphic unit diversity. Geomorphic adjustment was rapid following the restoration of Allt Lorgy due to a large high flow event that occurred two years after restoration, in the wake of what was Hurricane Bertha. The rate of morphological adjustment and the evolution of geomorphic unit diversity for other rivers that adopt a similar process-based restoration strategy will be a consequence of the sequence of high flow events that follow channel works. More broadly, the findings of this investigation support calls for rivers to be given freedom space so they can adjust to variations in water, sediment flux and biology. From a methodological perspective, the application of GUT, which classifies geomorphic units using only topography, thalwegs, and wetted and bankfull extents as inputs, reduces the subjectivity associated with qualitative geomorphic unit mapping methods and doesn't require hydrodynamic numerical modelling for unit classification. For the Allt Lorgy restoration project, geomorphic unit classification was undertaken for the entire bankfull extent of the project from three repeat high-resolution topographic surveys. Such time-series of high-resolution topographic surveys are increasingly being acquired in fluvial environments; GUT enables the evolution of fluvial form to be consistently quantified enabling investigation of changes in geomorphic unit diversity in response to natural variability in water and sediment flux, and river management interventions.

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## Tables

Table 1 Reach-scale geomorphic change between the pre-restoration and first post-restoration survey (2012 to 2014) and the first and second post-restoration surveys (2014 to 2016). Geomorphic change was calculated using a probabilistic thresholding approach at the 80% confidence interval.

| **Time period** | **2012 to 2014** | **2014 to2016** |
|---|---|---|
| **Total Volume of Erosion, $m^3$** | 864 ± 225 | 256 ± 90 |
| **Total Volume of Deposition, $m^3$** | 519 ± 244 | 166 ± 86 |
| **Total Net Volume Difference, $m^3$** | -344 ± 333 | -89 ± 125 |
| **Average Depth of Erosion, m** | 0.54 ± 0.14 | 0.40 ± 0.14 |
| **Average Depth of Deposition, m** | 0.17 ± 0.30 | 0.27 ± 0.14 |

Table 2 Project-scale in-channel geomorphic unit total area, abundance, evenness and diversity. Full diversity across the 14 different geomorphic units that were mapped would result in a diversity index (H) of 2.64, evenness (J) of 1.00 and dominance (D) of 0.00.

| **Survey year** | **2012** | **2014** | **2016** |
|---|---|---|---|
| **Total area, $m^2$** | 5011 | 6170 | 6545 |
| **Diversity, H** | 1.40 | 2.04 | 2.05 |
| **Evenness, J** | 0.53 | 0.77 | 0.78 |
| **Dominance, D** | 1.23 | 0.60 | 0.58 |

Table 3 Segregation of the sediment budget by mechanism of geomorphic adjustment between the pre-restoration and first post-restoration survey (2012 to 2014), and the first and second post-restoration surveys (2014 to 2016). Mechanisms of geomorphic adjustment were classified manually using expert judgement. Geomorphic change was calculated using a probabilistic thresholding approach at the 80% confidence interval.

| **Mechanism of Geomorphic Adjustment** | **2012 to 2014** | | **2014 to 2016** | |
|---|---|---|---|---|
| | **Total Volume*, $m^3$** | **% volumetric change** | **Total Volume*, $m^3$** | **% volumetric change** |
| Bank Erosion | -692 ± 157 | 50.0 | -180 ± 51 | 42.7 |
| Diagonal Bar Development | 310 ± 139 | 22.4 | 64 ± 33 | 15.2 |
| Bank-Attached Bar Development | 116 ± 59 | 8.4 | 50 ± 26 | 11.8 |
| Pool Scour | -54 ± 21 | 3.9 | 20 ± 9 | 4.7 |
| Channel Filling | -23 ± 13 | 3.8 | -9 ± 4 | 7.3 |
| Structurally-Forced Plunge Pool Scour | 17 ± 7 | 2.9 | 2 ± 1 | 0.5 |
| Channel Lowering | -40 ± 8 | 1.7 | -2 ± 1 | 2.1 |
| Bar Sculpting | -18 ± 7 | 1.3 | -27 ± 15 | 6.4 |
| Structurally-Forced Riffle Development | 52 ± 25 | 1.2 | 31 ± 16 | 0.5 |
| Bench Development | 0 | 0.0 | 2 ± 1 | 0.5 |
| Head Cut | 0 | 0.0 | 4 ± 2 | 0.9 |

*Negative values are erosional, positive values are depositional.

Table 4 Segregation of the sediment budget by reach between the pre-restoration and first post-restoration survey (2012 to 2014), and the first and second post-restoration surveys (2014 to 2016).

| **Sub-Reach** | **2012 to 2014** | | | | **2014 to 2016** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Volume of Erosion, $m^3$** | **Volume of Deposition $m^3$** | **Total Net Volume Difference, $m^3$** | **Cumulative Volume Change, $m^3$** | **Volume of Erosion, $m^3$** | **Volume of Deposition $m^3$** | **Total Net Volume Difference, $m^3$** | **Cumulative Volume Change, $m^3$** |
| 1 | 108 ± 27 | 18 ± 10 | -90 | -90 | 61 ± 14 | 30 ± 15 | -3 | -3 |
| 2 | 404 ± 100 | 242 ± 107 | -161 | -251 | 85 ± 29 | 110 ± 56 | 25 | 22 |
| 3 | 267 ± 67 | 95 ± 49 | -172 | -423 | 51 ± 21 | 12 ± 7 | -39 | -17 |
| 4 | 59 ± 18 | 151 ± 73 | 92 | -331 | 59 ± 25 | 14 ± 8 | -45 | -62 |

## Figures

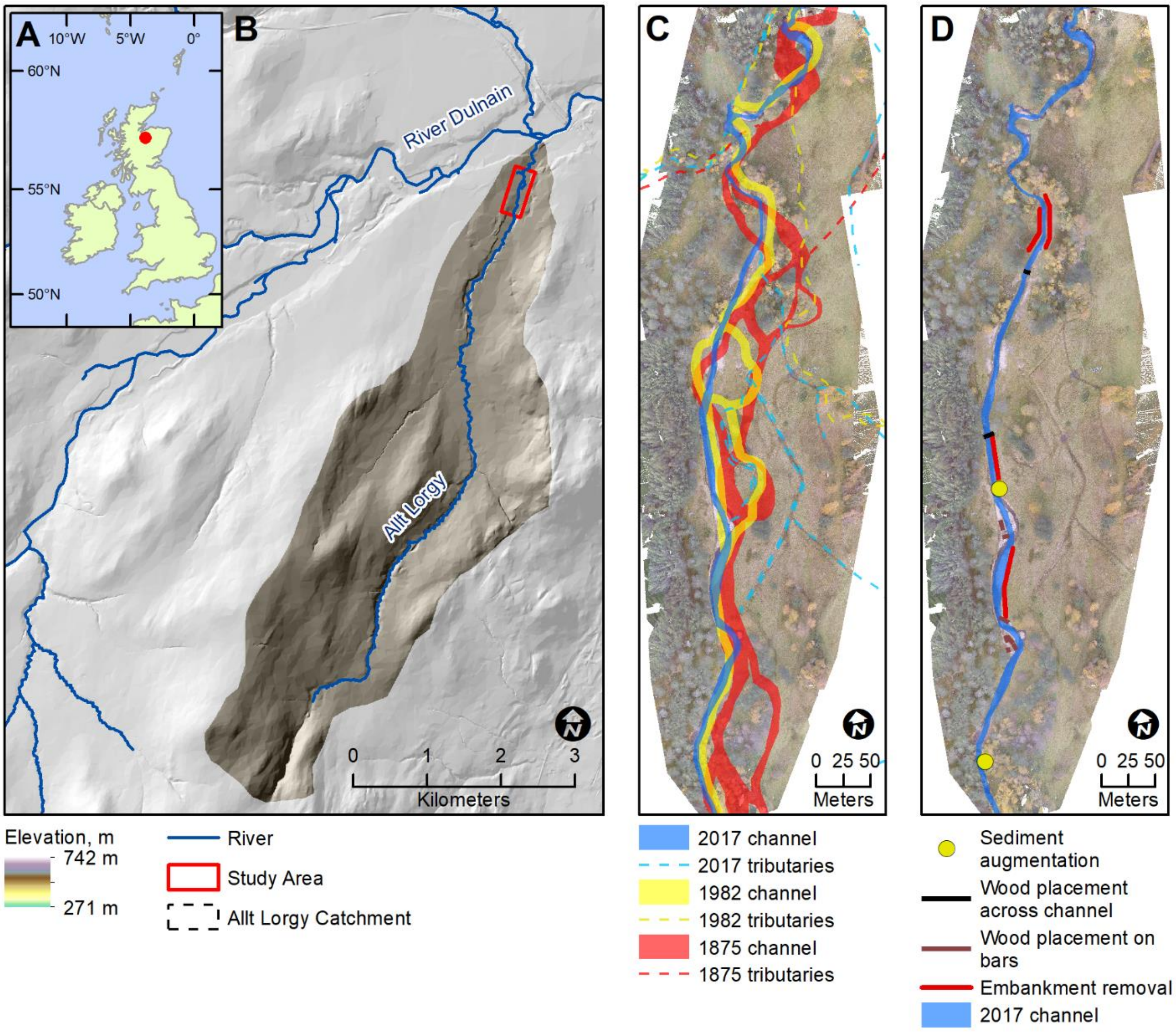

Figure 1 (a) Location of the Allt Lorgy catchment in Scotland. (b) Allt Lorgy catchment and study reach location map. (c) Historic and pre-restoration planform based on Ordnance Survey maps from 1875 (County Series 1:10,560 mapping, 1st Edition 1846 – 1899), 1982 (National Grid 1:10,000 series mapping, 1st Edition 1969 – 1996) and 2017 (Mastermap 1:1250 mapping, May 2017). The background aerial photograph was produced using SfM MVS Photogrammetry using imagery acquired in October 2016 from a DJI Phantom 3 UAV. (d) Restoration measures undertaken in August-September 2012.

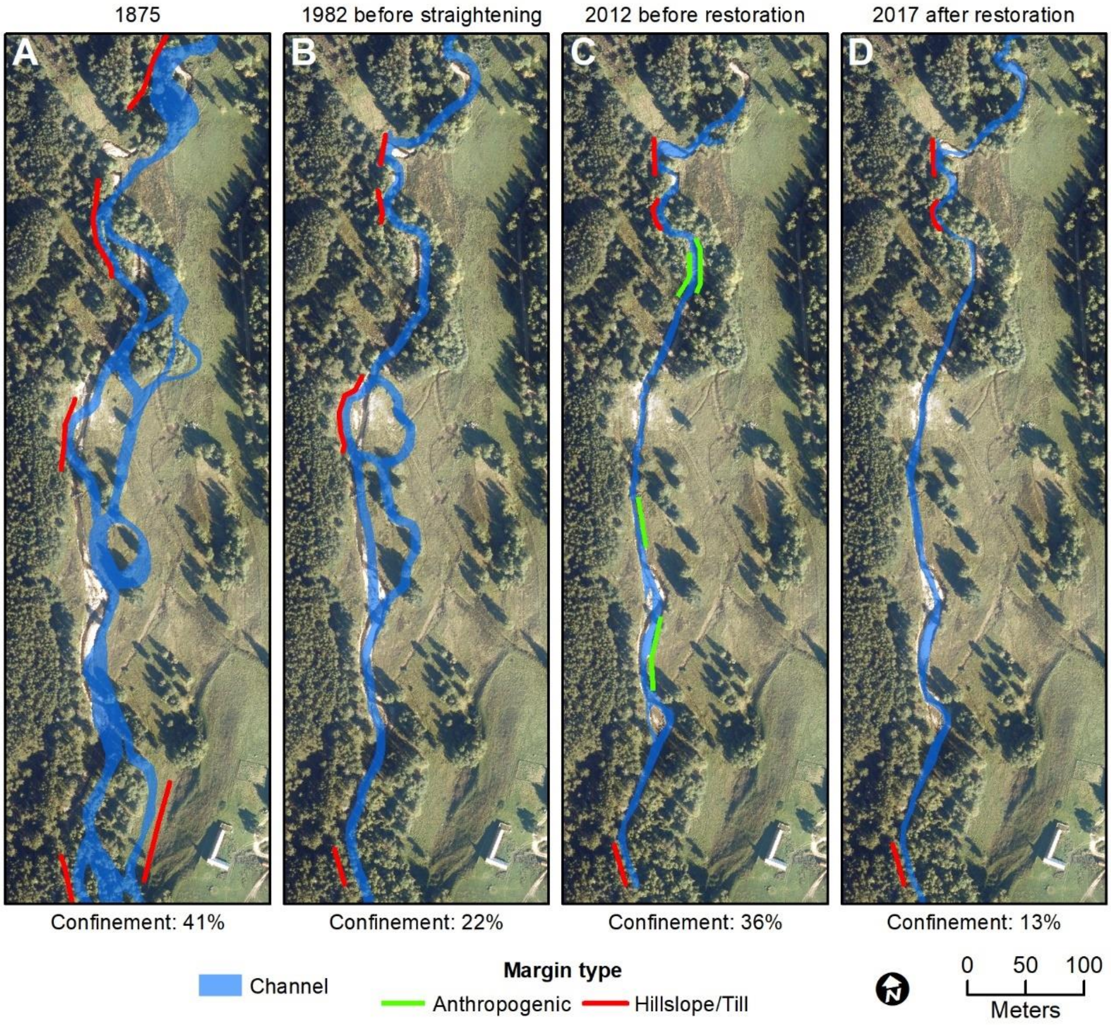

Figure 2 Analysis of valley setting and confinement for (a) 1875, (b) 1982 before straightening, (c) 2012 before restoration and (d) 2017 after restoration. 1875, 1982 and 2017 channel positions were extracted from Ordnance Survey maps (see Figure 1). Confinement was calculated using equation 1 of O'Brien et al. (2019). 2012 channel positions were mapped during a topographic survey (described in Section 2.2). Valley Bottom was mapped using the Ordnance Survey Terrain 5 m Digital Terrain Model. Geology was assessed from Smith (Smith, 2013). Aerial photography is © Getmapping Plc.

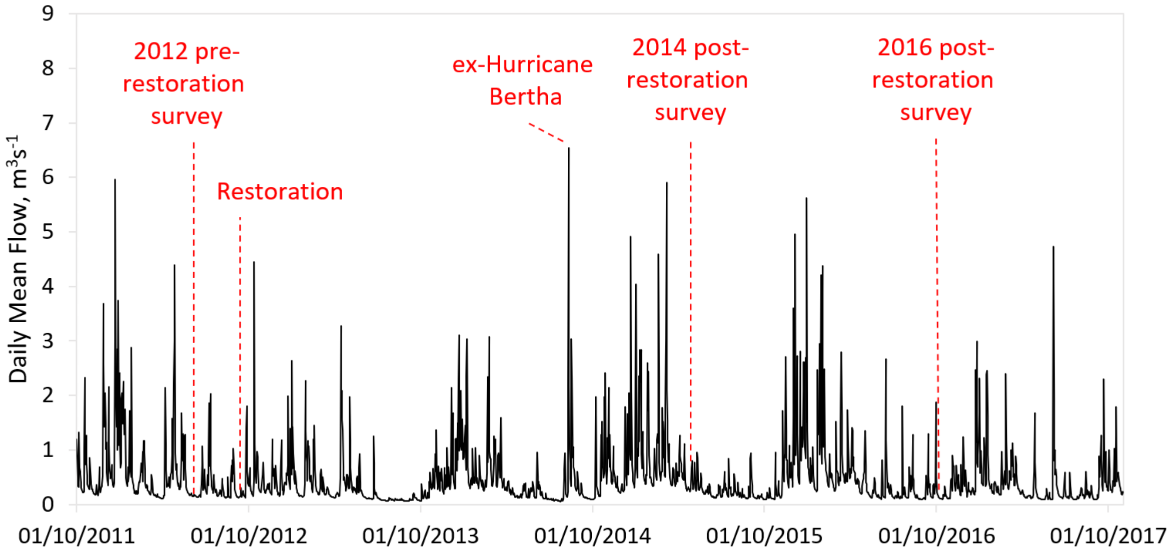

Figure 3 Allt Lorgy hydrograph showing the timing of restoration, topographic surveys and ex-Hurricane Bertha. Hydrograph was produced by catchment area scaling of the discharge record at the nearest downstream gauging station (Balnaan Bridge on the River Dulnain). The timescale shows hydrological years (1 October to 30 September). Data from the UK National River Flow Archive https://nrfa.ceh.ac.uk/data/station/info/8009.

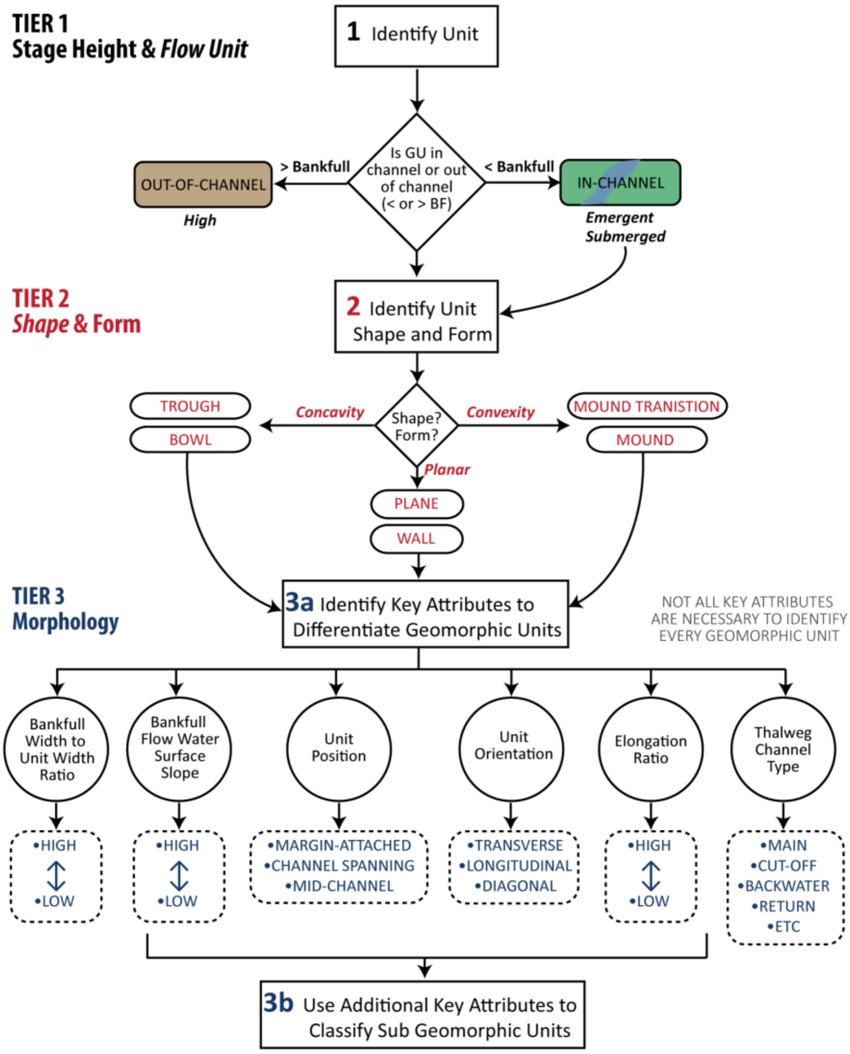

Figure 4 The Geomorphic Unit Tool's tiered framework. Tiers 1, 2 and 3 are associated with deriving flow, topographic- and geomorphic-related geometry respectively (Bangen et al., 2017).

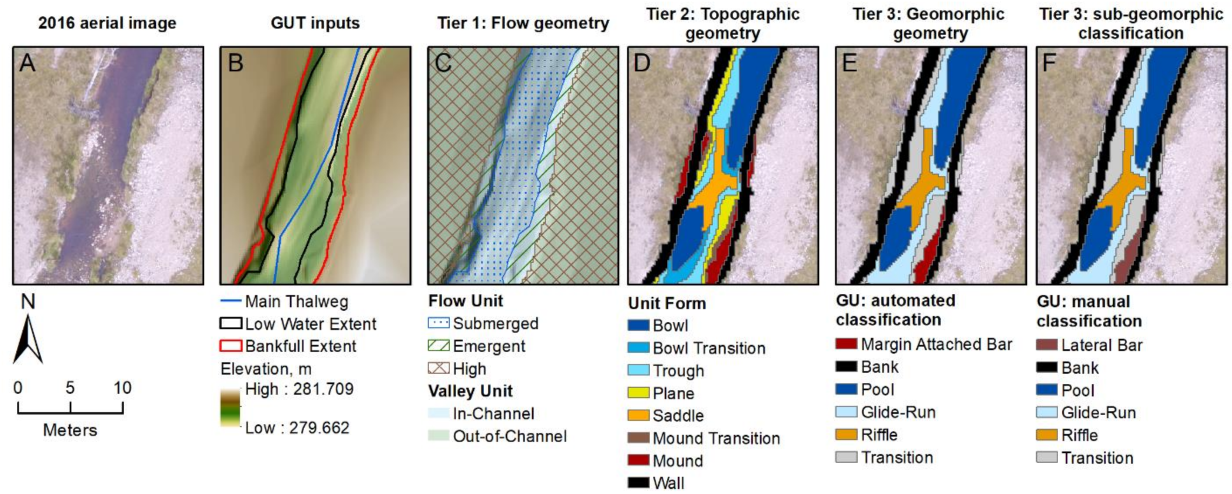

Figure 5 Example of Geomorphic Unit Tool inputs and outputs.

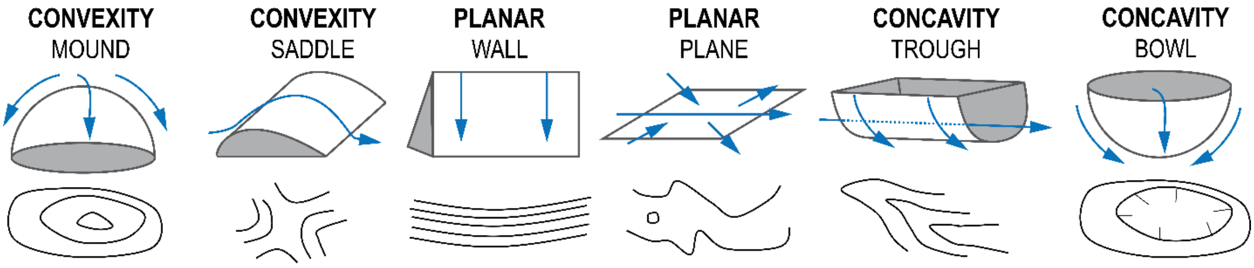

Figure 6 Generalised topographic shape and contour signatures for each of the tier 2 topographic units delineated by GUT (Bangen et al., 2017)..

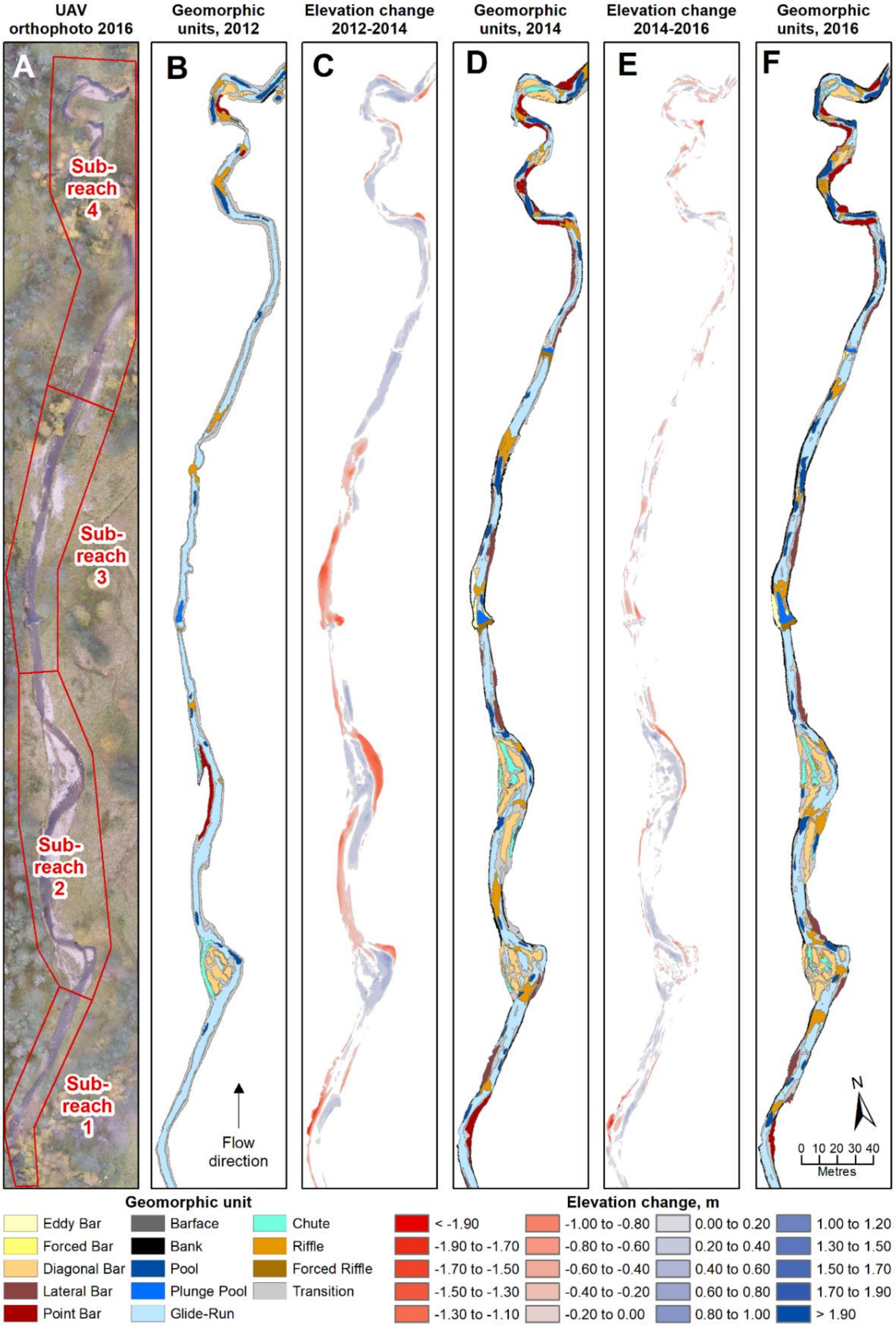

Figure 7 Geomorphic Unit and Elevation Change mapping. Geomorphic change was calculated using a probabilistic thresholding approach at the 80% confidence interval.

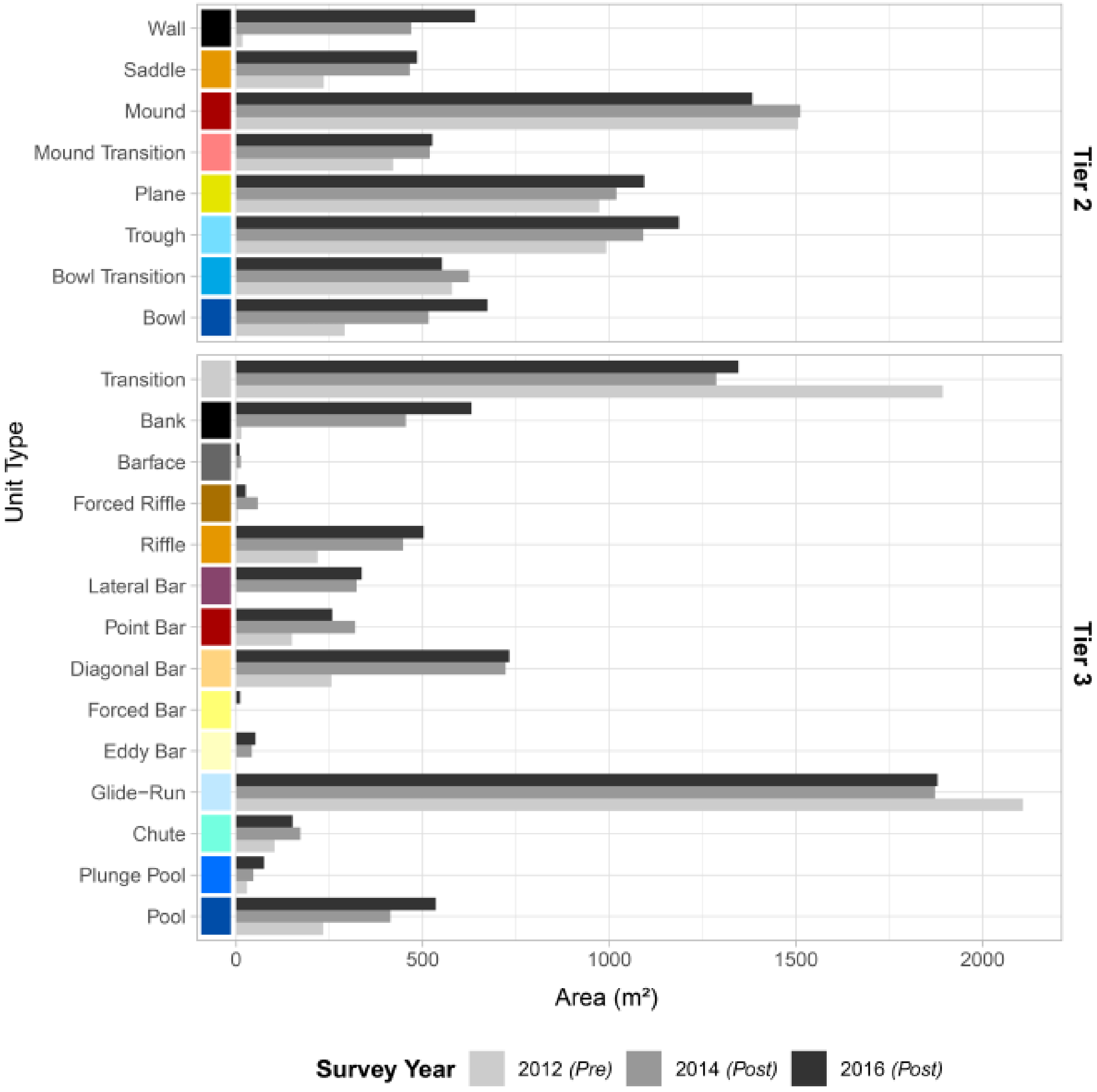

Figure 8 Total area covered by each tier 2 and tier unit for 2012, 2014 and 2016. Data used to generate this figure are available in Supplementary Table 1.

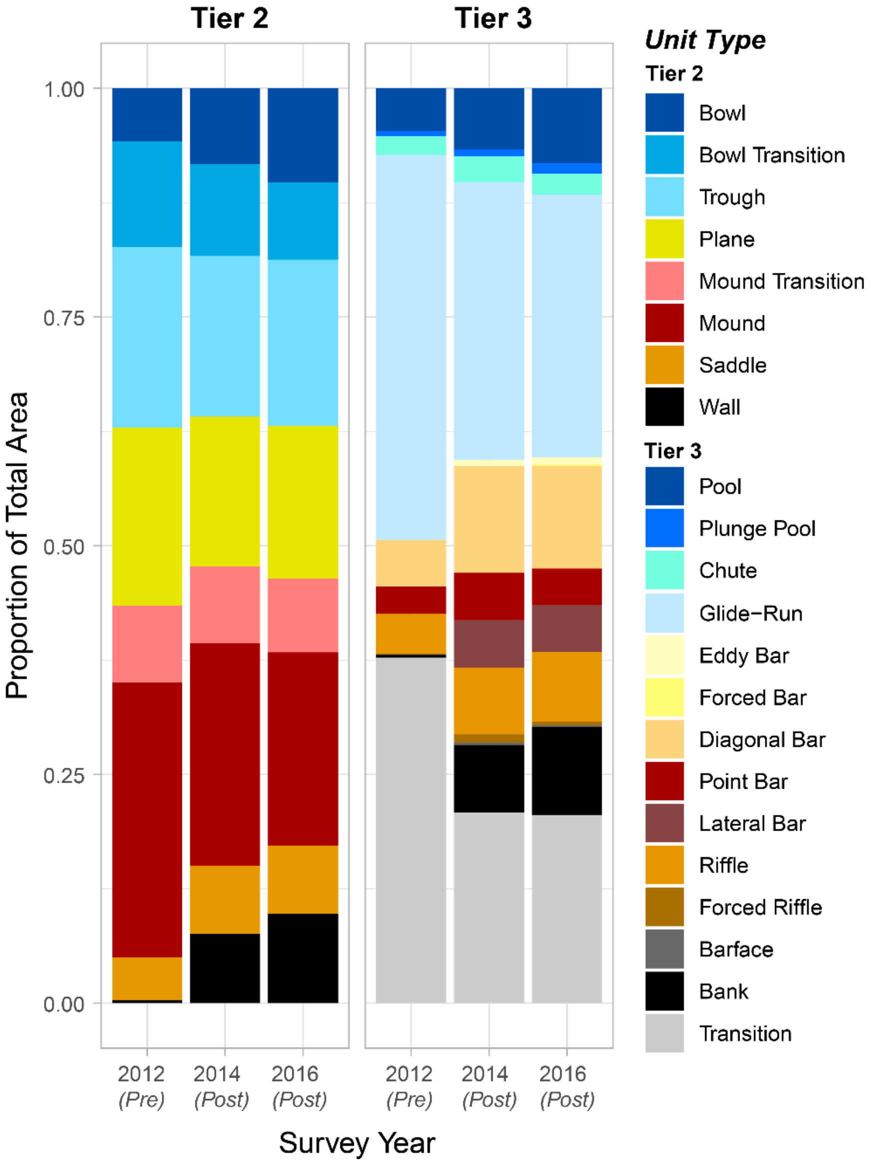

Figure 9 Proportion of tier 2 and 3 units that covered in-channel units for 2012, 2014 and 2016 surveys. Proportions are calculated from the total bankfull area for each year. Data used to generate this figure are available in Supplementary Table 2.

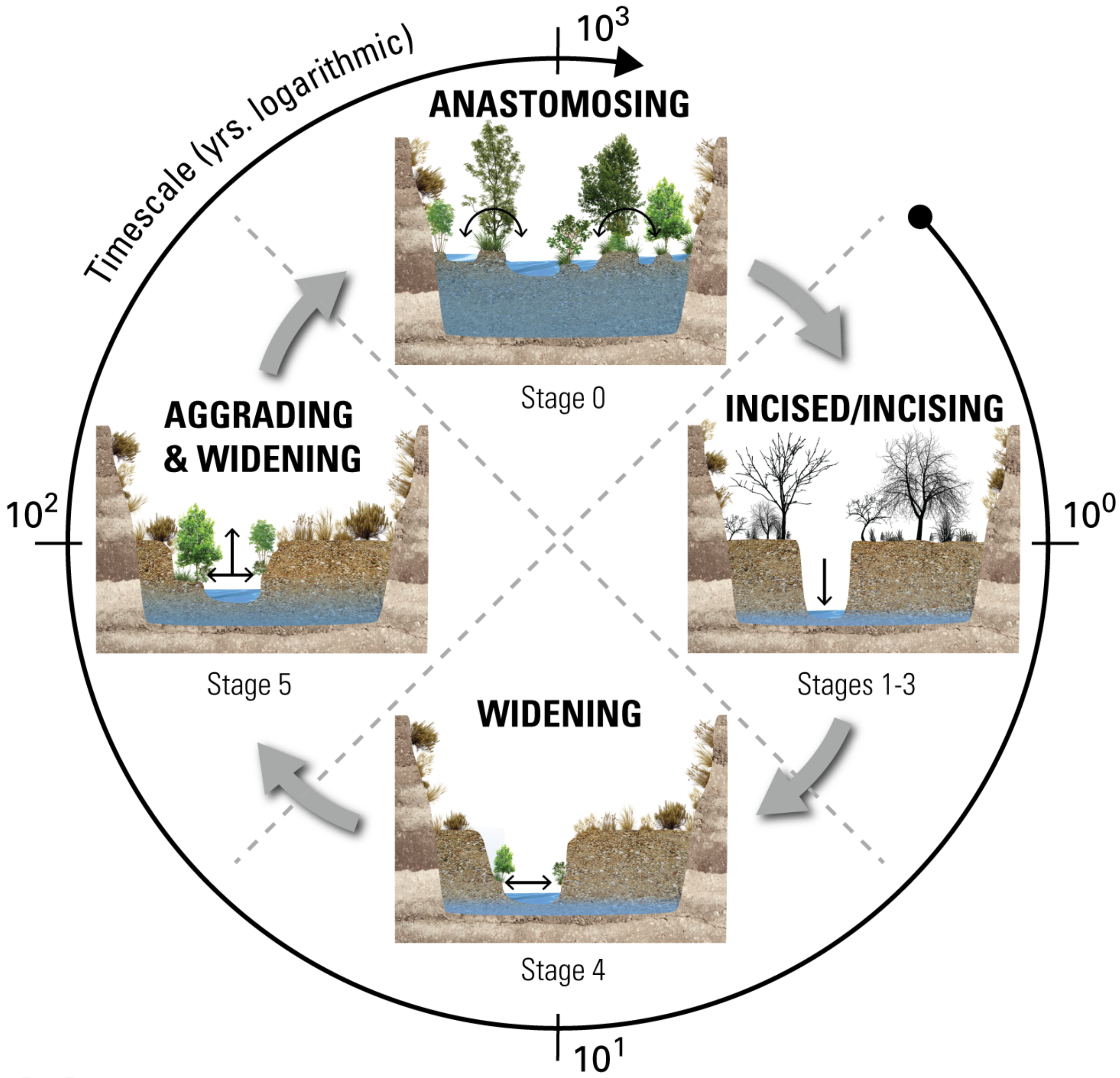

Figure 10 A riverscapes evolution model (Pollock et al., 2014; Wheaton et al., 2019) based upon a simplification and adaptation of Cluer and Thorne's (2014) stream evolution model.

## Supplementary Tables

Supplementary Table 1 Total area and proportion of reach covered by tier 2 units for 2012, 2014 and 2016. Proportions are calculated from the total bankfull area for each year.

| Unit Form | Area, $m^2$ | | | Proportion, % | | |
|---|---|---|---|---|---|---|
| | 2012 | 2014 | 2016 | 2012 | 2014 | 2016 |
| Bowl | 291.0 | 516.1 | 673.7 | 5.8 | 8.3 | 10.3 |
| Bowl Transition | 578.2 | 623.6 | 551.4 | 11.5 | 10.0 | 8.4 |
| Mound | 1506.2 | 1512.2 | 1382.8 | 30.1 | 24.3 | 21.1 |
| Mound Transition | 420.2 | 519.3 | 525.8 | 8.4 | 8.4 | 8.0 |
| Plane | 973.4 | 1018.8 | 1094.2 | 19.4 | 16.4 | 16.7 |
| Saddle | 234.6 | 464.9 | 484.4 | 4.7 | 7.5 | 7.4 |
| Trough | 991.5 | 1091.4 | 1187.0 | 19.8 | 17.6 | 18.1 |
| Wall | 16.9 | 469.6 | 640.6 | 0.3 | 7.6 | 9.8 |

Supplementary Table 2 Total area and proportion of reach covered by tier 3 units for 2012, 2014 and 2016. Proportions are calculated from the total bankfull area for each year.

| Geomorphic Unit | Area, $m^2$ | | | Proportion, % | | |
|---|---|---|---|---|---|---|
| | 2012 | 2014 | 2016 | 2012 | 2014 | 2016 |
| Bank | 14.5 | 455.1 | 631.2 | 0.3 | 7.4 | 9.6 |
| Barface | 2.4 | 12.9 | 9.4 | 0.0 | 0.2 | 0.1 |
| Chute | 103.3 | 172.6 | 151.5 | 2.1 | 2.8 | 2.3 |
| Diagonal Bar | 255.1 | 721.7 | 732.2 | 5.1 | 11.7 | 11.2 |
| Eddy Bar | 0.1 | 42.0 | 51.6 | 0.0 | 0.7 | 0.8 |
| Forced Bar | 0.1 | 0.1 | 11.3 | 0.0 | 0.0 | 0.2 |
| Forced Riffle | 4.1 | 58.5 | 25.4 | 0.1 | 0.9 | 0.4 |
| Glide-Run | 2108.3 | 1872.2 | 1879.7 | 42.1 | 30.3 | 28.7 |
| Lateral Bar | 0.1 | 322.7 | 336.7 | 0.0 | 5.2 | 5.1 |
| Plunge Pool | 28.9 | 45.9 | 74.9 | 0.6 | 0.7 | 1.1 |
| Point Bar | 149.9 | 318.9 | 257.9 | 3.0 | 5.2 | 3.9 |
| Pool | 232.9 | 413.3 | 535.1 | 4.6 | 6.7 | 8.2 |
| Riffle | 218.8 | 447.8 | 502.4 | 4.4 | 7.3 | 7.7 |
| Transition | 1892.9 | 1286.6 | 1346.3 | 37.8 | 20.9 | 20.6 |