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RESEARCH ARTICLE

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# Biogeomorphic recovery of a river reach affected by mining

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## Abstract

Environmental changes are impacting river systems worldwide. These arise from factors such as flood magnitude–frequency changes, direct human management interventions, inadvertent human impacts on sediment supply and fluvial regimes and landscape-scale changes in climate. Historical and active metal mining is significant in this regard. Here, we investigate morphodynamic changes within a reach of the River Ystwyth, Wales, since 1845. We analyse historical and contemporary information derived from maps, river flow records (1962–2021), metal analyses of sediment samples (1970s and 2021), ground geomorphological surveys (1970s and 1986–1987) and remotely sensed imagery (2001–2021) to investigate changes during a period of active metal mining followed by a century of post-mining recovery. During the studied period, an initially meandering river was transformed into a braided one, subsequently reverting to a single sinuous channel. Sinuosity reduced from 1.31 in 1845 to 1.09 in 1982 before recovering to 1.39 in 2019. Inversely, the braiding index reduced from a maximum of 2.0 in 1987 to 1.5 in 2021. Evolution in planform was associated with a change from expansive bar formation and avulsion under braided conditions to lateral bar accretion and associated bank erosion along a sinuous single channel. The initial 19th-century channel pattern and floodplain instability seems to have been related to mining sediment toxicity effects rather than a response to high sediment volumes, with recent recovery and channel style reversion being attributable to vegetation encroachment and biomass stabilization of the floodplain. Causal factors of recent recovery appear to be colonization by gorse (*Ulex europeaus*) in the absence of physical control measures and a reduction in grazing by the native rabbit population because of a disease-induced decline in their numbers. These results highlight the importance of riparian vegetation in addition to sediment balance and hydrological processes in controlling fluvial responses to environmental changes.

KEYWORDS
bar morphology, channel change, grazing, mining, vegetation succession

## 1 | INTRODUCTION

The impact of anthropogenic legacy sediments on river channel morphology and dynamics, including sediment inputs as the result of mining, is recognized as significant (Gilbert, 1917; Gregory, 2006; James, 2018; James & Marcus, 2006; Lewin et al., 1977; Richards, 1992). Models relevant to the evaluation of sediment input from mining have been developed by James (2018), who considered amongst other factors the impact of sediment waves (Brewer & Lewin, 1998; Bull, 1991; Gilbert, 1917; Lewin, 1977; Lewin & Macklin, 1987; Macklin & Lewin, 1989), aggradation–degradation episodes and channel evolution models (Schumm et al., 1984; Simon & Hupp, 1986; Simon & Rinaldi, 2006). These provide useful frameworks for evaluating geomorphic recovery from mining disturbance in the form of gross sediment input.

However, as identified by Lewin et al. (1977), volumetric input from mining may not be the sole influence on channel pattern change, with factors such as contamination by toxic metals and restricted riparian vegetation growth being significant. Further to this, Stecca et al. (2019) observed that the interplay of numerous, complex and continuously varying potential controls at reach level, such as the local channel gradient and the calibre/stability of local bank–floodplain sediments, make it difficult to generalize cause–effect relations.

In this study we present an analysis of channel change on a reach of the River Ystwyth, Wales, 1845–2021. Here, the combination of active river processes with heavy metals in the river sediments resulted in large open areas of bare sediments rich in metallophyte lichen species and a predominantly short, sparse vegetation cover. The development of a braided river planform and unusual ecology led to designation of the reach as a Special Area of Conservation (SAC; Countryside Council for Wales, 2008) and to it being used as an analogue for post-glacial braided rivers in archaeological studies (Chu & Hosfield, 2020; Hosfield & Chambers, 2004).

This study seeks to explore:

- The detailed nature of channel planform and sedimentation change during mining activity and for a century subsequently.
- Differences in the morphology and dynamics of the active channel and depositional bar forms as a driver of planform character.
- The extent to which observed changes, particularly channel planform recovery, can be attributed to alternative controlling factors.

In mid-Wales, three potential controls (flood magnitude–frequency, sediment input and riparian vegetation cover) have been suggested by Brewer et al. (2001) to influence ongoing channel planform change. The physical controls of flood response and sediment input correspond to the conceptual models proposed by James (2018) to account for the physical behaviour and characteristics of anthropic fluvial sedimentation events, whilst the nature and development of riparian and aquatic vegetation (Brewer & Lewin, 1998; Gran & Paola, 2001; Gurnell, 2014; Hicks et al., 2007; Kleinhans & van der Berg, 2011; Lelpi et al., 2022; Winterbottom, 2000) have equally been widely noted as an intrinsic control on channel pattern change at reach level.

## 2 | METHODS

### 2.1 | Study area

The River Ystwyth, West Wales (catchment area 193 km$^2$), rises in the Cambrian Mountains and flows westward to a confluence with the Rheidol estuary at Aberystwyth (Figure 1a). In the lower 40 km of the river, sections of wider valley floor are separated by steeper rock-cut channels (Brown, 1952). The river channel actively migrates in these wider sections unless confined by roads, railways or the valley sides (Higgs, 1997; Lewin et al., 1977). The ecology of the River Ystwyth is impacted by heavy metal contamination associated with past mining activity (Carpenter, 1924; Davies, 1987; Erichsen Jones, 1940, 1958; Griffith, 1918; Higgs, 1997; Lewin et al., 1977; Newton, 1944). Mining dates to Roman times but large-scale mechanized ore processing became prominent in the 18th century. Industrial-scale mining and processing between 1792 and 1920 (AditNow, 2019; Bick, 1996) delivered crushed and comminuted material into the river at several locations.

The study reach at Grogwynion (Figures 1a and b), approximately 32 km upstream of the Rheidol confluence, occupies one of the wider sections of valley floor. Mean river discharge at the Pont Llolwyn gauging station (30 km downstream, Figure 1a) is 6.09 m$^3$ s$^{-1}$ in the period 1962–2021 (NRFA, 2021). At Grogwynion, the river channel is located within a steep-sided, 200 m-deep valley and is confined to the north by the valley side and to the south by a road located at the foot of the southern side of the valley. The reach gradient is 0.015 (Lewin et al., 1977) and channel sediments are predominantly coarse ($D_{50} = 40 \pm 10$ mm, 95th percentile $= 96 \pm 27$ mm; Chu & Hosfield, 2020), consisting mainly of locally derived Silurian shales and gritstones.

The reach is adjacent to former lead mine workings and 3.5 km to the south of the major Frongoch lead and zinc mine (Figures 1a and b). Palumbo-Roe et al. (2009) estimated that there were 20 mine entrances associated with the two sites. There are further mine sites in the vicinity, notably 7.5 km upstream at Cwm Ystwyth. Commercial mining at both local sites commenced in the late 1790s and ceased at Grogwynion by 1879 (Coflein, 2022) and Frongoch by 1904 (Bick, 1996), with peak production being between 1860 and 1880 (Lewis, 1967). At Grogwynion, the mineralized seams were accessed by adits high on the valley side (Figure 1b) and transported to the valley floor for processing. Material from the tailings heaps at Grogwynion and Frongoch was reprocessed at Gwaithgoch adjacent to the Grogwynion mine site between 1920 and 1930, before being transported elsewhere by rail.

Coarse waste from the adits was deposited on the valley side where it remains visible as scree. With the possible exception of the Craig Goch adit (Figure 1b), there is no evidence of substantial direct input of this material onto the floodplain. The tailings heap containing processed material (Figure 1b) is confined behind a river bund and well protected from the river (Palumbo-Roe et al., 2009), with input of metals into the river being limited to leachate. The presence of the bund is visible on 1886 mapping and has remained undisturbed by channel migration. It is notable that the median size of the well-rounded, channel and floodplain sediments is considerably coarser than both the sand-grade, angular, crushed rock in the tailings heap (Palumbo-Roe et al., 2009) and much of the waste associated with the adits. Modelling by Gamarra et al. (2014) suggested that contaminated fine sediment transfer peaked ca. 1930 and the key impact of metal mining was the supply of limited washing of fines (silt, clay) from worked spoil.

At the time of the designation of the Grogwynion SAC (2004) a mosaic of habitats, known as shingle heath, had developed on the river gravels and was attributed to the impact of high concentrations of Pb, Zn and Cd on riparian vegetation colonization and growth. These heathland communities are rare in southern Britain and the designated reach supported the largest known area in England and Wales (Countryside Council for Wales, 2008). Shingle heath incorporates open areas of bare shingle, heather (*Calluna vulgaris*), lichens (e.g. *Vezdaea acicularis*, *Gyalidea subscutellari*) and Calaminarian grassland patches. Recently, the native woody shrub, gorse (*Ulex europeaus*)

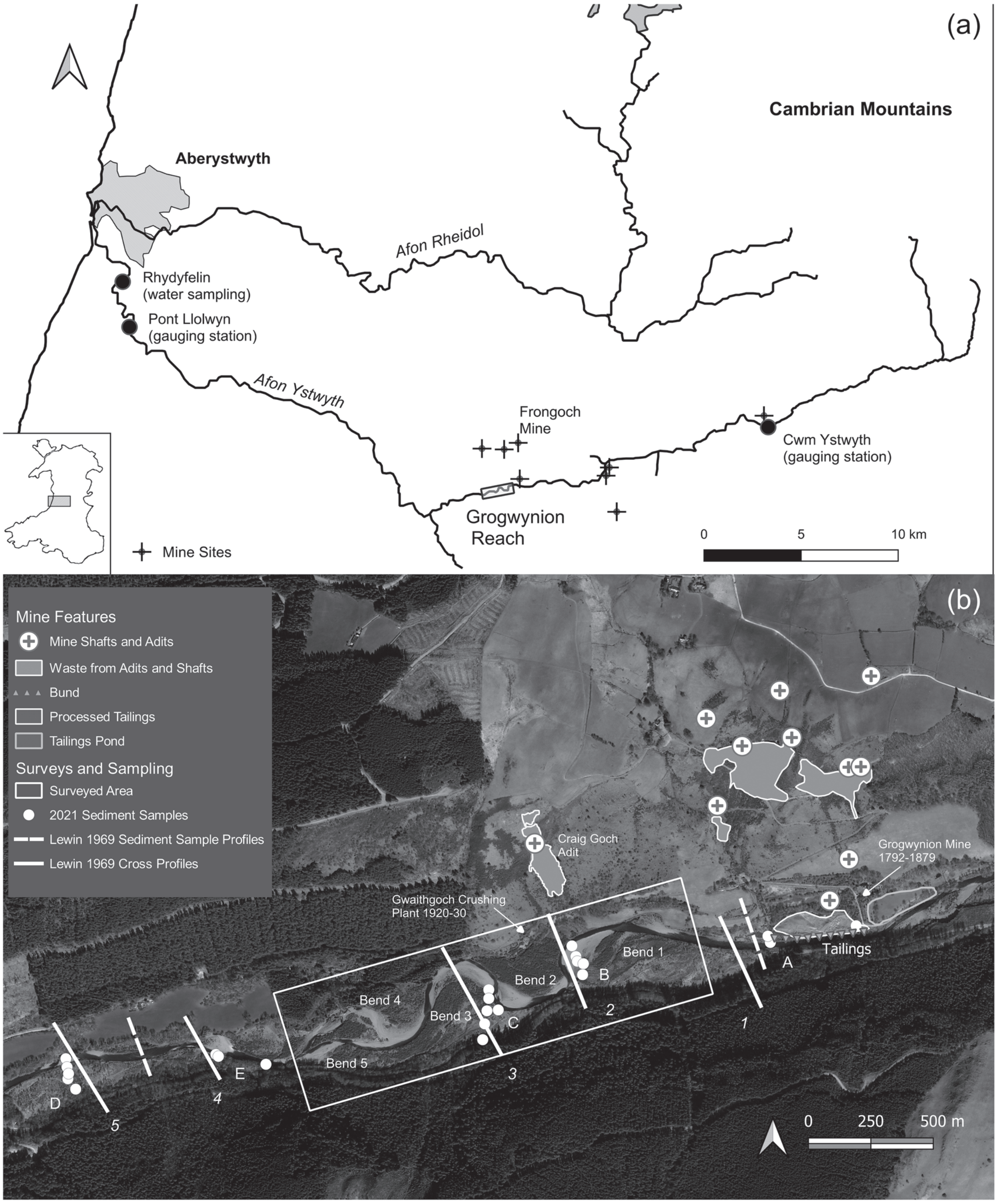


**FIGURE 1** (a) Location of the Grogwynion reach on the Afon Ystwyth in relation to the Cwm Ystwyth and Pont Llolwyn gauging stations and the Rhydyfelin water sampling site. (b) The Grogwynion mine site and reach. The major features of the mine site—such as the adits, spoil heap and processing plant—are shown. The diagram of the field site depicts its five studied bends, the locations of the cross-profiles and sediment sampling transects investigated by Lewin et al. (1977) and the sediment sampling locations investigated in 2021 (image, Google Earth 2021 © CNES/Airbus).

has started to colonize the reach. This species is widely established on river gravels elsewhere in the region (Brewer et al., 2001), but its widespread occurrence at Grogwynion is a recent phenomenon.

## 2.2 | Investigative approaches

The present research synthesizes evidence of changes from historical maps, remote sensing imagery, ground surveys and sediment (metal) analyses, and investigates the possible causes using flood magnitude–frequency analysis, and evaluations of the sediment balance and vegetation change.

### 2.2.1 | Channel planform evolution

Changes in the river planform between 1845 and 2021 were investigated using 16 historical sources (Table 1), including a tithe map, Ordnance Survey maps (1:2500, 1:10 000, 1:10 560 scales), field surveys and Google Earth images. These map and image sources were

**TABLE 1** Historical map and image sources used in the analysis of planform change

| Date of survey | Source |
|---|---|
| 1845 | Tithe Map (from Lewin et al., 1977) |
| 1886[a] | Ordnance Survey 1:2500 County Series 1st Edition |
| 1904[a] | Ordnance Survey 1:2500 County Series 1st Revision |
| 1948[a] | Ordnance Survey 1:10 560 County Series 3rd Revision |
| 1960 | Survey published in Lewin et al. (1977) |
| 1969 | Survey published in Lewin et al. (1977) |
| 1982[a] | Ordnance Survey National Grid 1:10 000 Latest Version |
| 1986 | Field Survey |
| 1987 | Field Survey |
| 2001 | Aerial Digimap © Getmapping plc |
| 2006 | Google Earth © Bluesky, Infoterra, COWI A/S |
| 2009 | Google Earth © Getmapping plc |
| 2012 | Google Earth © Maxar Technologies |
| 2014 | Google Earth © Maxar Technologies |
| 2019 | Google Earth © CNES/Airbus. Bing Maps © TomTom |
| 2021 | Google Earth © CNES/Airbus |

[a] Downloaded from EDINA Historic Digimap Service http://digimap.edina.ac.uk.

georeferenced, using 2019 imagery as the base reference within QGIS (v3.22). The active channel on each data source was digitized to facilitate measurement of the relative position and sinuosity of the main channel.

The variety of sources of differing scale and accuracy (Table 1) introduces many potential sources of error when extracted data are compared (Grabowski & Gurnell, 2016). The accuracy of the mapping of rivers on tithe surveys is highly spatially variable. However, the Ordnance Survey have consistent mapping conventions for river edges on the map scales employed (Harley, 1975). Measurements from aerial imagery are subject to error, mainly as a result of differences in river stage among images, but also variations in image resolution and in visual interpretation during digitizing. The field planimetric surveys were probably the most spatially accurate historical source. Nevertheless, they rely on triangulation from defined base points. In summary, although the spatial resolution of the datasets, the river positions marked on the map sources and the extent of inundated area of the image sources reflect the methods of data capture, mapping conventions and river stage at the time of acquisition (Fuller et al., 2013), together they provide a good visual impression of the characteristics of planform change over a 175-year period. However, when quantitative comparisons of channel positions are attempted, these are subject to the above error sources as well as image co-registration errors introduced during georeferencing (Leonard et al., 2020). Complete error analysis is challenging, but Leonard et al. (2020) suggest that where the signal of channel change is large, and the aim is not to quantify the magnitude of volumetric change, a computationally intensive method of uncertainty analysis is probably not needed. In the present research, map overlays and related error analyses were confined to the set of aerial images covering the period 2001–2021 and thus to a single source type. RMS errors associated with the georeferencing of these images followed the method adopted by Merritt and Cooper (2000), Comiti et al. (2011) and Schook et al. (2017). Determined errors ranged from 3.1 to 16.6 m, indicating that quantitative measurements deduced from the imagery should be treated with caution (Schook et al., 2017).

Channel planform change was quantified using two indicators: main channel sinuosity and a braiding index. Sinuosity was considered for all the historical sources and was determined by plotting a mid-line along the main channel between two fixed points at the upstream and downstream ends of the reach for each of the available plan images, and then comparing the path length to a straight base line between the two end points. The end points correspond to the limits of the field surveys made in 1986–1987 and where there has been limited channel migration due to topographic constraints. A braid–channel ratio was also calculated for the better-resolution, post-1986, data following the method of Friend and Sinha (1993), which compares the total mid-channel lengths of all channels in the reach with the length of the mid-line of the main channel. Potential stage dependence of the braid–channel ratio was considered by examining its correlation with the mean daily flow at the Cwm Ystwyth gauging station, located 16 km upstream (Figure 1a), on the survey dates.

### 2.2.2 | Channel and bar morphology

A more detailed analysis of planform change was undertaken for two time periods where sufficiently detailed information was available: 1986–1987 and 2001–2021.

Field planimetric survey information for June 1986 and August 1987 supported identification of detailed changes in the channel planform and related bar–bedform development. Monthly oblique aerial photography from a cliff-top viewpoint over the reach supported interpretation of the evolution of bedforms between the two survey dates.

High-quality aerial imagery of the reach between 2001 and 2021 allowed quantification of planform change during the period 2001–2021, when there were five discrete meander bends in the reach (Figure 1b). Bends 2 and 4 (Figure 1b), which were unconstrained by the valley sides, were selected for detailed investigation. For each, an axis of migration was defined; measurements were made of the movement of the outer cut bank between each aerial survey; and a radius of curvature was visually estimated for each bend at each time period by fitting a circle to the bend dimensions (Leopold & Wolman, 1960). Growth and change in the areas of sediment deposition at these bends were also investigated from the changing position of the outer cut bank and the changing extent and position of areas of recent sedimentation, determined by their relative absence of weathering coloration and vegetation cover, an approach similar to that used by Merritt and Cooper (2000), Dean and Schmidt (2011) and Nelson et al. (2013). This enabled tracking of progressive bend migration and incremental changes in sedimentation within the channels.

### 2.2.3 | Potential influences on channel change

*Flood magnitude and frequency*

Changes in flood magnitude and frequency were assessed using peak over threshold (POT) data available from the Pont Llolwyn gauging station (Figure 1a). A POT discharge, defined to identify approximately three to five flood peaks a year, has been estimated to be 64.57 $m^3\ s^{-1}$ for this gauging station over the period 1962–2021 (NRFA, 2021). Following Langbein (1949), Gordon et al. (1992), Naden (1993) and White and Greer (2006), partial-duration flood series recurrence intervals using POT data were calculated for two time periods, 1975–1995 and 1996–2021, to enable a comparison of flow magnitude–frequency during time periods when the study reach was identified to display different planforms. The breakpoint year 1996 was selected from inspection of the POT data and closely corresponds with the start of an observed increase in sinuosity in the reach.

#### *Sediment budget*

In the absence of detailed historical measurements of sediment transport or the channel profile, or the availability of repeat LiDAR surveys, assessment of the reach sediment budget was challenging. An approximation was made by comparing five cross-sections field-surveyed in 1969 (Figure 1b; Lewin et al., 1977) with those derived from a 2012 1 m-resolution LiDAR survey (Natural Resources Wales, 2015). The 1969 cross-sections were digitized, geolocated and overlain on cross-sections derived from the 2012 survey to give an indication of cross-profile change at two sections within the reach (2, 3 in Figure 1b), one (1) upstream and two (4, 5) downstream. Minor adjustments were made to the relative elevation of the pairs of profiles by assuming that the higher-profile sections that were not affected by channel migrations between the surveys should not have undergone any significant change in elevation. The resulting profiles supported visual, qualitative comparisons but full quantitative comparisons were not made because the 1969 cross-sections were not tied to a datum and both datasets are subject to different but notable sources of measurement error (Smith et al., 2004). Neither the LiDAR data nor the measured cross-profiles, measured just to the water's edge of each channel, depict the channel bed bathymetry.

A more general appraisal of incision in the reach was made by comparing features mapped on the 1:2500 scale Ordnance Survey maps of 1886 and 1904 with the 2012 LiDAR survey paying attention to the existence and position of any terrace features. In addition, the total tonnage of waste from the Grogwynion mine was calculated using the estimates provided by Palumbo-Roe and Coleman (2010) and compared to the tonnage of waste remaining in the tailings heap derived by calculating the volume of the tailings determined from the 2012 LiDAR survey of the site.

#### *Vegetation cover*

Changes in the extent of exposed riverine sediments were investigated by digitizing the limits of areas under vegetation cover displayed in aerial images for the period 2001–2021 and then calculating the area of exposed sediments and water for each image date. The tone, texture and colour of the darker vegetated areas were readily distinguished from the much lighter, exposed sediments and water in the channel. The classification was verified using contemporary oblique photographs and, for recent imagery, direct field observations.

The development of scrub dominated by *Ulex europaeus* was quantified for two dates, 2001 and 2019, for which particularly clear aerial images were available. The boundaries of scrub areas were digitized, and their total area estimated for each date. Wherever possible, these evaluations were verified using field observations and oblique photographs. Observations of the root structure of individual *Ulex* plants were made along banks where the *Ulex* was being undercut and on uprooted plants deposited following major floods in 2019–2020.

#### *Heavy metal contamination*

To assess changes in the level of contamination, transect sampling undertaken by Lewin et al. (1977) in 1969 was repeated in 2021, replicating sampling stratification by landform features. In addition to the sampling locations used by Lewin et al. (1977), which were upstream and downstream of the study reach, additional transects and point locations were sampled within the study reach (Figure 1b). A reference sample was also obtained from the nearby upstream mining tailings heap.

The samples were analysed by X-ray fluorescence (XRF) using a Thermo Scientific Nitron XL3t instrument. Each sample was air-dried, sieved to <2 mm, homogenized and then analysed for 240 s following Caporale et al. (2018) and Jelecevic et al. (2021). Three analyses were performed on each sample and the results were averaged. Levels of Pb, Zn and Cu were obtained, but Cd levels were consistently below the detection limit. Although a full particle size analysis of the <2 mm fraction of each sample was not carried out, the texture of each was assessed to establish whether any broad differences in the mix of sand to finer sediments was apparent.

Evidence of changes in heavy metals dissolved in the river water was obtained from the literature and from measurements conducted on water samples obtained near the mouth of the Ystwyth at Rhydelfelin (Figure 1a) by Natural Resources Wales.

## 3 | RESULTS

### 3.1 | Channel planform evolution

The channel position in the Grogwynion reach has migrated actively and extensively in the period 1845–2021 (Figure 2). There appear to be two periods of broadly contrasting morphology.

Low-sinuosity planforms showing multiple channels are evident on Ordnance Survey maps dating from 1886, in contrast to earlier mapping (1845) and documentary sources reported by Lewin et al. (1977). This relatively low-sinuosity form, with a high-stage braided pattern, persisted until at least 1987. A second period, captured in images dating from 2001 to 2021, shows increasing main-channel sinuosity and single-channel dominance (Figures 2 and 3). A trend towards lower values of the braiding index that are broadly inverse to the increases in sinuosity since 2000 (Figure 3) is also apparent, but this conclusion is heavily influenced by the presence of an outlier value in 1987. Although there was no correlation between values of the braid channel index and mean daily flows measured at the Cwm Ystwyth gauging station, the higher values of the index may reflect a time-dependent, localized and incomplete adjustment of secondary channels following major flood events.

### 3.2 | Channel and bar morphology

In-channel features, especially bars, are closely associated with channel planform. The field mapping and aerial images available for the study reach have the potential to reveal the character and dimensions of such features and how they may have changed as planform has changed.

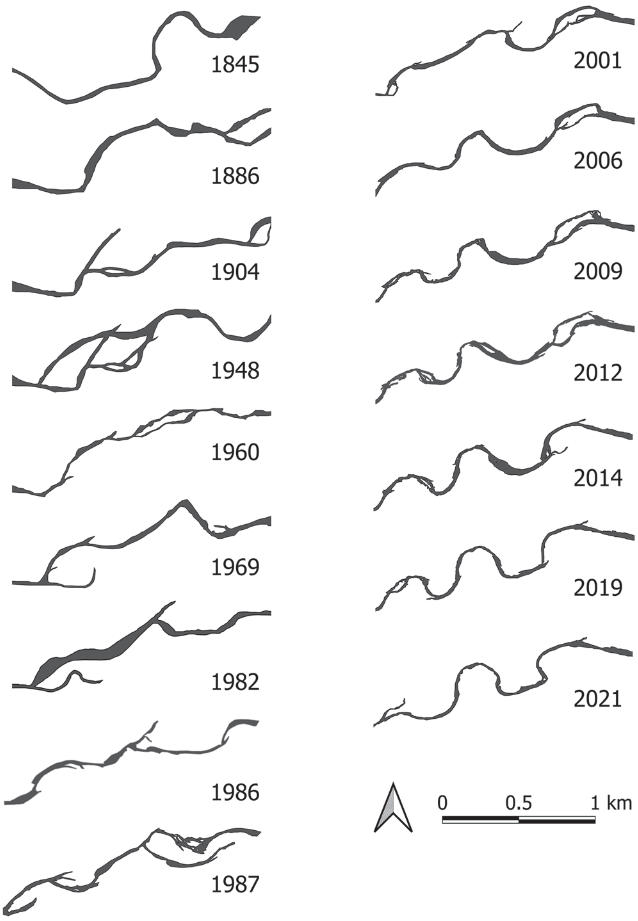


**FIGURE 2** River channel boundaries within the Grogwynion reach displayed on maps (1845–1982), captured during field surveys (1986, 1987) and defined by the extent of the water-covered area in aerial images (2001–2021). These represent low-stage surveys. Braiding in 1986–1987 at high flows was greater than indicated by the channel margins, as plotted on map surveys.

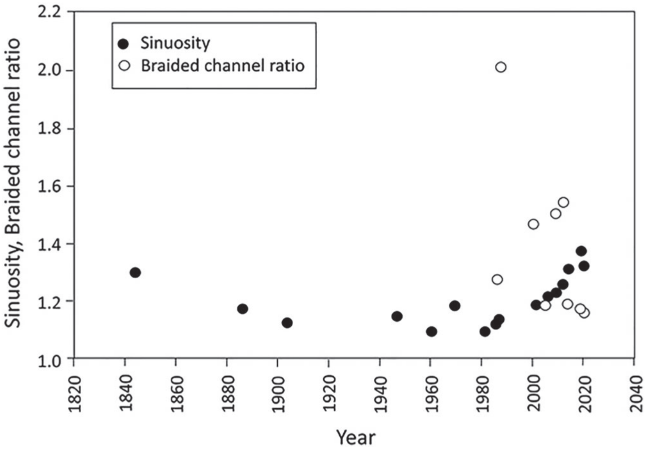


**FIGURE 3** Variations in main channel sinuosity (1845–2021) and braiding channel ratio (1986–2021) within the Grogwynion reach.

### 3.2.1 | 1986–1987

Detailed field mapping was conducted in 1986 and 1987 (Figure 4), towards the end of the period of low-sinuosity planforms (Figure 3). The mapping reveals channel changes in the study reach following two closely spaced flow events on 19 November and 30 December 1986. Peak discharges of these two events, recorded at the Pont Llolwyn gauging station (Figure 1a) were, respectively, 112.9 and 150.8 $m^3 s^{-1}$. Based on an analysis of POT flows for the period from 1975 to 2000, these have estimated return periods of approximately 2.6 and 8.6 years, respectively.

The study reach showed three main responses to these events (Figure 4): channel avulsion, lateral migration and compound bar development. These are all linked, since compound bar development reduces the cross-sectional area of the active channel and causes the diversion of flow against the banks. This induces bank erosion and lateral migration, and avulsion over previously abandoned areas.

Monthly oblique photographs reveal that the most significant channel avulsion occurred during the 19 November event as a result of the vertical aggradation and enlargement of the compound bar at the upstream end of the study reach (Figure 4: Location A) causing flow to be diverted over an extensive gravel area into a channel abandoned during a major event in August 1973 (Lewin et al., 1977). During subsequent events, the avulsion path became increasingly well-defined and remained the dominant channel in the upstream section of the reach (Figure 2).

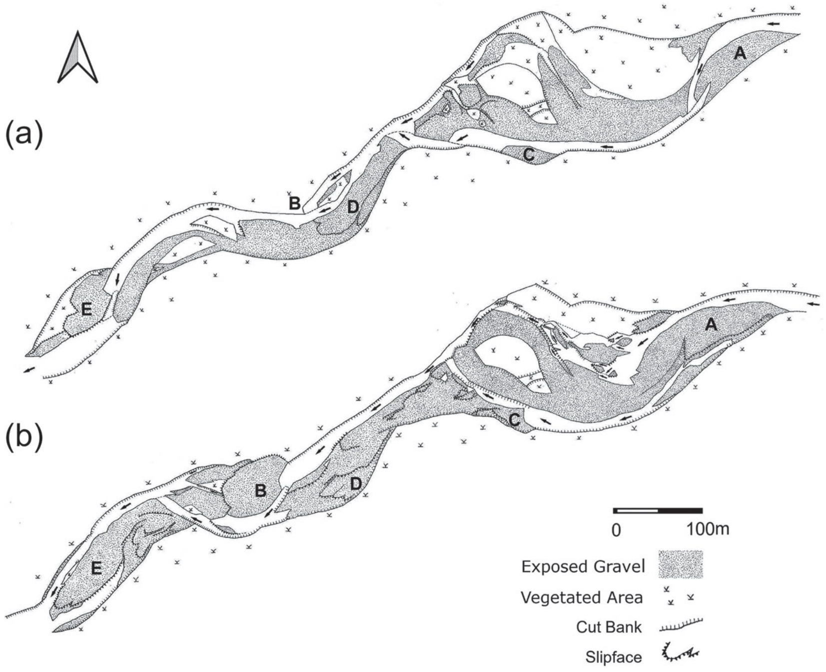
Local gravel transport during both events resulted in the development, enlargement and modification of both large-scale bars and smaller bedforms. Three types of bedform development were observed. First, the initiation of a bar as a linguoid unitary bedform where flow expanded onto areas adjacent to the active channels and was unconfined by adjacent floodplain banks (Figure 4: Location B). Second, accretion to pre-existing bars led to vertical, lateral, downstream and upstream growth of the bar features, particularly where the active channel was confined by the adjacent floodplain (Figure 4: Locations A and E). Third, linguoid and elongate bedforms developed within channels, with their form controlled by the channel morphology and scaled to the channel dimensions (Figure 5: Location C). Smaller linguoid bedforms were observed to have migrated over exposed gravel areas adjacent to the active channels (Figure 5: Location D). To deposit gravel in a large bar (Figure 4: Location E), the high-flow channel must have occupied much of the width of the valley floor, whilst the area north of Location C (Figure 4) must have braided to deposit the fresh gravel either side of an apparent island. Lobe D (Figure 4) shows modification by higher flows unrelated to the position of the residual low-flow channel.

The most significant bank erosion was the direct result of flow diversions produced by the development of bar forms during the 30 December event. Lateral erosion of adjacent banks continued after this event, associated with the attachment of smaller gravel bedforms to the flanks of the larger bed forms (Figure 4: Location B).

### 3.2.2 | 2001–2021

Since 2001, major avulsions have been less common and the main channel has become progressively more sinuous (Figure 2). The most significant channel changes have resulted from lateral meander migration, where this is unconstrained by the valley side to the north and road embankment/valley side to the south (Figure 5). Locally, outer bank migration is also apparent, relative to the valley axis, both in an upstream and downstream direction, reflecting sequential increases in

**FIGURE 4** Distribution of bars, cut banks and riparian vegetation along the Grogwynion reach in June 1986 (a) and August 1987 (b).



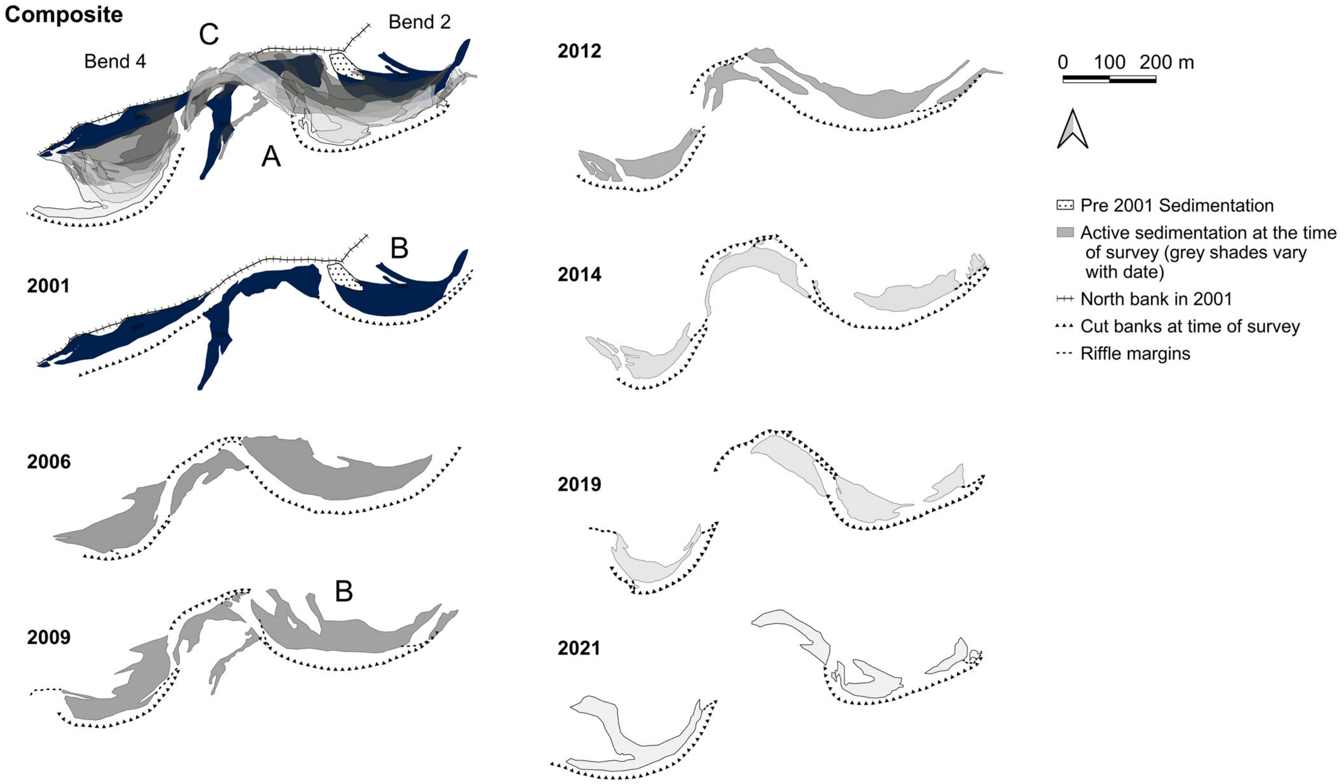


**FIGURE 5** The changing extent of active channels, sedimentation (unvegetated, unweathered bar surfaces) and cut banks at bends 2 to 4 of the Grogwynion reach between 2001 and 2021 and an overlay composite.

bend tortuosity (Figure 5: Location A). Multiple channels are rare compared to pre-1987 surveys, with a single channel present for the length of the reach by 2019 (Figure 2). A major bifurcation at the upstream end of the reach in 2001 had evolved into a single channel by 2014 (Figure 2).

The detailed depositional forms and the associated migration (Figure 5) of two unconstrained bends (bends 2 and 4, Figure 1b) during the period 2001–2021 show progressive migration. This results from the formation of mid-channel and point bars in areas of flow expansion with commensurate erosion of the adjacent outer bank during high-stage events, such as during a 130 $m^3$ $s^{-1}$ event in October 2000. Bar growth has resulted predominantly from lateral expansion into the accommodation space created by the erosion of the outer bank. Flow has diverged across the bar surfaces with, in some instances, slip faces and sediment lobes developing at the inner and downstream edges of the bars (Figure 5: Location B) as falling-stage features sympathetic with the low-flow, sinuous channel outlines.

As sinuosity has increased, the channels at the exit of the bends have converged with the outer bank of the succeeding bend at a highly oblique angle (60–80°) (Figure 5: Location C), resulting in flow convergence and enhanced scour along the outer bank of the succeeding bend. Bank erosion adjacent to these scours represents the primary location for bend migration and the source of sediments that are deposited on the adjacent lateral bar or, in some cases, as a mid-channel bar. These areas of sedimentation extend to the point of convergence with the succeeding bend. Slip faces have developed at the point of junction, and these themselves represent locations of flow expansion which may expand in both upstream and downstream directions (Figure 5: Location C), becoming points of accumulation both at the downstream end of the upstream bar and at the head of the succeeding downstream bar. The increase in sinuosity has been associated with a decrease in the radius of curvature of bend 2 (274 to 170 m) and bend 4 (720 to 205 m), with annual rates of lateral bend migration averaging up to 10 m.

Channel avulsion during flood events remains a significant, if more infrequent, mechanism, with an avulsion, meander cutoff and channel abandonment occurring in 2019–2021 at the downstream end of the study reach (Figure 6). Here, bank erosion and migration of the upstream bend between 2014 and 2019 allowed an initial reoccupation and enlargement of an historic abandoned channel, occupied by low grasses and sedges (Figure 6, April 2019 image), with an eventual avulsion occurring across the meander during flood events in October 2019 (107 $m^3$ $s^{-1}$) and February 2020 (123 $m^3$ $s^{-1}$) (Figure 6, April 2021 image).

## 3.3 | Potential influences on channel change

### 3.3.1 | Flood magnitude and frequency

Flood magnitude–frequency analyses of POT discharges monitored at the Pont Llolwyn gauging station for the periods 1962–1995 and 1996–2021 (Figure 7a) show a distinct increase in magnitude for floods, up to a return interval of approximately 10 years, since 1996. Floods exceeding 107 $m^3$ $s^{-1}$, the estimated bankfull stage, have become more frequent (Figure 7b). Exceptional floods exceeding 140 $m^3$ $s^{-1}$ are apparent throughout the period of record, with a 248 $m^3$ $s^{-1}$ event in December 1964 being a notable outlier.

### 3.3.2 | Sediment budget

Comparison of the 2012 LiDAR survey and recent satellite imagery with 1886 and 1904 map sources (Figure 8) shows no evidence of recent incision in the active area of the reach, but local lateral expansion through undercutting of terraces of presumed Holocene age (Macklin & Lewin, 2009) is evident.

Comparative cross-profiles obtained from 2012 LiDAR data at the same locations as field surveys made by Lewin et al. (1977) in 1969 (Figure 1b) show some evidence of incision of the floodplain in cross-profiles located upstream (Figure 9, cross-profile 1, A) and downstream (Figure 9, cross-profiles 4 and 5, B) of the study reach, where the main channel position has been stable. At these profiles, floodplain incision is estimated to be in the region of 50–80 cm. However, cross-profiles 2 and 3 (Figure 9), which lie within the study reach, show no clear evidence of either incision or aggradation of the floodplain. The incision or aggradation of individual channels cannot be assessed because the bed profile was not accurately surveyed.

The total mass of the waste from Grogwynion, estimated using the figures of Palumbo-Roe and Coleman (2010), was between 17 500 and 88 740 t. The area of the tailings heap currently visible from satellite imagery is 10 268 $m^2$, containing an estimated 76 675 t. Further waste remains in the vicinity of the adits.

### 3.3.3 | Vegetation cover

Examination of the aerial images between 2001 and 2021 indicates a reduction in exposed riverine sediments (ERS) from 36% (0.19 $km^2$) to 20% (0.10 $km^2$) of the total floodplain-active channel area (Figure 10). The reduction in the area of ERS is progressive, with increases being noted following major flood events in December 2012 and October 2020, but not following similar events in October 2008 and January 2018. Detailed analysis of the 2001 and 2019 images also shows a change in the character of the vegetated areas, with expanses of sparse, low vegetation being replaced by scrub dominated by gorse (*U. europaeus*) on more recently reworked sediments, and by dense, marshy grassland on areas unaffected by channel migration or avulsion since 1982 (Figure 11). The area covered by scrub has increased from 9% (0.045 $km^2$) to 32.5% (0.17 $km^2$) of the floodplain–channel area between 2001 and 2019.

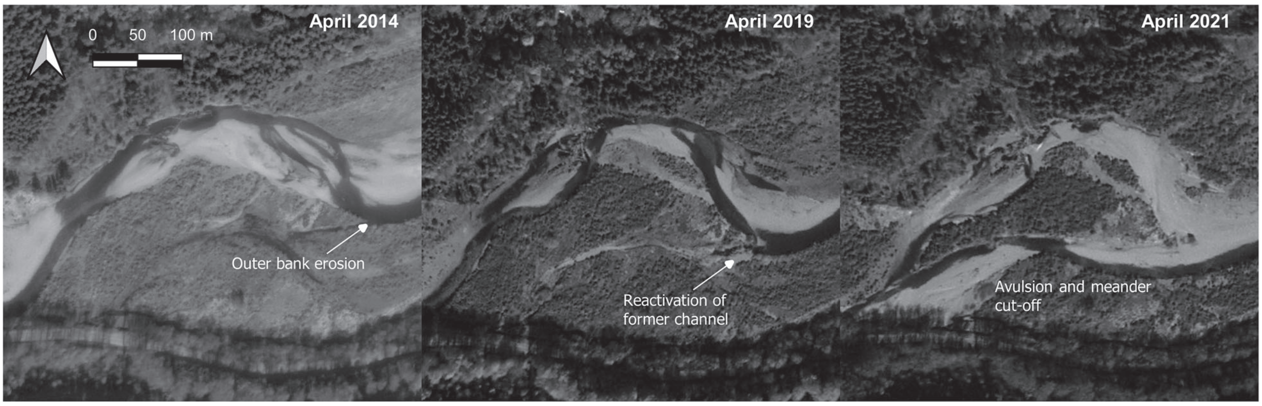


**FIGURE 6** Progress of a channel avulsion initiated by flood events in October 2019 and February 2020 at the downstream end of the Grogwynion reach (images: Google 2014 © Maxar Technologies, Google 2019 © CNES/Airbus, Google 2021 © CNES/Airbus).

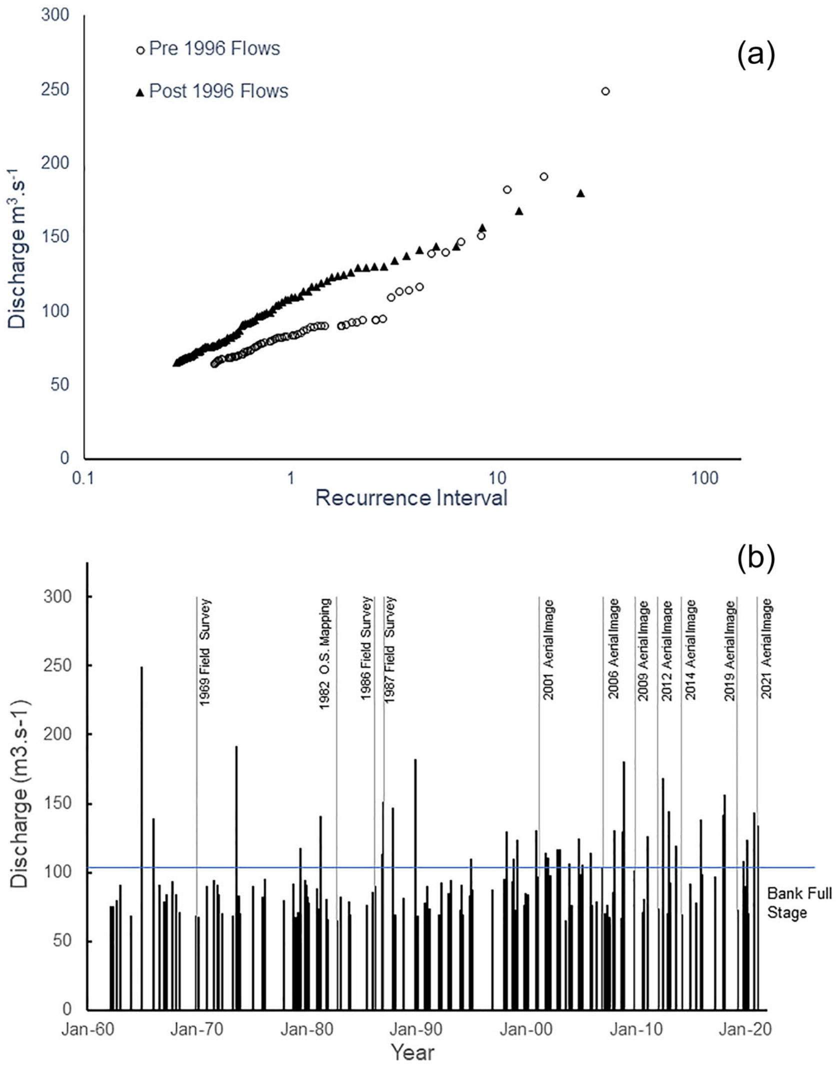


**FIGURE 7** (a) POT flood flows (>64.6 m$^3$ s$^{-1}$) monitored at the Pont Llolwyn gauging station, 1962–1995 (white circles) and 1996–2021 (black triangles) in relation to their estimated recurrence intervals. (b) POT flood flows 1962–2021 showing the relationship to dates of the channel surveys and the bankfull discharge.

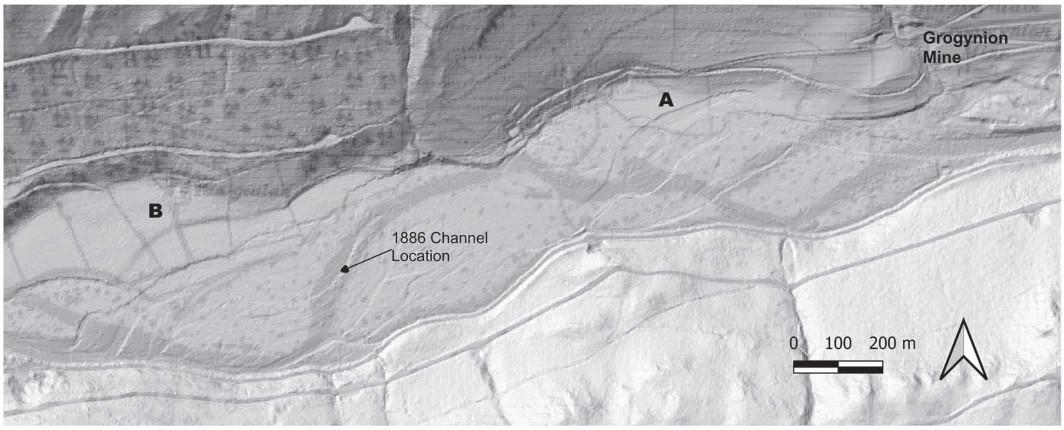


**FIGURE 8** Image shows 1886 Ordnance Survey map overlain on a 2012 LiDAR hillshade image. Locations A and B identify where there has been expansion of the active area and erosion of Holocene terraces since 1886 (EDINA Historic DigiMap Service, 2017; Natural Resources Wales, 2015). OS map source: 1:2500 County Series 1st Edition [TIFF geospatial data], scale 1:2500, tiles: card-sn6971–1, card-sn7071–1, card-sn7171–1, updated 30 November 2010, historic, using EDINA Historic Digimap Service http://digimap.edina.ac.uk, downloaded 2017-07-26 18:03:42.529.

Observation of the *U. europaeus* root structure exposed on uprooted plants and in cut banks shows the common presence of a single tap root, 20–40 cm in length, and a mat of finer roots spreading laterally under each plant in the top 10 cm of the substrate. Individual plants vary in height, but the canopy of older specimens reached up to 3 m in height with rigid stems, typically 2–4 cm in diameter, and with a dense crown of spikey leaves. The *U. europaeus* plants occurred individually, in small clumps and in extensive areas that were dense and impenetrable (Figure 11).

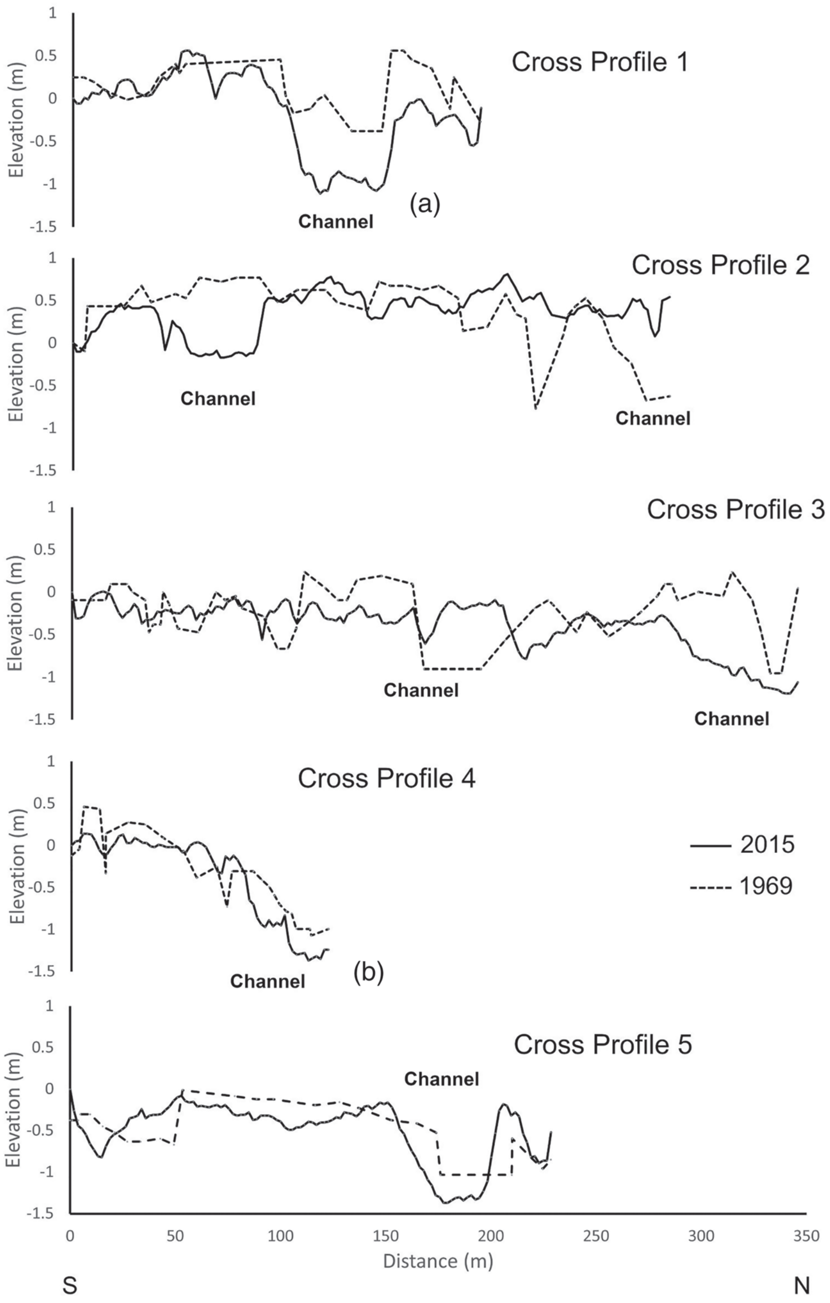


**FIGURE 9** Cross-profiles 1 to 5 (Figure 1b) surveyed by Lewin et al. (1977) in 1969 and extracted from a 2015 LiDAR survey.

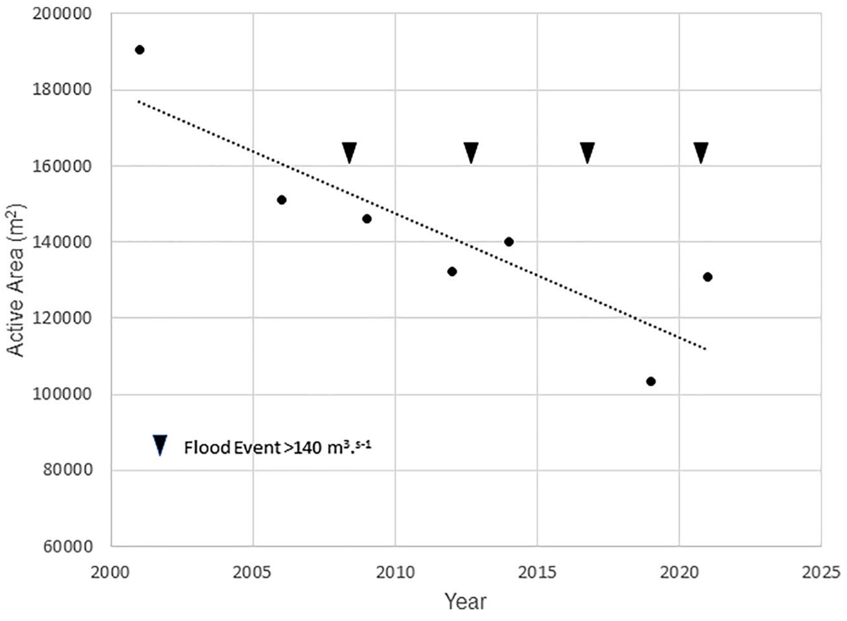


**FIGURE 10** Changes in the active area (channel + ERS) in the Grogwynion reach 2001–2021 showing the relationship with recent major floods.

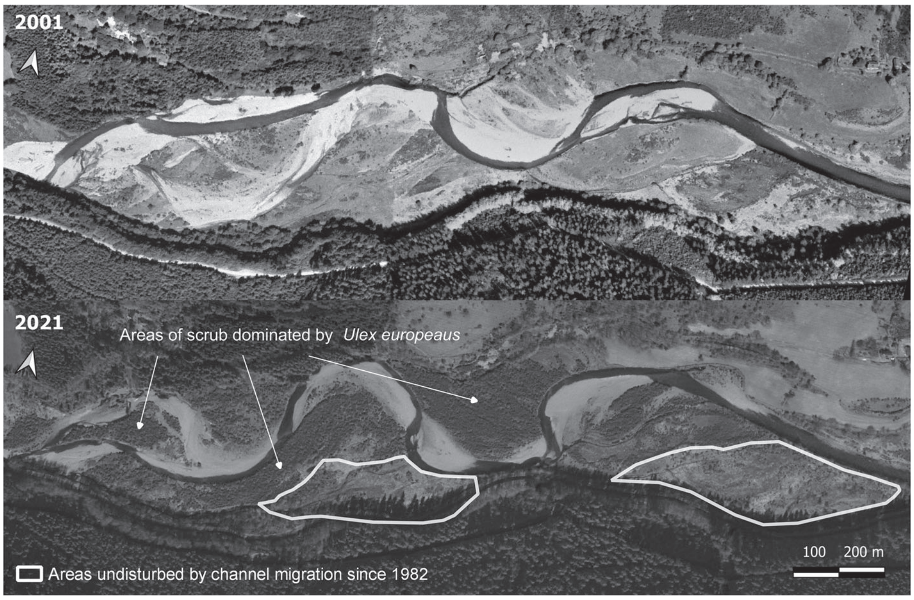


**FIGURE 11** The Grogwynion reach in 2001 and 2021 showing areas that have remained undisturbed since 1982 and the encroachment of scrub across more recently disturbed areas (images: Aerial Digmap 2001 © Getmapping plc, Google 2021 © CNRS/Airbus).

### 3.3.4 | Heavy metal contamination

Published concentrations of lead in solution for water samples mainly taken close to the river mouth suggest a progressive decline over a period of 100 years (Table 2). This temporal decline is less clear from frequent observations collected close to the river mouth at Rhydyfelin over the last 25 years (Figure 12a). However, concentrations of cadmium and zinc observed at the same site and over the same time period both show a statistically significant decline (Figures 12b and c).

Sediment samples collected from the study reach in 2021 along sampling transects A and D (Figure 1b) were close to the sampling transects investigated by Lewin et al. (1977). Box and whisker plots summarize the 1969 and 2021 concentrations of lead, zinc, copper and cadmium in the <2 mm sediment fraction in ppm (Figures 12d–g). The numbers of samples are very small (A1977 = 4, A2021 = 2, D1977 = 5, D2021 = 5), preventing any statistical testing. Furthermore, different methods were used by Lewin et al. (1977) (atomic absorption spectrometry, AAS) and this study (XRF). Although previous studies have shown the strong correlation between the results obtained by XRF and AAS for Pb, Zn and Cu (Clark et al., 1999; Radu & Diamond, 2009), actual levels may be site-specific (Caporale et al., 2018). Small sample sizes and different laboratory methods mean that comparisons require caution. However, with the exception of zinc at site A (Figure 12e), the plots hint at either no change or a small reduction in concentrations of the four metals between the two dates.

If the 2021 samples are considered in relation to their environmental setting, some spatial patterns can be tentatively observed (Figures 12h–j), although the number of samples is once again small. Cadmium was below the detection limit in all samples. A single sample taken from the upstream spoil heap (Figure 1b) shows far higher concentrations of lead, zinc and copper than all other samples. Despite the small number of samples, the box and whisker plots reveal the highest concentrations in samples from the contemporary, vegetated, floodplain (including samples from areas under scrub and grassland and within vegetated abandoned channels), the lowest in samples from terraces and intermediate levels in samples taken from the unvegetated active channel and contained bars. Despite the small sample numbers, Kruskal–Wallis tests reveal statistically significant differences in zinc ($p = 0.027$) and lead ($p = 0.001$) levels, and multiple pairwise comparisons using Dunn's procedure show zinc levels to be significantly lower ($p < 0.01$) in terrace than other samples and lead levels to be statistically significantly lower ($p < 0.01$) in active channel and terrace samples than in floodplain samples. Furthermore, all levels of lead and zinc in these samples are lower than those obtained in a single floodplain sample located within 10 m of the spoil heap (Figures 12h–j).

**TABLE 2** Dissolved lead concentrations recorded in the River Ystwyth

| Date | Dissolved lead concentration[a] (mg $L^{-1}$) | Source |
|---|---|---|
| 1919 | 0.4 | Carpenter (1924) |
| 1924 | <0.1 | Carpenter (1924) |
| 1939 | <0.05 | Laurie and Jones (1938) |
| 1991 | 0.058 | Fuge et al. (1991) |
| 2020 | 0.008 | Natural Resources Wales |

[a] All measurements were taken close to river mouth, 32 km downstream of the study area, except those of Fuge et al. (1991) who reported measurements 7.5 km downstream and noted a decline in contamination with distance downstream.

## 4 | DISCUSSION

### 4.1 | Changes in channel form

Exploration of various historical sources dating from the period 1845–2021 indicates a change in planform stability that commenced after the 1987 survey and is clearly apparent in subsequent sources from 2001 onwards (Figure 2).

Lewin et al. (1977), commenting on the study reach prior to 1977, described the significant transition in channel planform following the commencement of extensive mining in the valley in 1792 from a

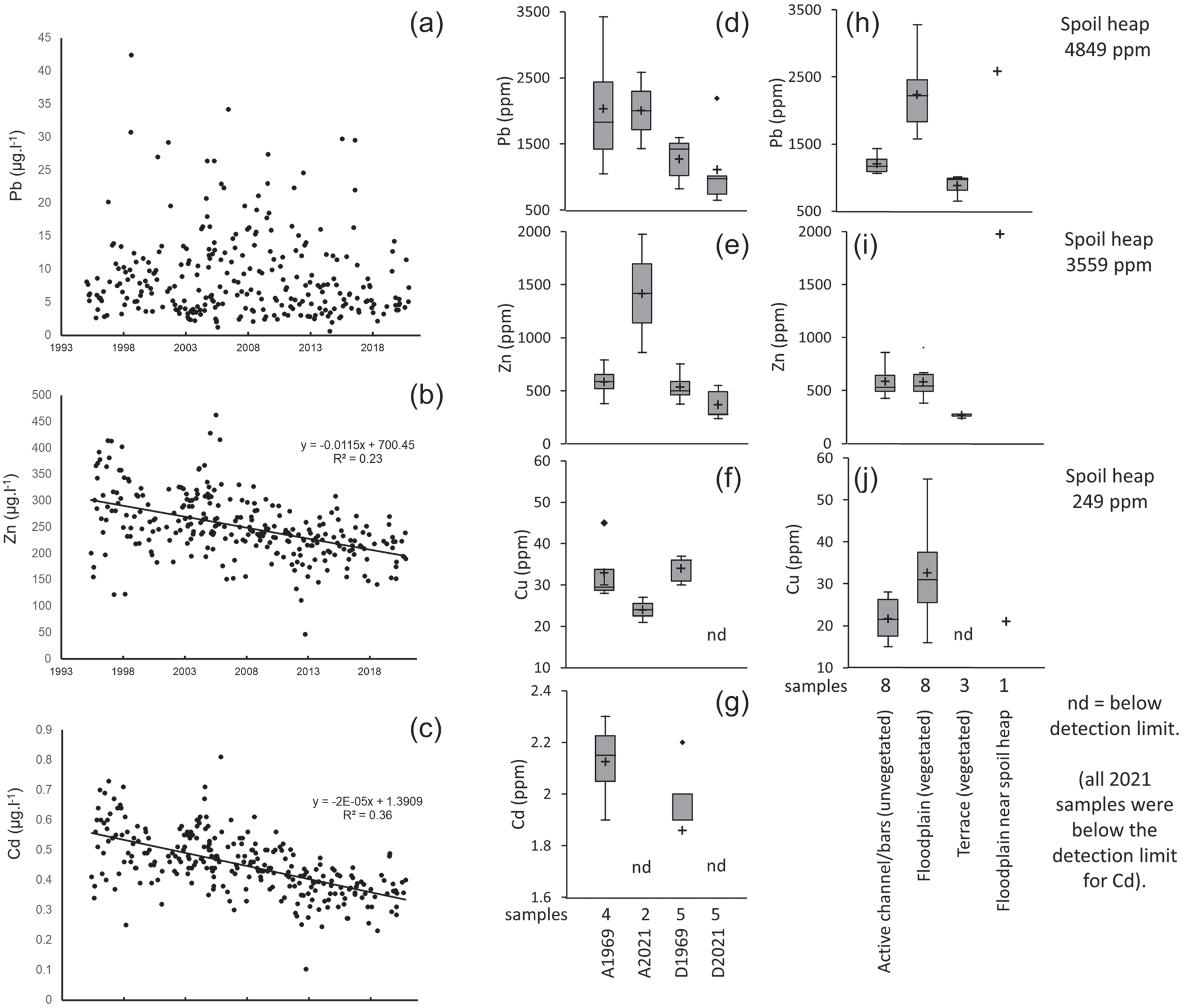


**FIGURE 12** Scatterplots showing temporal changes in the concentrations of cadmium (a), zinc (b) and lead (c) [μg $L^{-1}$] in water samples taken by Natural Resources Wales at Rhydyfelin near the mouth of the Ystwyth. Box and whisker plots of concentrations in ppm of lead (d), zinc (e), copper (f) and cadmium (g) in sediment samples taken at transects A and D (Figure 1b) in 2021 in comparison with samples taken nearby in 1969. Box and whisker plots of concentrations in ppm of lead (h), zinc (i) and copper (j) in sediment samples taken from different channel–floodplain surfaces in 2021. Note that the box and whisker plots display the mean (black cross), median and upper/lower quartiles (the three horizontal lines of the box) and the maximum/minimum values (the whiskers) unless there are major outliers (marked beyond the whiskers as black diamonds); where only a single sample was taken, this is represented by a black cross.

sinuous single channel to a lower-sinuosity form marked by extensive gravel flats and a braided appearance. They argued that this braided appearance at high-flood stage resulted from a lack of stabilizing vegetation and the flooding of inactive channels. Changes in channel location occurred during flood events due to avulsion into abandoned channels and lateral and confluence bar sedimentation. Following Foulds et al. (2014), it is possible that the planform in part reflects a flood-rich period that occurred in the time period 1900–1960.

However, the sedimentological evidence presented through field mapping and oblique photographs captured between 1986 and 1987 complements the earlier map evidence for a braided channel at high stage and shows that a low-sinuosity form persisted well beyond 1960. Channel responses to two floods include both avulsion and lateral channel migration associated with incremental, complex bar formation in areas of flow expansion. These observations are commensurate with the mechanisms noted by Ashmore (1991), Bridge (1993), Ferguson (1993), Ashworth (1996), Williams et al. (2016) and Yang (2020) from experimental and field observations. Complex bars formed mid-channel in situations where the channel was less constrained by semi-stable floodplain banks, or as attachments to lateral bars where the channel was more constrained.

In contrast, the analysis of images from 2001 to present (Figures 2 and 5) reveals that channel migration has occurred more gradually than previously and primarily through bank erosion and point bar accretion. Sinuous channels have continued to evolve, in contrast to the avulsion and overbank splay forms formed during braiding. Mid-channel bar formation and subsequent channel division has become infrequent, reflecting changes in channel geometry and greater prevalence of scour at the apex of bends, and associated downstream inner bank sedimentation as noted by Eke et al. (2014)

and van der Lageweg et al. (2014). Sustained avulsion into overbank areas has also become less common. Although overbank flow into abandoned channels occurs in major flood events, these flow paths do not become permanent avulsions unless there is significant erosion, removal of vegetation and enlargement at the point of avulsion, as occurred during the cutoff of bend 5 between 2019 and 2021 (Figure 6).

These observations indicate that a major change has occurred in channel dynamics within the study reach since previous analyses (Higgs, 1997; Lewin et al., 1977) and substantially (140 years) after the local cessation of mining. This requires explanation.

## 4.2 | Causes of channel changes

### 4.2.1 | Sediment budget: Aggradation and sediment transfer

Based on comparison with other locations in the UK it would be convenient to attribute the changes in planform in the reach to 'geomorphic recovery' in the form of an aggradation–degradation episode or as a response to a sediment wave (James, 2018). Lewin et al. (1983), Lewin and Macklin (1987) and Macklin and Lewin (1989) presented evidence of floodplain aggradation accompanied by a change from a meandering to a braided planform followed by incision and reversion to a single channel in several rivers affected by mining in the UK. They argued that this was a consequence of an initial input of mining waste that destabilized slope and floodplain deposits, followed by riverbed incision as the 'slug' of mining sediments transferred downstream through the river system, leaving stabilized deposits as delivery of mining sediment inputs attenuated. This does not seem to be the pattern in the Grogwynion reach: there is no evidence of large volumes of coarse sediment input (Lewin et al., 1977; Palumbo-Roe et al., 2009) causing aggradation and a related unstable planform in the reach. Coarse waste associated with mining adits formed scree on the valley sides that, with one possible exception, did not enter the river channel. The nature of waste processing (Moissenet, 1866; Palumbo-Roe et al., 2009), involving crushing of the ore and flotation extraction before the largely sand grade waste was deposited, limited the amount of coarse waste. In addition, the tailings heap from the Grogwynion mine was and continues to be protected by a reinforced embankment, limiting the amount of any sediment input. Comparison of the tonnage retained in the tailings heap at the mine site with estimates of total waste production (Palumbo-Roe & Coleman, 2010) supports the conclusion that direct input was small.

Similarly, the reversion to a single channel does not seem to be related to reach incision. A comparison of five cross-profiles measured in 1969 and using 2012 LiDAR data (Figure 9) shows no significant differences in the profiles measured within the study reach and only limited floodplain incision (40–60 cm) in sections upstream and downstream where channel lateral movement is restricted by the valley sides or embankments. Examination of recent LiDAR surveys and historic mapping dating from the cessation of major mining activity shows no evidence of terracing and, in certain areas, some lateral expansion of the active zone (Figure 8). In addition, the avulsion of the channel at the downstream end of the reach during 2019–2021 (Figure 6) and the observed presence of bedload sediments deposited across stable overbank areas (Figure 5) supports the contention that incision is not currently present or not significant locally within the study site.

A more plausible scenario is that channel instability in the reach was not due to the volume of sediment but the consequence of fine contaminated sediment and solute inputs from local and upstream mining sites (Lewin & Macklin, 2010) (Figure 1a) during the period of extensive mining (1792–1904), and possibly some leakage during the spoil reprocessing between 1920 and 1930. Consequent changes in the vegetation assemblage as a result of metal contamination led to the formation of a shingle heath with low stability under flood conditions. The present sediment balance in the reach, as postulated by Lewin et al. (1977), is due to localized reworking of the current floodplain. This provides a continuous source of sediment, supplemented by sediments delivered from upstream and eroded locally from Holocene terraces and the valley sides where the channel has impinged, and from the channel bed upstream where incision is occurring.

We therefore do not believe that a changing sediment budget, representing a form of 'geomorphic recovery', explains the changes in channel form that have been observed.

### 4.2.2 | Flood magnitude and frequency

Flood magnitude–frequency analysis highlights the more frequent occurrence of flood flows since 2000, at least up to approximately 140 $m^3$ $s^{-1}$ (Figure 7). This accords with Foulds et al. (2014), who identified a flood-rich period in the Cambrian Mountains between 2007 and 2012 due to wetter than average conditions associated with a negative Summer North Atlantic Oscillation (SNAO). A greater frequency of such higher flows might be expected to lead to a greater frequency of avulsion events, lower sinousity and an expansion of the area of ERS (Higgs, 1997; Lewin et al., 1977), but this is not supported by our observations of the study reach in 2001–2021 (Figures 2 and 10). This indicates that any connection between flood frequency and channel planform in this period is indirect. This contrasts with Brewer et al. (2001, 2009), who concluded that climate/land-use controls on flow regime, and a *reduced* frequency of flood events (in the late 20th century), were major determinants of the reduction in exposed riverine sediments across a number of Welsh rivers.

### 4.2.3 | Changes in vegetation cover

Riparian vegetation is a major control of channel dynamics in addition to flow and sediment processes (see reviews by Corenblit et al., 2007, 2009; Gurnell, 2014; Gurnell et al., 2012, 2016; Lelpi et al., 2022). The more extensive and denser growth of grasses and, particularly, the establishment of large expanses of scrub dominated by *U. europaeus* since the end of the 20th century have accompanied the observed changes in channel planform and stability and appear to be major influencing factors. The influence of vegetation type, and vegetation change, as a factor inducing a change from a braided to single-thread channel planform has been observed experimentally by many researchers (e.g. Bertoldi et al., 2015; Braudrick et al., 2009; Gran & Paola, 2001; Tal & Paola, 2010; van Dijk et al., 2013). Hicks et al. (2007) showed that a braided river will evolve into a single-thread channel if floods are too infrequent to contain the vegetation growth, supporting Paola's (2001) hypothesis that the tendency of a river to braid will be influenced by the river's ability to turn over its bed within the characteristic time required for vegetation to develop to a scour-resistant state. Kleinhans and van der Berg (2011) similarly argue that vegetation significantly affects channel mobility, noting that high sinuosity is in part caused by dense vegetation that resists cutoff by chute channel formation. Restriction on chute formation represents one contrast between the channel patterns observed in 1986–1987 (Figure 4) and those apparent at present, with channel-parallel chute and lobate bar forms (e.g. Figure 4: Location D) being less common and lobate forms and scroll bars attached to existing lateral sediments being more prevalent (Figure 5).

*Ulex europaeus* is a stress-tolerant competitive species (Grime et al., 2007). It can germinate and survive in a wide range of conditions, including on metalliferous mine wastes (Lottermoser et al., 2011; Rees & Hill, 2001), exhibiting quick growth. It regenerates entirely from seeds, which can remain viable for up to 28 years in the soil and are dispersed by several mechanisms (Grime et al., 2007; Roberts & Florentine, 2021). Within the Grogwynion reach, the establishment of *U. europaeus* provides a dense above-ground canopy up to 3 m tall, which may have three main influences on channel change. First, it provides significant flow resistance across floodplain and vegetated bar surfaces in comparison with other lower-profile, more flexible vegetation in the study reach, and thus it has the potential to slow flow velocities and induce deposition of transported sediments. Parker et al. (2011) similarly noted that point bars became erosion-resistant and stabilized by vegetation growing in fine sediment, and Zen et al. (2017) described how riparian woody vegetation could drive the formation and stabilization of scroll bars that in turn coalesced to build floodplains on the inner banks of meander bends. Second, *U. europaeus* stands along the outer bank tops of active channel margins in the reach also seem to act as a deflective barrier, not just slowing overbank flow velocities but also deflecting much of the flow back into the main channel. Finally, *U. europaeus* possesses dense, woody root systems with tap roots and the ability to develop adventitious roots in response to burial or flow damage. These root systems stabilize the plants, resist plant uprooting and reduce land surface erosion by overland flow, including avulsions. However, field observations suggest that the roots have a lesser influence on bank erosion, where they may become undercut on the outer channel banks, and so may not slow lateral channel migration.

At Grogwynion, based on observations of bends 2 and 4 in the period 2001–2021, we postulate that the rapid growth of *U. europaeus* on exposed inner bank sediments has enhanced 'bar-push' and 'bank-pull' processes of meander development (Allmendinger et al., 2005; Parker et al., 2011; Zen et al., 2017), with rapidly accreting point bars inducing erosion at the outer bank by steering flow in a manner that forces the high-velocity core towards the concave bank (Dietrich & Smith, 1983; Eke et al., 2014; van der Lageweg et al., 2014). This in turn enhances point bar growth by creating accommodation space. In experimental work, Rominger et al. (2010) and Bywater-Reyes et al. (2018) demonstrated that vegetation cover on point bar surfaces resulted in reduced flow velocities upstream of the bar and flow being steered away from the vegetated surface. These processes are stage-dependent (Parker et al., 2011; Pizzuto, 1994). Pizzuto (1994) found that larger floods favoured bank erosion on the outside of bends, whereas smaller floods induced bank deposition at the inside of bends, indicating that 'bar-push' and 'bank-pull' mechanisms work in tandem, allowing the channel to migrate while maintaining a bankfull width that is broadly constant over several flood cycles.

The combination of the relatively rapid processes of floodplain and bar stabilization due to *U. europaeus* colonization and the rapid erosion of the outer channel banks across several flood cycles is reflected in the rate of channel migration and the observed increase in channel sinuosity. The presence of a high-velocity zone during flood conditions at the downstream end of bend 4, consequent erosion of the outer bank and the presence of a former channel only partially infilled with overbank sediment seem, in combination, to be significant factors in the avulsion and meander cutoff of bend 5.

### *Heavy metal contamination*

The previously distinct sparse vegetation assemblage along the Grogwynion reach reflects the presence of heavy metals (Countryside Council for Wales, 2008; Joint Nature Conservation Committee, 2021). The recent establishment of extensive areas of *U. europaeus* on recently reworked sediments and dense grass on areas unaffected by channel migration since 1982 represents a significant recent change in the plant ecology of the reach (Figure 11). Carline (2020) highlighted the potential consequence of reducing metal contamination levels on the ecology of the reach as the result of mining remediation works upstream, and it is reasonable to hypothesize an association between levels of contamination and vegetation change. However, our overall analysis of metal contamination levels (Figure 12) shows that there have been no significant reductions of levels in the sediments in the past 50 years and the establishment of *U. europaeus* therefore seems to have been independent of the overall levels of sediment metal contamination.

Rapid colonization of river margins by *U. europaeus* has been noted in many river margin environments (e.g. Hicks et al., 2006) as part of a natural succession involving initial development of a soil profile under lower-order plant mats providing a foundation for shrub establishment (Calder, 1961). Simkin (2017), in a study of rivers affected by heavy metal contamination in the North Pennines, reported similar changes in vegetation cover to those observed in the study reach over a 10-year period. She suggested that nitrogen fixing under *U. europaeus* leads to irreversible changes and attributed the changes in vegetation cover to nitrification, pedogenesis, the leaching of heavy metals down the soil profile and the introduction of sediment during flooding. These findings indicate that once established, the presence of *U. europaeus* is sustained.

Metal levels in the reach show considerable variability according to depositional environment (Figures 12h–j). Sediments on exposed weathered surfaces show lower levels of contamination, whilst differences between levels observed in unvegetated active channel sediments and vegetated floodplain sediments are likely to be more a reflection of differences in the finest size fractions of the samples (e.g. Bradley, 1989; Jelecevic et al., 2021; Lewin et al., 1977). There is, however, no clear correlation between vegetation type and contamination levels. The observed contrast in the vegetation cover on recently active surfaces and those that had not been reworked since at least 1982 (Figure 11) more probably reflects the level of disturbance in that period and thus probably the degree to which pedogenesis had occurred in the undisturbed areas (Simkin, 2017).

### *Disturbance and grazing*

The sensitivity of Calaminarian Grassland habitat to scrub invasion is widely recognized and management of *U. europaeus* scrub through grazing or physical control is required (The Wildlife Trusts, 2022). Some physical control work at Grogwynion seems to have taken place in 2008–2009, although with limited effect (Countryside Council for Wales, 2008). Simkin (2017) partly attributed *U. europaeus* colonization in the North Pennines to reduced grazing by a declining rabbit population and at Grogwynion, the impact of rabbits on *U. europaeus* growth has been noted in a management review (Countryside Council for Wales, 2008). Rapid establishment and growth (up to 40 cm vertical growth per year) of *U. europaeus* was observed following the introduction of the Myxomatosis virus in the 1950s, which caused major reductions in rabbit numbers (Thomas, 1968). Additionally, rabbit numbers have shown a 68% decline in Wales since 1995 (British Trust for Ornithology, 2019) following the introduction of viral Rabbit Haemorrhagic Disease (RHDV) in 1994 (Boag et al., 2016). If this national decline is reflected in the rabbit population local to Grogwynion, it is likely to have enabled the more widespread recent establishment of *U. europaeus*. Changes in animal grazing leading to more extensive vegetation growth, with consequences for channel planforms, has been noted elsewhere, for example in Yellowstone National Park, USA, where changes were attributed to the reintroduction of wolves (Beschta & Ripple, 2006; Ripple & Beschta, 2011). In combination with an absence of recent physical control measures, this tentatively seems to be a candidate mechanism for recent riparian vegetation encroachment.

## 5 | CONCLUSIONS

Channel pattern changes in the River Ystwyth, driven by industrial-scale mining between 1792 and 1904 that led to heavy metal contamination of channel and floodplain sediments, resulted in a highly active channel zone exhibiting multiple channels, especially at high flows. This was strongly evident as recently as 1987. Since 2001, channel planforms have reverted to single, more sinuous forms. Sinuosity reduced from 1.31 in 1845 to 1.09 in 1982, before recovering to 1.39 in 2019. Inversely, the braiding index reduced from a maximum of 2.0 in 1987 to 1.5 in 2021. Evolution in planform was associated with a change from expansive bar formation and avulsion under braided conditions to a dominance of lateral bar accretion and associated bank erosion along a sinuous single channel with a lower incidence of avulsive change.

Such changes substantially post-date (>100 years) the cessation of mining in the region. In contrast to other studies of the geomorphic recovery from disturbance due to anthropocentric sediment input from mining, changes in channel form do not appear to be a response and recovery from large volumes of coarse sediment input. We have also discounted the impact of high-magnitude flood events driving avulsions because more recent planform patterns and flood frequency data indicate that channel avulsion has become less frequent since 2000, despite an increase in flood magnitude and frequency. Rather, the changes in channel sinuosity and associated changes in stability, bar formation and lateral channel migration appear to have resulted from changes in the floodplain ecology.

The highly unstable, often braided, planforms still in evidence in 1987 depended on the development of a mosaic of habitats, known as shingle heath, that were highly susceptible to erosion and avulsion during floods. Since 2001, the floodplain has been widely colonized by the fast-growing, dense, woody shrub *U. europaeus*. Its extensive root system is resistant to surface erosion, although susceptible to undercutting by lateral erosion, and its dense, rigid, closely spaced growth acts as a barrier to overbank flows and avulsion. It is postulated that recent changes in channel form primarily result from extensive colonization and rapid growth of *U. europaeus*.

One plausible hypothesis for vegetation change in the reach was metal contamination levels in the sediments. However, no significant changes in levels were found from those measured 50 years ago. Therefore, a more likely cause of expansion of *U. europaeus* is reduced levels of natural grazing due to a disease-related fall in the rabbit population.

Overall, this study highlights the influence of a broader set of anthropogenic influences on channel change from mining activity than just legacy sedimentation. In the present case, mining has affected the quality of the sediments delivered to the river, and the quality of the sediments and animal grazing have affected the species composition and biomass of the riparian vegetation. Riparian grazing by native animal species has also been affected by the human introduction of diseases. It confirms the significance of vegetation as a control on channel pattern, as suggested in laboratory and field studies in other circumstances. This study is also of significance at a regional level as we have demonstrated possibly irreversible changes to a stretch of river that had previously been awarded a high designation for its ecological and geomorphological characteristics.

## ACKNOWLEDGEMENTS

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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