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1. Introduction

Since 2000 there have been a series of large, damaging floods in the UK which have raised concerns that extreme events may become more frequent in a warming climate (Huntingdon, 2006; Pall et al., 2011). Recent examples include the ‘millennium floods’ of autumn 2000 (Marsh and Dale, 2002), Boscastle storm of 2004 (Roca and Davison, 2009), Helmsley flood, North Yorkshire, 2005 (Hopkins et al., 2010), UK-wide flooding in in 2007 (Blackburn et al., 2008) and more recent severe events in Cumbria during autumn 2009 (Sibley, 2010; Stewart et al., 2010) and parts of Cornwall during winter 2010 (Sibley, 2011). These floods have been generated by a combination of convective summer storms and more prolonged cyclonic frontal rainfall, often in the autumn. Although some of the larger rivers in Wales have been affected by these events over the past decade or so (lower Severn and Wye in autumn 2000), there have been no large floods of comparable nature to events elsewhere in the UK in upland catchments that drain west Wales. Flooding in June 2012 dramatically changed this picture with widespread property flooding in the Rheidol, Leri and Clarach catchments (Figure 1), evacuation of caravan parks and post-event reports of ‘the biggest in living memory’ (Cambrian News, 2012). Closer inspection has revealed the magnitude of this flood event to be more common than first thought, with similar floods having occurred in the last 50 years (Cambrian News, 1964, 1973; Newson, 1975, 1980).

In the immediate post-flood period, hydrological, geomorphological and geochemical surveys were made of the worst affected river systems with a view to characterising the magnitude and impact of this event. The principal aims of this report are to: (1) outline the key meteorological and hydrological characteristics of the rain storm and subsequent flood; (2) evaluate the impacts and implications of this event in terms of geomorphological work and contaminant dispersal throughout the affected river systems.

2. Synoptic conditions

June 2012 was generally cooler, cloudier and wetter than average in the UK (Table 1). It was the wettest start to summer since records began in 1910 and equal wettest in the England and Wales record which began in 1766. June 2012 was also one of the most cyclonic in 140 years (Eden, 2012). These unseasonal conditions are characteristic of the North Atlantic Oscillation in its negative summer mode, which causes the southward displacement of the jet stream and associated delivery of Atlantic depressions across the UK (Folland et al., 2009). Since 2000 there has been a tendency towards more negative summer NAO values (Figure 2) associated with large flood events. Increased cyclonic activity and heavy rainfall in June caused widespread and severe flooding in England and Wales, although some of the worst high flow events occurred in several river catchments in west Wales (Leri, Clarach and Rheidol) on 8th and 9th of June. The depression which caused this flood event is believed to have been the deepest in June since before 1900 (Eden, 2012). Figure 3 shows the general synoptic situation at midday on Friday 8th June, characterised by a deep area of low pressure centred on northern England and occluded fronts over Wales.

2.1. Rainfall

Rain began to fall at approximately midnight on 8th June across Ceredigion. The highest totals were recorded on the western upslopes of the Cambrian Mountains immediately east of Aberystwyth (Table 2; Figure 4) as moist air was lifted over the Plynlimon massif. Daily rainfall totals at low elevation sites were unremarkable, typically less than 50 mm (Bow Street, Frongoch and Gogerddan), but increased significantly at sites above 180 m AOD in the Rheidol and Leri catchments (Dinas, Bontgoch and Pwllpeiran). The highest 24 and 36 hour totals (146-183 mm) were recorded on a southeast-northwest axis across Ceredigion and correlate well with landscape evidence (landslides and gullies) of heavy rainfall (Figure 4). Hourly intensities were modest (5-8 mm hr^{-1}) with a maximum of 11.2 mm hr^{-1} recorded at Bontgoch in the early hours of 9th June. Cumulative rainfall totals show relatively steady rates of accumulation up to ca. 20 hours into the rainfall event (Figure 5). At this point the behaviour of rainfall in the Rheidol-Leri and Ystwyth catchments diverged. There was a pronounced second pulse of heavy precipitation in the former catchments (Table 3), although this was especially marked in the Leri headwaters from 1-6 am on 9th June. In contrast, hourly totals, which for 20 hours had been greater in the Ystwyth catchment (Trawsgoed and Pwllpeiran) than in the Rheidol/Leri catchments, began to decline after ca. 20:00 on 8th June. The second heavy pulse of rainfall in the Leri headwaters (Figure 6a) was critical in causing flash flooding in the early hours of Saturday 9th June as soils in the catchment will have been saturated and hillslope runoff very rapid.

Although rainfall totals in the Cambrian Mountains were high, they were not extreme and do not approach any UK records. One day rainfall events of 10 and 100 year return periods are 110-120 mm and 190-210 mm for the Cambrian Mountains east of Aberystwyth (Faulkner, 1999), indicating that the fall of 146 mm at Dinas was less than 1:100 magnitude. Historically, there have been several 24 hour falls (rain day) in Wales greater than June 2012 (Table 4). However, the majority of these are well below other UK heavy 24 hour falls (Table 5), notably Seathwaite in 2009 (316.4 mm), as well as other comparable totals over shorter durations (see Hand et al., 2004). Storm rainfall in 2012 appears to have been similar in many respects to the last serious flood events in the Aberystwyth area in December 1964 (Cambrian News, 1964) and August 1973 (Cambrian News, 1973; Newson, 1975, 1980 (Table 6, Table 7). The summer 1973 event was very similar to 2012, as flooding was associated with persistent heavy rainfall and cyclonic conditions (Newson, 1973; 1980). Although daily totals were lower in 1973 compared to 2012, when short duration accumulations are examined there are some notable differences. At Dinas in 2012, rainfall was steady for 24-36 hours. In 1973 there was a core 6 hour spell of heavy rain (Newson, 1975). This is particularly noticeable when 2 and 6 hour totals are compared; 6 hour totals at Dinas, Bontgoch, and Pwllpeiran in 2012 were 25-35 mm lower compared to similar upland sites in 1973 (Table 2, Table 6) . Maximum intensities were also in the order of 20-25 mm hr^{-1} in 1973, compared to 8-11 mm hr^{-1} in 2012. Furthermore, rainfall was heavier over lower lying areas near Aberystwyth in 1973 with 48 hour totals of 90-100 mm, compared to <70 mm in 2012.

A decade earlier (1964) there was a similar event, although this was a winter storm and its principal effects were felt in the Dyfi and Ystwyth catchments. Reports at the time describe a ‘night of terror’ in the Ystwyth valley (Cambrian News, 1964). Although the Rheidol, Clarach and Leri systems were not badly affected, many areas that flooded in 2012 (Borth, Bow Street and Capel Bangor) were also flooded in 1964, with numerous bridges and roads washed away and several large landslides. Rainfall totals in 1964 were much higher in the Ystwyth headwaters compared to 2012 (Table 2, Table 7), with a daily fall of 121.9 mm at Cwmystwyth, an event that would rank second to the Dinas daily total of 2012. Although media reports at the time suggested events of 2012 were unsurpassed in living memory (Cambrian News, 2012), clearly this was inaccurate. This seems to bear out the views of Rhodda et al., (2009) that extreme events are quickly forgotten, with the most recent storms and floods often described as the ‘worst in living memory’. Other serious flood events that occurred at the margins or beyond the range of living memory include June 1935, when large parts of Aberystwyth were submerged (Welsh Gazette, 1935), June 1919 when the Leri overflowed (Welsh Gazette, 1919) and October 1886 (Cambrian News, 1886). The 1886 event appears to have been far larger than June 2012 as it affected areas that were not flooded on 8th-9th (Plas Crug and Aberystwyth railway station) -Trefechan Bridge also collapsed during this event.

3. Runoff

Soils in the west Wales uplands are generally thin and typified by shallow peats and soil pipes (Jones, 1997). In such areas, water tables tend to be close to surface and respond quickly to rainfall through saturation-excess overland flow. This was the case in June as conditions prior to the flood were relatively wet. Typical rainfall totals for the two days prior to the flood were 40-60 mm. Figure 6 shows hydrographs for gauged locations in west Wales affected by flooding in June. The smaller and steeper Leri catchment has the shortest lag and peak lag times (Table 8) and the swift rainfall response is clear. Rainfall-runoff response on the Ystwyth was markedly different to the other catchments due the heaviest rain falling on the morning of 8th June, causing a steep rise with further rain causing a prolonged period of high flow. The response of the Rheidol was similar to the Leri as levels rose, levelled off and then increased again following heavy overnight rainfall on 8th/9th

June. The Rheidol catchment is regulated by Nant-y-moch, Dinas and Cwm Rheidol reservoirs, giving noticeably longer hydrograph recession. Runoff in the Clarach catchment was generally more subdued. Although the Clarach rises at ca. 400 m AOD, large areas of the catchment are characterised by relatively gentle slopes and deeper soils between Penrhyncoch and Llangorwen, giving slower drainage and longer lag and peak lag times.

3.1 Gauged flow data

In historical terms, the highest mean gauged daily flow and annual maximum on the Leri at Dol-y-bont were 19.3 $m^3 s^{-1}$ and 37.5 $m^3 s^{-1}$ in March 1998 and September 1989, respectively. These values compare to figures of 42.8 $m^3 s^{-1}$ and 89.2 $m^3 s^{-1}$ for the June 2012 event, outstripping, by a significant margin, historical values. By ca. midday on 8th June the Leri was running close to these historical flows (25-30 $m^3 s^{-1}$) and had begun to fall. Had there been a continued ease in rainfall the Leri flood event would have been notable but not remarkable. Peak flows on the Ystwyth were lower than historical gauged data. Prior to June 2012 the maxima for mean gauged daily and annual maximum flows were 132.5 $m^3 s^{-1}$ and 249.0 $m^3 s^{-1}$, recorded in December 1964, compared to 113.3 $m^3 s^{-1}$ and 127.0 $m^3 s^{-1}$ in June 2012. The historical context of flows on the Rheidol is more difficult to evaluate. After 1984 data are unreliable due to problems with the rating equation at Llanbadarn. However, prior to 1984 the highest annual maximum flow was 196.4 $m^3 s^{-1}$ (extrapolated) (August, 1973).

3.2 Discharge estimates

Due to the fact that many of the worst affected rivers are poorly gauged, or gauges were out of range during the peak of flooding, flow reconstruction was undertaken based on topographic and palaeostage data. Table 9 and Figure 7 show discharge estimates for several main rivers and steep mountain streams calculated using the slope-area method. The highest discharge estimates are in the Rheidol and Leri catchments. At Borth, ca. 2 km downstream of Dol-y-bont, slope-area (66 $m^3 s^{-1}$) and gauged (89.3 $m^3 s^{-1}$) estimates are comparable. Although the estimate at Borth is lower than the upstream figure, the entire floodplain at Dol-y-bont was inundated and water ponded behind embankments. As a result there would have been appreciable attenuation of the flood peak downstream. Upstream of Dol-y-bont, the estimate at Tal-y-bont (91 $m^3 s^{-1}$) also compares well. On the Rheidol, the estimated flow at Pwllcenawon, ca. 4 km upstream of Llanbadarn, is 128 $m^3 s^{-1}$. This is a straight, incised cobble-bed reach and there was limited floodplain flow. This site probably provides a realistic estimate of discharge which is applicable to locations downstream (e.g. Llanbadarn) as there are no major tributaries in between. Discharge upstream of Pwllcenawon, at Troedrhiwsebon, has been estimated at 114 $m^3 s^{-1}$. Adding the discharge of the Melindwr tributary to this figure would give a flow of ca. 158 $m^3 s^{-1}$ at Pwllcenawon, which is 0.8 km downstream of the Melindwr confluence. Although this would give an upper estimate for the flow at Pwllcenawon, floodplain topography and trashline evidence on the Melindwr at Dolypandy indicate that much of the floodplain flow (which accounts for 93% of the discharge at this site) would have drained via palaeochannels on to a high terrace of the Rheidol and was probably ponded. A second cross section, located further downstream, was surveyed at Dolypandy across an engineered, smooth concrete banked and gravel/cobble bed channel. Scour and trash marks suggest this channel was running near capacity and would have been discharging ca. 14 $m^3 s^{-1}$ into the Rheidol at its confluence. Together with the upstream estimate at Troedrhiwsebon, a discharge of ca. 130 $m^3 s^{-1}$ at Pwllcenawon and in Aberystwyth seems realistic. If pre-1984 flow data on the Rheidol are accurate, then the flood of 1973 was larger than 2012.

In order to take into account different catchment sizes, Figure 8 shows discharge estimates divided by drainage area upstream of the flow reconstruction site (i.e. specific discharge). The highest values are evident on some of the smaller and steeper systems (Ceulan, Melindwr and Leri headwaters). None of the reconstructed flows approach the theoretical ‘catastrophic flood’ curve of the Institute of Civil Engineers, although they do approach the normal maximum flood (Figure 8). It is notable that the highest specific discharge estimates for June 2012 fall well below estimates for similarly small, steep upland catchments that have experienced extreme floods in the UK (Lynmouth and Boscastle).

Two methods have been used to evaluate the frequency of flows. First, annual maximum flow data for the Leri and Ystwyth have been ranked and return periods calculated using a variety of commonly used formulae (Table 10). Based on these formulae the June flood at Dol-y-bont has a frequency of between 40 and 80 years. Return periods can also be estimated by comparing the extent of flooding to defence structures of known design standard. At Dol-y-bont, embankments were overtopped that have a design standard of 1:50. This indicates that return period estimates greater than 50 years (Table 10) are probably more accurate. However, similar to most rivers in the UK, the gauge record is too short to allow meaningful estimates of flood frequency to be made. Further downstream at Borth, embankments of 1:100 and 1:50 design standard were not breached; this is consistent with upstream storage and a lower discharge estimate at this site. Based on the available data, a return period of 50 to 80 years seems likely for the Leri flood. On the Rheidol floodplain at Blaendolau, floodwaters extended beyond a 1:100 embankment near Blaendolau railway bridge but did not extend beyond a similar standard defence at Glanyrafon. Water levels were also lower than 1:200 defences in the centre of Aberystwyth. Trashline evidence shows that floodwater at Blaendolau extended beyond the 1:100 defences by overtopping the Vale of Rheidol railway embankment, not the flood defence. This indicates the return period for flooding at Blaendolau was less than 100 years. Return periods on the Ystwyth (Table 10) were in the order of 4 years.

3.3 Floodplain development

Although the June 2012 flood was a significant event, rainfall and flood return periods were not extreme. A significant contribution to the impact of this high flow event, compared to earlier documented floods, was floodplain development. Figure 9 shows the present day and 1906 Rheidol floodplain. A century ago the area was occupied by several isolated farms, the fringes of Llanbadarn and the main railway line. One hundred years later the farm at Glanyrafon has made way for a large industrial estate and the floodplain downstream has been developed for housing and retail. The latter area was particularly badly affected in 2012. Of particular concern is the development of floodplain areas for camping and caravanning where there are large numbers of temporary residents at high exposure to flood risk (McEwen et al., 2002). Several caravan parks (238 individual units) were flooded in west Wales and, although there were no fatalities, this type of land use is particularly vulnerable to flood damage. There were similar problems in 1973 when an inshore lifeboat was dispatched to rescue holiday makers at a caravan site near Llanbadarn (Cambrian News, 1973). The danger of such development cannot be underestimated as there is a mismatch between the inherent, high susceptibility of caravans to flood damage and the hazardousness of the floodplain environment (McEwen et al., 2002). For example, 87 people were killed at campsite in Spain during a flash flood (Barredo, 2007). Continued pressure and building on floodplains in west Wales means that the events of June 2012 are likely to be repeated.

4. Geomorphological impacts

The most common geomorphological response to high flows was floodplain aggradation (20-50 cm) with gravel and cobbles in upland and piedmont reaches (Figure 10c) and thick sand layers (30-40 cm) in lowland reaches. The highest rainfall totals and estimated specific discharges were in the upper Leri catchment and this is where the most notable geomorphological impacts occurred. Large areas of gravel and cobbles were mobilised, causing local channel bed aggradation (ca. 1 m) and avulsion (Figure 10a). A significant proportion of the material that caused these channel changes was sourced from a series of large landslides (Figure 10b, Figure 11) on steep slopes (20-24%) that are very similar in nature to widespread peaty slides and bursts reported in 1973 (Newson, 1975, 1980). These slides probably occurred during the second spell of very heavy rain as soils were already saturated and pore-water pressures high, especially as there had be ca. 40 mm of rainfall over the two previous days. The total amount of sediment displaced by these landslides was ca. 477 m^3, although only the larger failure and a third, smaller feature further up the river valley reached the channel. Although the upper Leri landslides could be traced to a series of natural pipe networks at the peaty soil/colluvium-diamicton/bedrock interface, instability may also have been caused, in part, by a steep vehicle track (Figure 10b) upslope that would have been conveying water from the track to hillslopes during the storm. Both slides are located in hillslope hollows with associated flush zones and the contributing areas of these hollows would probably have extended very close to the vehicle track during the event. Significant geomorphological impacts were also observed on other steep vehicle tracks where large gullies and were cut (Figure 10d) and associated sediment fans deposited (Figure 10e).

Although some of the geomorphological impacts were quite spectacular in the upper Leri area, overall channel changes were limited to a single sedimentation zone. Prior to 2012 the channel here was single thread with multiple gravel and cobble bars. These features were mobilised and added to during the flood as sediment supply was high from slopes and channel banks. The post-flood channel, before dredging, remained essentially single thread and demonstrated a robust response to flows of this magnitude. The valley floor at Llawr-y-cwm-bach is characterised by several terraces and palaeochannels, indicating that cycles of aggradation, avulsion and incision are typical of this site. Several hillslope scars also testify to previous mass movements (probably 1973 and 1964) on steep slopes with widespread subsurface drainage.

5. Contaminant dispersal

5.1. Flood sediment

All floodplains that were inundated in June 2012 received significant loads of fine-grained sediment. Immediate post-flood sampling of these deposits was undertaken to identify the extent and magnitude of contaminant dispersal from upstream locations of historical metal mining. Figures 12, 13, 14 and 15 show the location of overbank sediment samples and heavy metal concentrations in the rivers Ystwyth, Rheidol, Leri and Clarach. Levels of contamination vary between catchments and between metals. For Pb and Cu (Figures 12 and 15), the Clarach system, including the Stewi and Silo, is the most contaminated with the majority of flood sediment samples containing 5000-30 000 mg kg^{-1} (Pb) and 100-1500 mg kg^{-1} (Cu). Metal levels are especially high in the Silo sub-catchment and headwater areas of Cymsymlog and Cymerfyn. There are numerous large spoil tips adjacent to these small rivers and Pb concentrations are over 25 000 mg kg^{-1}. The highest single sediment concentration for Pb in any catchment was found on the Silo mainstream at ca. 61 000 mg kg^{-1}, ~1 km upstream of Penrhyncoch. Similar distributions of elevated Pb levels are found in the Ystwyth headwaters immediately downstream of Cwmystwyth and its historical mine works, with peak concentrations of ca. 54 000 mg kg^{-1} and consistently high concentrations along the length of the river (1000-5000 mg kg^{-1}). Some of the lowest Pb concentrations are found in the Rheidol and Leri systems, especially the latter. These rivers experienced some of the highest flows and concentrations may have been diluted by ‘clean’ hillslope sediment. This may be especially true in the Leri system, where several large landslides introduced large volumes of colluvium, diamicton and peat. Given the extent of historical mining activity in the Leri headwaters and abundance of waste tips, concentrations for all elements seem anomalously low.

Cadmium concentrations (Figure 14) are elevated across the study catchments. The highest values are evident in the Rheidol system, typically 2-10 mg kg^{-1}, as well as downstream of the Cwmystwyth mining complex, with a peak concentration of ca.14 mg kg^{-1}. Cadmium enrichment is less pronounced around the Clarach and Leri mining areas (ca. 1-5 mg kg^{-1}). Although zinc (Figure 13) was historically mined in west Wales, the severity of contamination from this element is relatively low, although there are notable exceptions. As may be expected, downstream of Cwmystwyth and its extensive riverside waste tips, concentrations are quite high (1000-3000 mg kg-1). On the Rheidol there is a further area of contamination in the vicinity of the Melindwr confluence. There are several large mining areas on this small system around Old Goginan and Cymbrwyno, both with exposed, easily eroded waste tips. Zinc concentrations are also relatively high throughout the Clarach catchment (1000-3000 mg kg^{-1}) but tend to be lower on the Leri, typically 100-500 mg kg^{-1}.

Plotting flood sediment concentrations relative to distance downstream and UK/European contamination thresholds shows that the majority of samples, especially for Pb, lie above guidance values (Figures 16, 17, 18 and 19). On the Ystwyth (Figure 16) only one sample, located upstream of Cwmystwyth, falls below UK Soil Guidance Values (SGVs). All other samples exceed, often by a very significant margin, UK and widely used Dutch thresholds. All samples exceed these thresholds for Pb on the Clarach (Figure 17) and the impact of the Silo sub-catchment is clear, with a noticeable increase in concentrations downstream of the Silo confluence. This pattern is also quite marked for Cu concentrations, but not Zn and Cd. Although Pb concentrations are generally high on the Rheidol (Figure 18), several samples fall between CLEA SGVs for residential and allotments and industrial use, although they do exceed Dutch intervention levels. Pb and Zn variability on Rheidol at ca. 13-15 km is caused by inputs from the Melindwr. Spikes at ca. 7-9 km have no obvious source and are probably related to localised bank erosion. In the Leri system (Figure 19) concentrations tend to range between the Dutch target value of 85 mg kg^{-1} and the upper CLEA boundary for industrial usage (750 mg kg^{-1}). There is a noticeable spike at ca.7.5 km downstream of the Cwmere-Cyneiniog –Leri junction. Both of the former tributaries are heavily mined.

With the exception of the Clarach (described above), the majority of Cu samples plot close to or just above the Dutch target figure of 36 mg kg^{-1} and do not approach the intervention threshold. There is an exception at Cwmystwyth where levels approach 120 mg kg^{-1} and samples near a waste tip were as high as 270 mg kg^{-1}. Given the history of the site (Mighall et al., 2002), these figures are unsurprising. Contamination associated with cadmium is more difficult to assess because CLEA guidelines are pH dependant. On the Rheidol (Figure 18) concentrations are quite variable and fall between lower and upper CLEA SGVs, with two samples approaching the upper residential/allotment limit. Similar patterns are evident on the Ystwyth (Figure 16), although two samples exceed the CLEA SGV of 8 mg kg-^{1} and one exceeds the Dutch intervention threshold of 12 mg kg-1. Concentrations plot very close to the Dutch target of 0.8 mg kg^{-1} on the Leri (Figure 19) and above this threshold (1-4 mg kg^{-1}) on the Clarach (Figure 17).

Although heavy metal concentrations found in flood sediments in west Wales are generally very high, they are consistent with earlier research in the Rheidol, Ystwyth and Clarach catchments which identified similarly high contamination levels (> 20 000 mg kg^{-1}) (Wolfenden, 1977), especially in the Clarach system, which appears to be especially polluted. Contamination levels reported in this study are also characteristic of river channel and floodplain sediments found in heavily mined catchments throughout the UK (Macklin et al., 1994; Rowan et al., 1995; Dennis et al., 2003, 2009). Given the long history of metal mining in Ceredigion there will be a store of highly contaminated sediment buried at depth in most floodplains. Eroding channel banks and waste tips are the two major sources of river sediment contamination in west Wales (Wolfenden, 1977).

5.2. Allotment sediment and vegetation

Heavy metal concentrations in allotment sediments collected at depth (0-50 cm) are comparable to flood sediment values (Figure 19). Although the sampling resolution is relatively coarse, for Pb, the upper 20 cm is contaminated above CLEA and Dutch intervention thresholds. All samples exceed the Dutch Pb target value. Zinc concentrations are more consistent, between 250 and 325 mg kg^{-1}, exceeding the Dutch target value but less than half of the intervention figure. Cadmium concentrations exceed 1.5 mg kg^{-1} and all samples exceed the Dutch target and lower CLEA threshold of 1 mg kg^{-1}. Copper levels are very similar to Pb and peak in the upper ca. 20 cm of the soil profile, exceeding the Dutch target value.

Sediment and vegetation concentrations from allotments on the Rheidol floodplain are shown in Table 11. Although SGVs are not directly applicable to vegetation samples, 7 out 12 vegetation samples would exceed Dutch soil target values. Concentrations are higher in silts deposited directly on to vegetation during the June floods. Similar to samples throughout the Rheidol catchment, Pb concentrations exceed the CLEA SGV for residential and allotments, as well as Dutch target values for Zn, Cd and Cu.

6. Key findings

- Rainfall totals during June 2012 were high but not extreme (<1:100) in an historical context. Where river flow estimates have been made and flood extents are known in relation to the design standard of flood defences, return intervals for this event range from <1:50 to <1:100. Archival searches show that very similar rainfall and floods events have occurred relatively recently in the Aberystwyth area (1964 and 1973). Meteorological, hydrological and geomorphological evidence suggests that rainstorms and floods of the magnitude experienced in June 2012 are typical of the Cambrian Mountains in west Wales and similar events should be expected in the future. There is no theoretical reason why a much larger cyclonic storm, similar to Cumbria 2009, could not occur in the area. Estimated maximum 24 hour rainfall for the Cambrian Mountains east of Aberystwyth is 300-400 mm (Houghton-Carr, 1999). This equates to rainfall totals 2.1 to 2.7 times greater than the heaviest fall of June 2012.

- A key factor that exacerbated the impact of this event compared to earlier high flows was floodplain development. Since 1906 there has been a dramatic increase in the urban area encroaching on the Rheidol floodplain. Caravan parks and campsites located on low lying riverside fields are especially vulnerable to inundation. Although there were no serious injuries associated with this event, there are examples from Europe of similar flash floods causing mass fatalities at campsites.

- The long history of metal mining in Ceredigion (Pb, Zn, Cu) means there are numerous easily eroded riverside waste tips and stores of heavily contaminated floodplain soils in all river systems. High flows in June 2012 mobilised significant quantities of contaminated material and deposited thick layers of metal enriched sediment on floodplains and allotments. The majority of flood sediment samples display metal concentrations, especially Pb, well above UK SGV and European guidelines. The Clarach system is particularly badly affected due extensive mine works in its headwaters. Floodplain contamination in west Wales is a chronic and long standing issue, but it is a problem shared with other river catchments in the UK that have a history of metal mining.

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Acknowledgements

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	Temperature						Sunshine		Rainfall			
Region	Max. temp. (°C)	Anomaly (°C)	Min. temp. (°C)	Anomaly (°C)	Mean. temp. (°C)	Anomaly (°C)	Sunshine (Hours)	Sunshine %	Rainfall (mm)	Anomaly (mm)	Rain days ($\geq$ 1 mm)	Anomaly (days)
UK	15.8	-1.0	8.8	0.4	12.3	-0.3	199.2	70	145.3	200	16.3	5.2
England	17.1	-1.0	9.7	0.6	13.4	-0.2	121.0	67	142.6	227	16.4	6.6
Wales	**16**	**-0.8**	**9.6**	**1.0**	**12.7**	**0.0**	**120.6**	**71**	**205.0**	**238**	**18.9**	**7.5**
England & Wales	16.9	-1.0	9.7	0.6	13.3	-0.2	121.0	68	151.2	229	16.8	6.7

Table 1. Meteorological summary for June 2012 (Met Office, 2012). Anomaly data show deviations from 1971-2000 averages.

Station	Catchment	Elevation (m AOD)	3 hour (mm)	6 hour (mm)	12 hour (mm)	24 hour (mm)	36 hour (mm)	48 hour (mm)
Dinas	Rheidol	280	25.4	46.2	81.6	146.4	183.4	186.2
Bontgoch	Leri	185	28.6	49.2	71.0	119.6	143.4	145.8
Pwllpeiran	Ystwyth	330	21.2	37.4	73.0	102.4	147.8	154.0
Cwm Rheidol	Rheidol	53	17.4	30.6	52.8	91.4	117.2	120.6
Tal-y-bont	Ceulan	65	-	-	-	73.0	-	97.0
Trawsgoed	Ystwyth	63	17.8	30.6	54.2	70.2	99.2	102.0
Gogerddan	Clarach	31	9.4	18.0	31.2	48.6	63.0	65.2
Bow Street	Clarach	15	8.4	15.2	26.2	39.0	51.6	53.8
Frongoch	Clarach	140	7.8	13.2	23.4	34.0	46.6	49.0

Table 2. Rainfall totals recorded in West Wales on 8th and 9th June 2012. Totals for 3, 6 and 12 hour durations are sliding accumulations and refer to any consecutive period during the rainstorm. Daily and 48 hour totals are fixed duration (9am-9am) standard rain day accumulations. Thirty six hour totals are end at 9 am on 9th June. The gauge at Tal-y-bont is manually read at ca. 8 am daily.

Dinas (Rheidol)	Pulse 1	Pulse 2
Rainfall duration (hrs)	9	8
Rainfall total (mm)	56.8	60.6
Max. intensity (mm hr^{-1})	8.2	8.8
Mean intensity (mm hr^{-1})	6.3	7.7
Bontgoch (Leri)		
Rainfall duration (hrs)	6	6
Rainfall total (mm)	30.0	49.2
Max. intensity (mm hr^{-1})	5.6	11.5
Mean intensity (mm hr^{-1})	5.0	8.2
Cwm Rheidol (Rheidol)		
Rainfall duration (hrs)	11	5
Rainfall total (mm)	48.0	24.8
Max. intensity (mm hr^{-1})	4.4	5.4
Mean intensity (mm hr^{-1})	6.2	5.0
Pwllpeiran (Ystwyth)		
Rainfall duration (hrs)	10	3
Rainfall total (mm)	60.8	18.8
Max. intensity (mm hr^{-1})	10.2	5.8
Mean intensity (mm hr^{-1})	6.1	4.7

Table 3. Rainfall statistics for the two main pulses of precipitation on 8th and 9th June 2012.

County	24 hour rainfall (9am-9am)	Location	Date
Mid Glamorgan	211.1	Lluest Wen Reservoir	11th Nov 1929
Gwynedd	197.4	Oakeley Quarry	28th June 1928
Powys	184.1	Blaenau Ryofer	3rd Nov 1931
Dyfed	165.6	Llynyfan Fach	3rd Nov 1931
Gwent	147.3	Abertillery	3rd Nov 1931
Ceredigion	**146.4**	**Dinas**	**8th June 2012**
Anglesey	136.7	Llansadwrn	10th Aug 1957
Clwyd	134.9	Hangmer	31st May 1924
South Glamorgan	122.9	Lisvane	14th Jul 1875
West Glamorgan	102.4	Cimla Reservoir	2nd Aug 1948

Table 4. The highest daily rainfall totals recorded in Wales (Webb, 1987), updated with the maximum June 2012 fall.

Location	Date	Rainfall (24 hr total)
Seathwaite, Cumbria	November 2009	316 mm
Martinstown, Dorset	July 1955	279 mm
Loch Quoich, Highland	December 1954	256 mm
Bruton, Somerset	June 1917	243 mm
Cannington, Somerset	August 1924	239 mm
Sloy, Highland	January 1974	238 mm
Lynmouth, Devon	August 1952	229 mm
Rhondda Valley, Wales	November 1929	211 mm
Kinlochquoich, Highland	October 1916	208 mm
Brundall, Norwich	August 1912	205 mm
Seathwaite, Cumbria	November 1897	204 mm
Camelford, Cornwall	June 1957	203 mm
Boscastle, Cornwall	August 2004	200 mm

Table 5. The ‘200 club’ of British rainfall events (after Burt, 2005).

5th August 1973			15th August 1977	
Duration (hrs)	Rainfall (mm)	Return period (yr)	Rainfall (mm)	Return period (yr)
48	149.0	>10	-	-
24	103.0	<10	-	-
12	95.5	20-50	-	-
6	72.7	20-50	98.0	>100
2	46.0	>20	90.4	100-1000
1	22.2	5	55.0	100-1000
0.5	11.0	<5	48.4	100-1000
0.25	5.5	<5	24.5	100-1000
5 minutes	1.8	<5	10.0	>50

Table 6. Rainfall statistics for storm events on the Plynlimon massif in 1973 and a smaller headwater storm in 1977 (Newson, 1975, 1980).

Station	24 hour rainfall (mm)
Cwmystwyth	121.9
Trawscoed	63.5
Llanilar	62.7
Cwmrheidol	79.0
Aberystwyth	50.8
Lletty-Evan-hen	77.7
Gogerddan	57.4

Table 7. Rainfall statistics for the 12th December 1964 storm which caused severe flooding in the Ystwyth and Dyfi catchments. These data were extracted from the British Rainfall digital archive, available for download from the British Atmospheric Data Centre (www.badc.ac.uk). Llety-Evan-Hen is located very close to the present day gauge at Bontgoch.

River / reach	Lag time (hours)	Peak lag time (hours)
Leri at Dol-y-bont	26.25	4.75
Rheidol at Llanbadarn	25.75	8.25
Ystwyth at Pont Llolwyn	17	17
Clarach at Llangorwen	34	25.75 (10.75)

Table 8. Lag times for gauged locations in West Wales, 8th & 9th June 2012. Lag time is the time from the base of the rising limb to maximum discharge or stage. Peak lag time is the time between maximum rainfall and maximum discharge/stage. Because rainfall and flow/stage data are at different resolutions (hourly and 15 minute), peak lag times are accurate to ± 0.5 hours. Two peak lag figures are given for the Clarach at Llangorwen. The time of 25.75 hours is based on the rain gauge at Gogerddan. However, this site is not representative of the upland part of the catchment which lies ca. 1 mile from the gauge at Bontgoch (10.75 hours).

River	Reach	Discharge ($m^3\ s^{-1}$)	Drainage area (km^2)	Specific discharge ($m^3\ s^{-1}\ km^{-2}$)
Leri	Llawr-y-cwm bach	21 – 31	7.0	3.0 – 4.4
Leri	Tal-y-bont	91	31.1	2.9
Leri	Borth	66	51.8	1.3
Ceulan	Tal-y-bont	34 – 45	11.1	3.1 – 4.1
Rheidol	Troedrhiwsebon	114	137.9	0.8
Rheidol	Pwllcenawon	128	169.2	0.8
Melindwr	Dolypandy	31 – 44	13.9	2.2 – 3.2
Clarach	Gogerddan	39	17.9	2.2
Clarach	Llangorwen	41	44.6	0.9

Table 9. Discharge estimates for the worst affected areas during June 2012. Based on the guidelines of Lumbroso and Gaume (2012), initial flow estimates at Llawr-y-cwm-bach, Tal-y-bont (Ceulan) and Dolypandy were suspected as being marginally too high relative to measured rainfall rates and catchment area. Lower estimates at these sites are based on maximum observed rainfall of 11 mm hr^{-1}.

Method	Return period	AEP	Leri RI (years)	Leri AEP	Ystwyth RI (years)	Ystwyth AEP
Hazen	n/(m-0.5)	(m-0.5)/n	78	0.01	4	0.2
Gringorten	(n+0.12)/(m-0.44)	(m-0.44)/(n+0.12)	70	0.01	4	0.2
Blom	(n+1/4)/(m-3/8)	(m-3/8)/(n+1/4)	63	0.02	4	0.2
Chegodayev	(n+0.4)/(m-0.3)	(m-0.3)/(n+0.4)	56	0.02	4	0.2
California	n/m	m/n	39	0.03	4	0.2
Weibull	(n+1)/m	m/(n+1)	39	0.03	4	0.2

Table 10. Return periods for gauged flows on the Leri and Ystwyth where *m* = rank order of event and *n* = record length.   Method, return period and AEP (annual exceedance probability) formulae taken from Selaman et al., (2007).

Material		Pb	Zn	Cd	Cu
Vegetation	Allotment vegetation leaf	107.82	261.61	**2.31**	13.62
	Allotment vegetation leaf	130.89	282.54	**2.19**	17.03
	Allotment vegetation stem	61.67	92.72	**2.30**	6.44
Sediment	Allotment vegetation sediment	**541.91**	274.15	**1.71**	43.20
	Allotment vegetation sediment	**508.45**	276.22	**1.78**	43.06
	Allotment vegetation sediment	**527.42**	267.52	**1.77**	42.35

Table 11. Heavy metal concentrations in flood sediment and vegetation, Aberystwyth. Bold values exceed CLEA SGVs for residential areas and allotments. Underlined values exceed Dutch target thresholds.

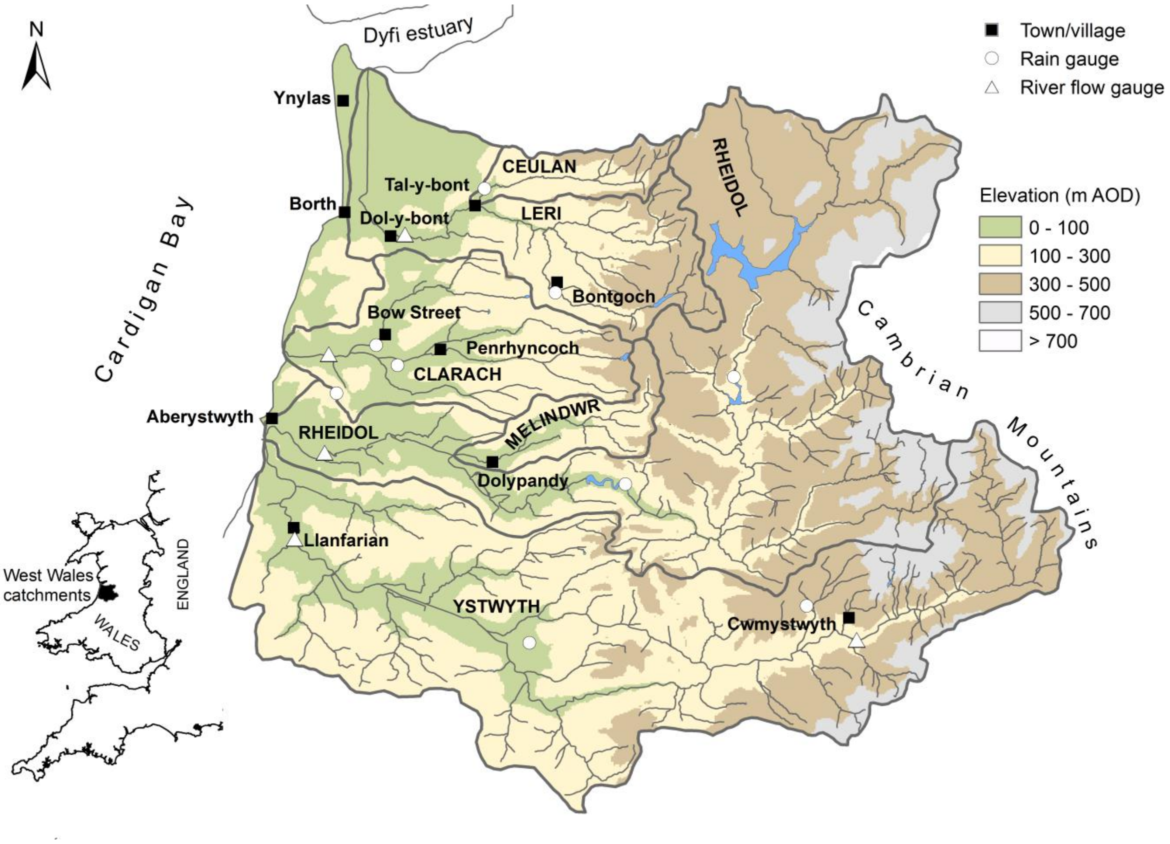

Figure 1. West Wales river catchments affected by flooding on 8th and 9th June 2012.

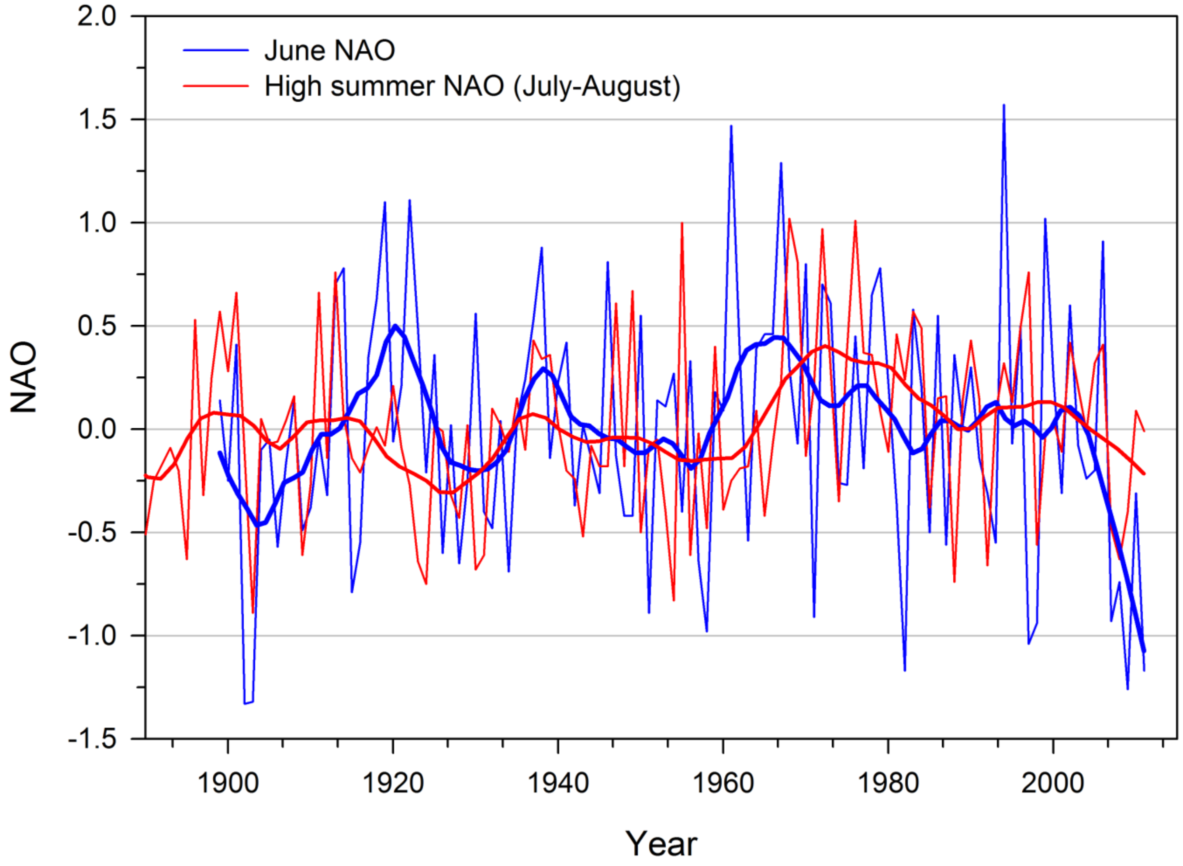

Figure 2. June and high summer NAO index data 1950-2011. SNAO July-August data of Folland et al., (2009) were supplied by the Met Office.

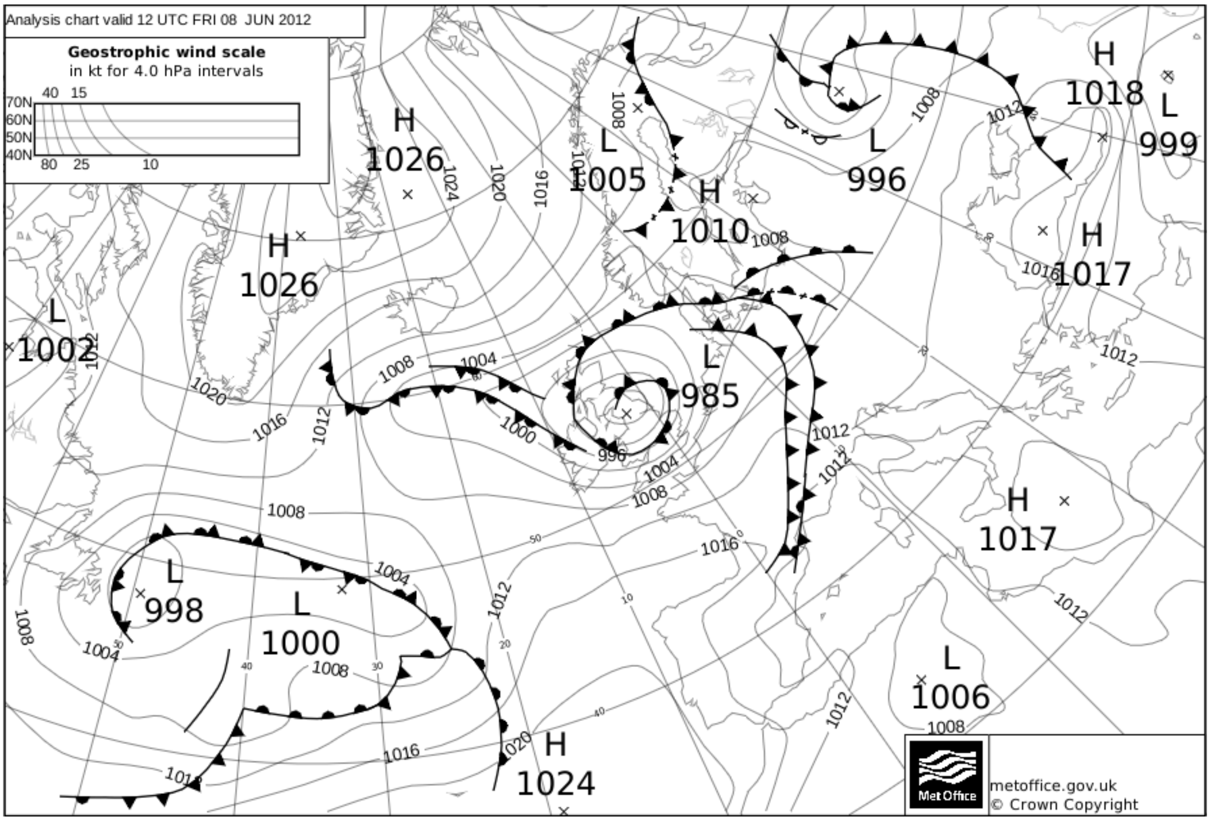

Figure 3. Synoptic chart at midday on 8th June 2012.

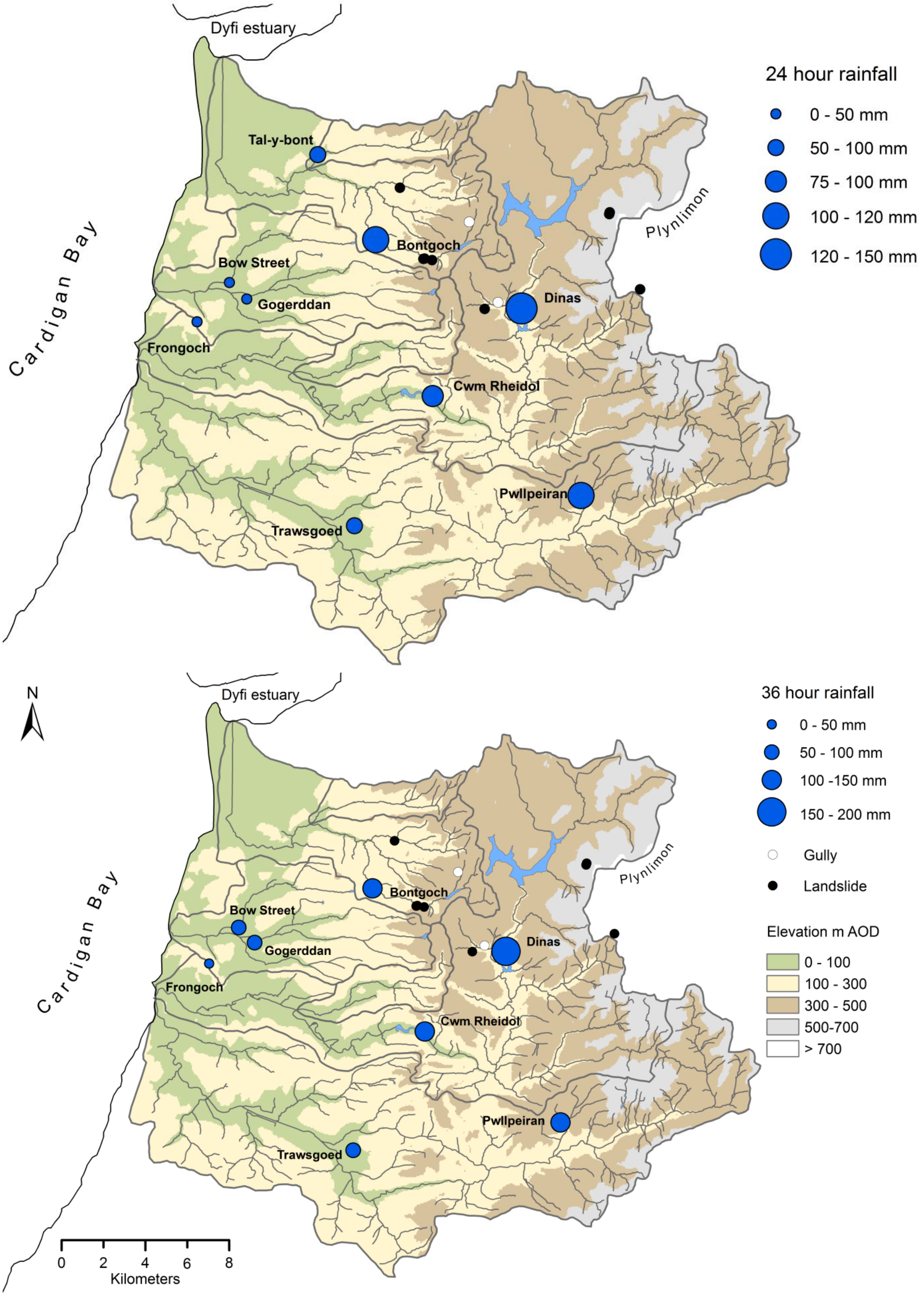

Figure 4. 24 hour and 36 hour rainfall totals recorded in west Wales on 7th and 8th June 2012. Major landslides and gullies are also shown.

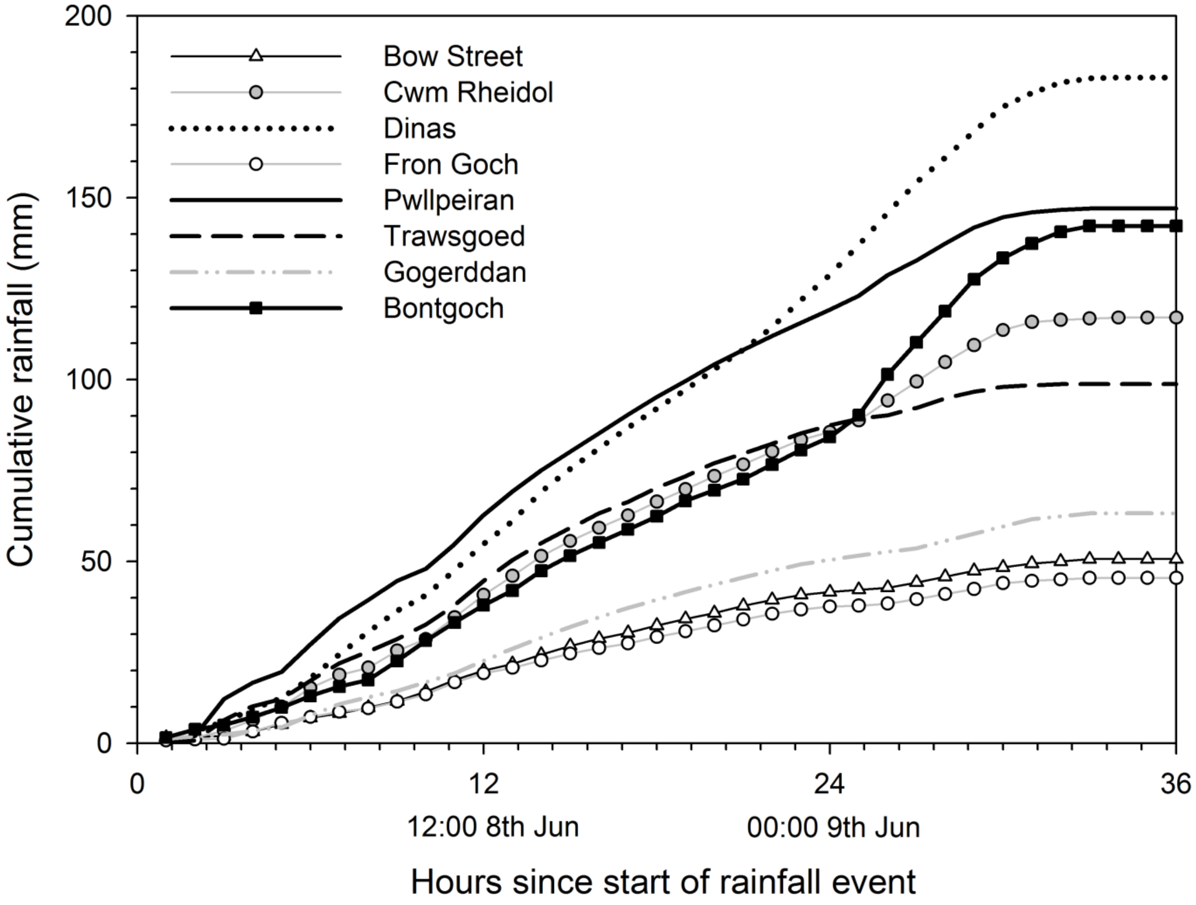

Figure 5. Cumulative rainfall totals from 00:00 on 8th June to 12:00 on 9th June.

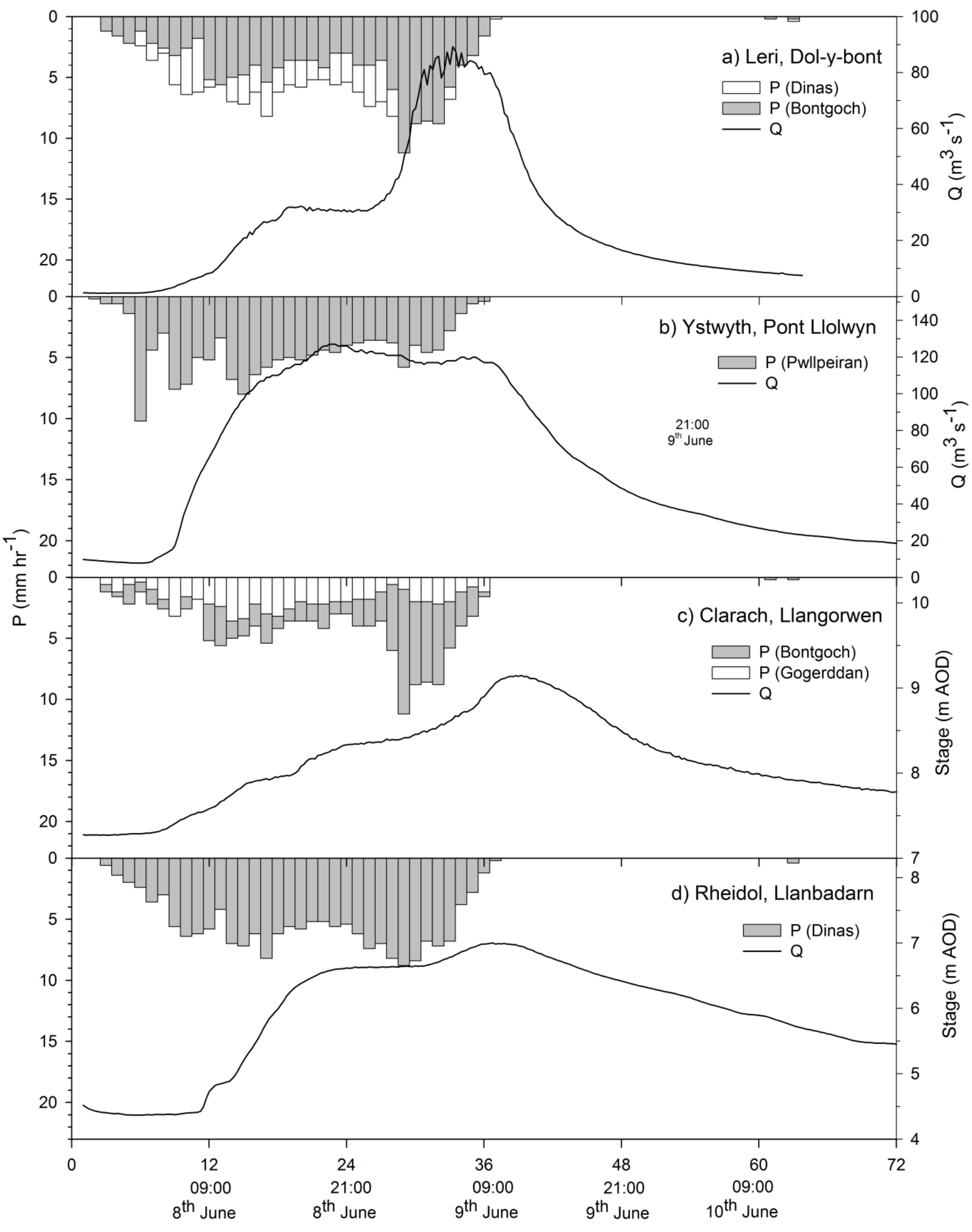

Figure 6. Hydrographs for the rivers Leri, Ystwyth, Clarach and Rheidol. The gauge at Dol-y-bont was damaged during the flood and peak flows have been estimated by the Environment Agency.

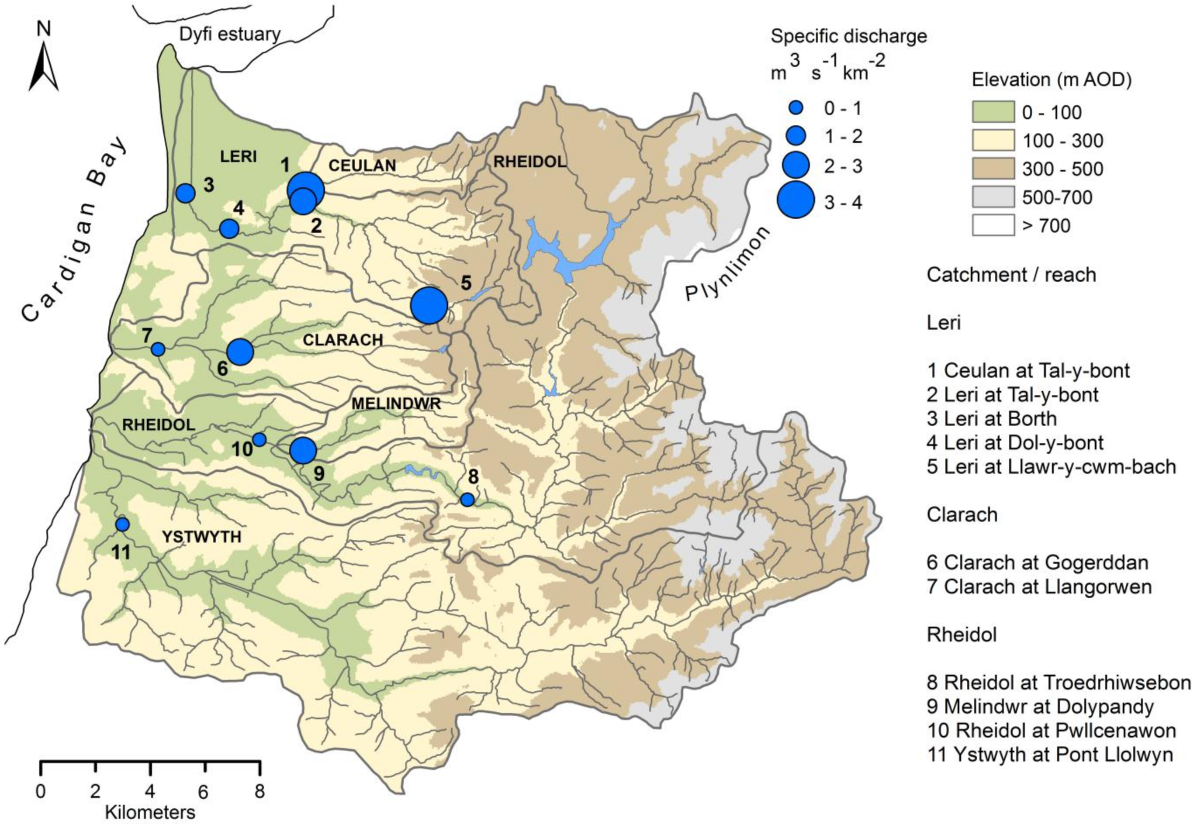

Figure 7. Specific discharge estimates for flow reconstruction sites on rivers in west Wales. Sites 4 and 11 are based on gauged flows. Locations with upper and lower specific discharge estimates (see Table 9) are plotted using mean values.

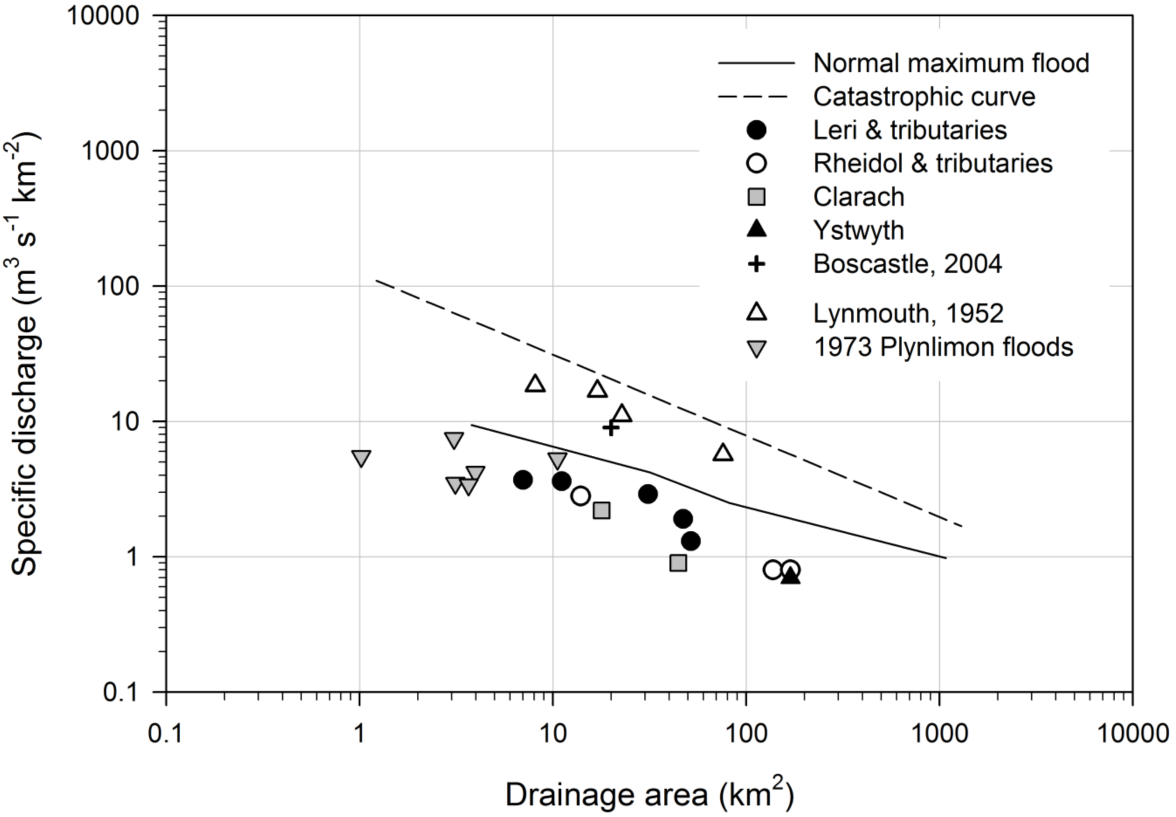

Figure 8. Specific discharge estimates for rivers in west Wales and other large upland floods. The normal maximum flood curve was updated by the Institute of Civil Engineers at the same time that the catastrophic curve was introduced (1960). Although the latter is based on statistical theory, it is not used for design purposes. Locations with upper and lower specific discharge estimates (see Table 9) are plotted using mean values.

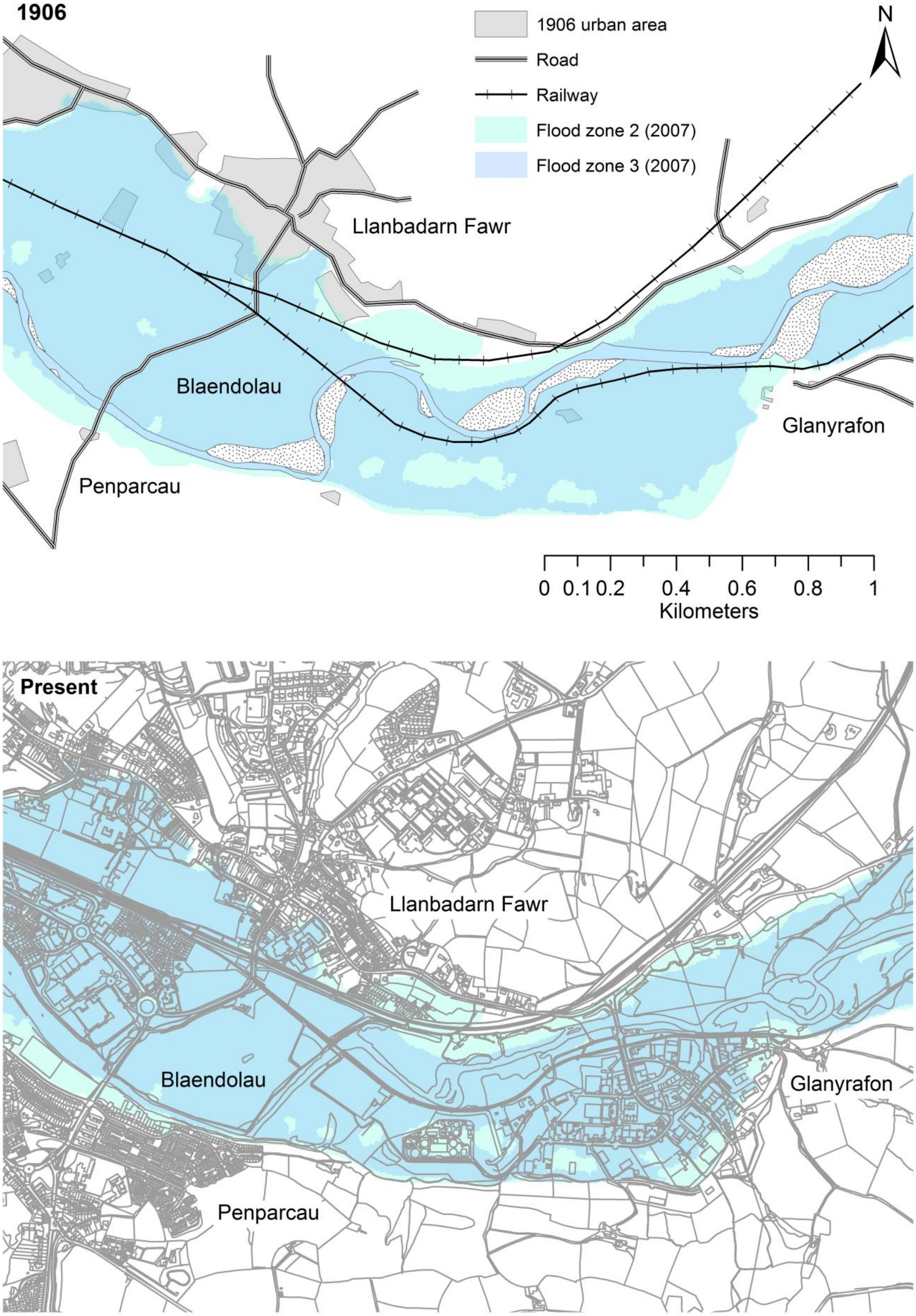

Figure 9. Floodplain development on the Rheidol floodplain, Aberystwyth, 1906-present.

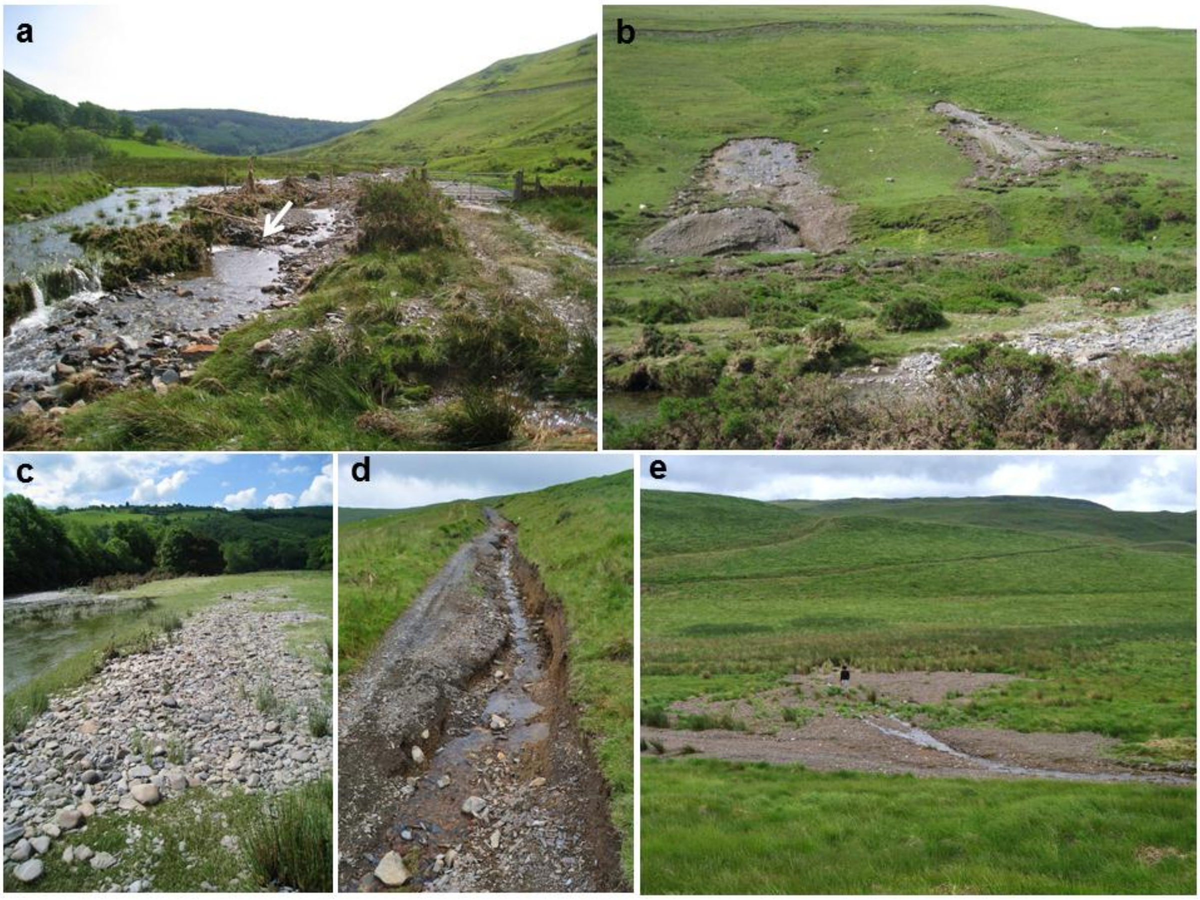

Figure 10. Geomorphic impacts of the June 2012 floods: (a) Leri at Llawr-y-cwm-bach. The white arrow indicates the pre-flood channel that aggraded upstream, forcing post-flood flow ca. 1 m higher, onto the floodplain and forming a knick point at the pre-flood bank top. Palaeostage is indicated by a trash line on the fence to the right. Cross-sections for flow reconstruction at this site were surveyed at a bedrock reach that appeared to have remained stable. Unfortunately, before the valley floor at Llawr-y-cwm-bach could be fully mapped, ca. 1 km of channel was dredged to its pre-flood form; (b) landslides at Llawr-y-cwm-bach. Note the vehicle track sloping across the top of the image; (c) cobble splay on the Rheidol floodplain; (d) gully (ca. 05 m deep) cut through a vehicle track near the source of the Leri; (e) gravel fan immediately downslope from (d) - note figure for scale.

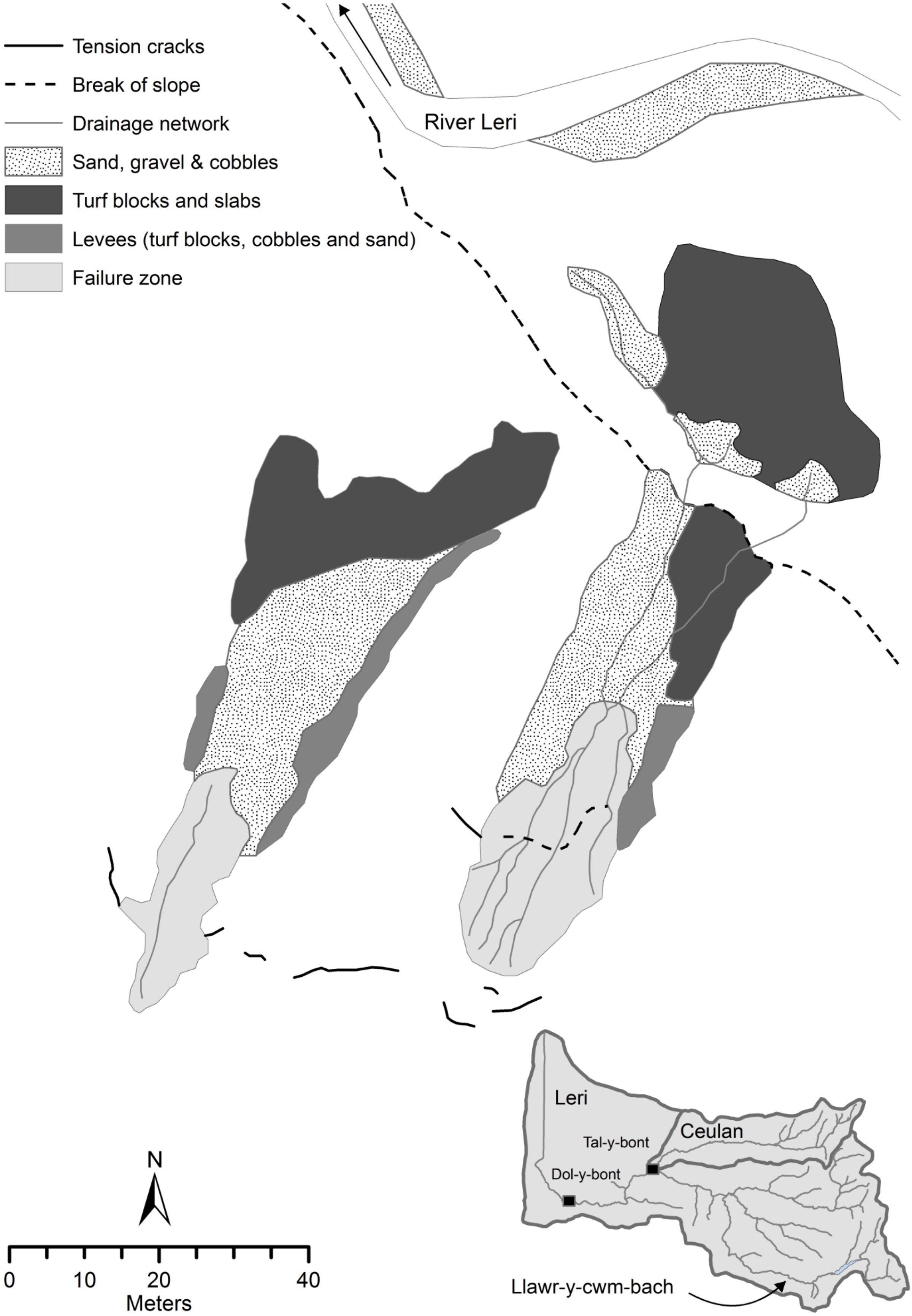

Figure 11. Landslides at Llawr-y-cwm-bach in the upper Leri catchment.

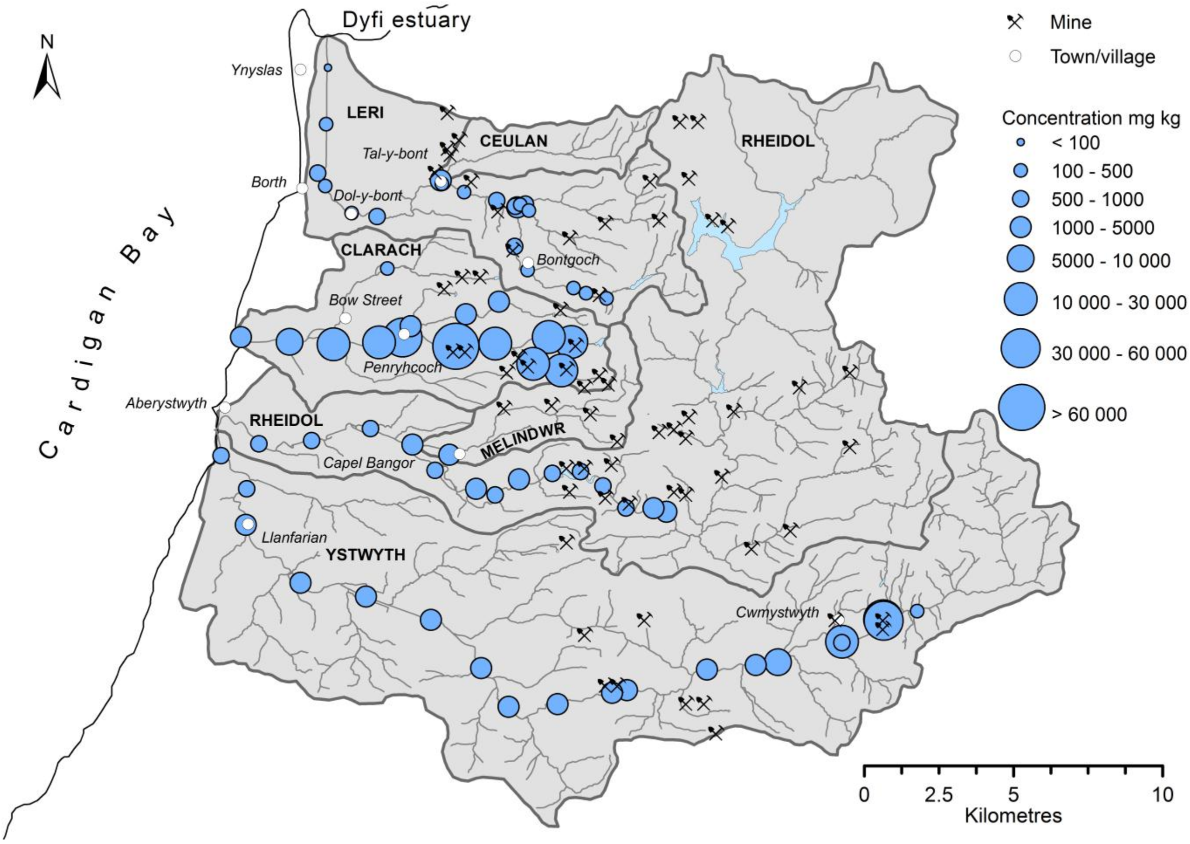

Figure 12. Pb concentrations in June 2012 flood sediment.

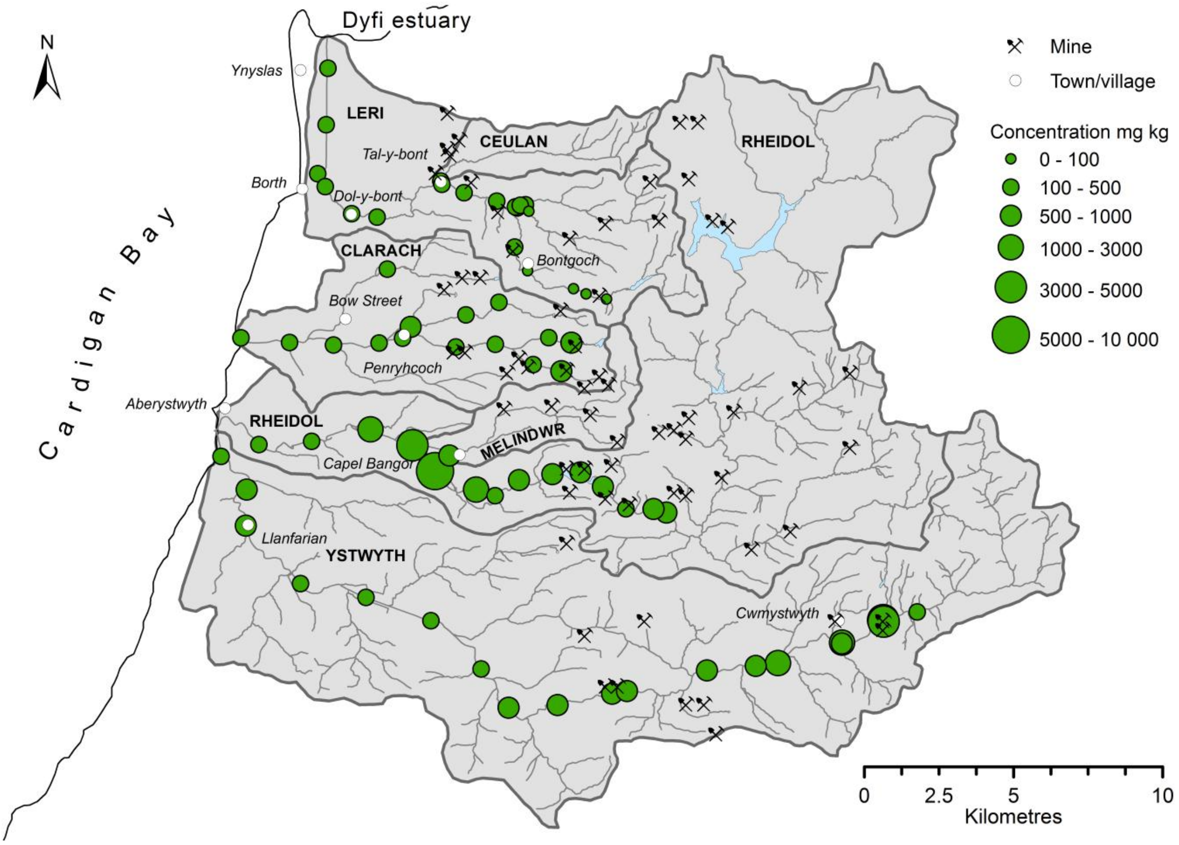

Figure 13. Zn concentrations in June 2012 flood sediment.

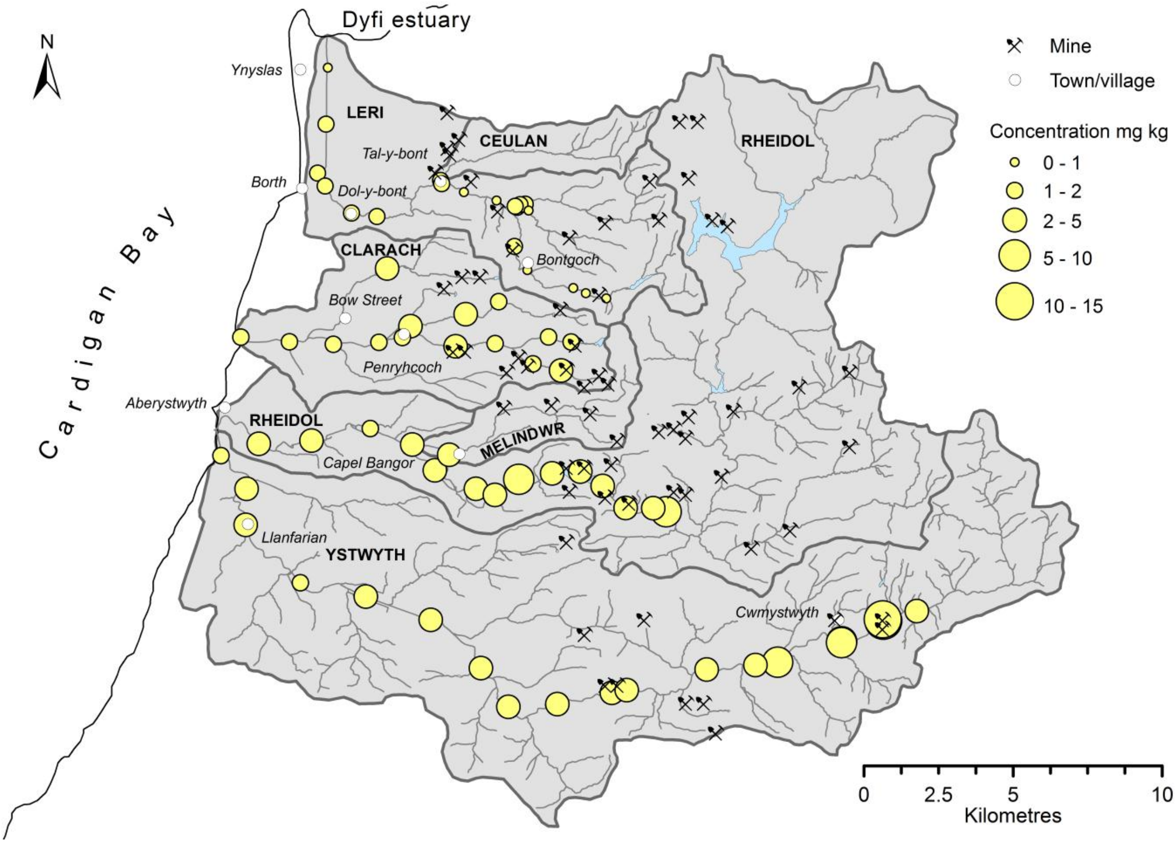

Figure 14. Cd concentrations in June 2012 flood sediment.

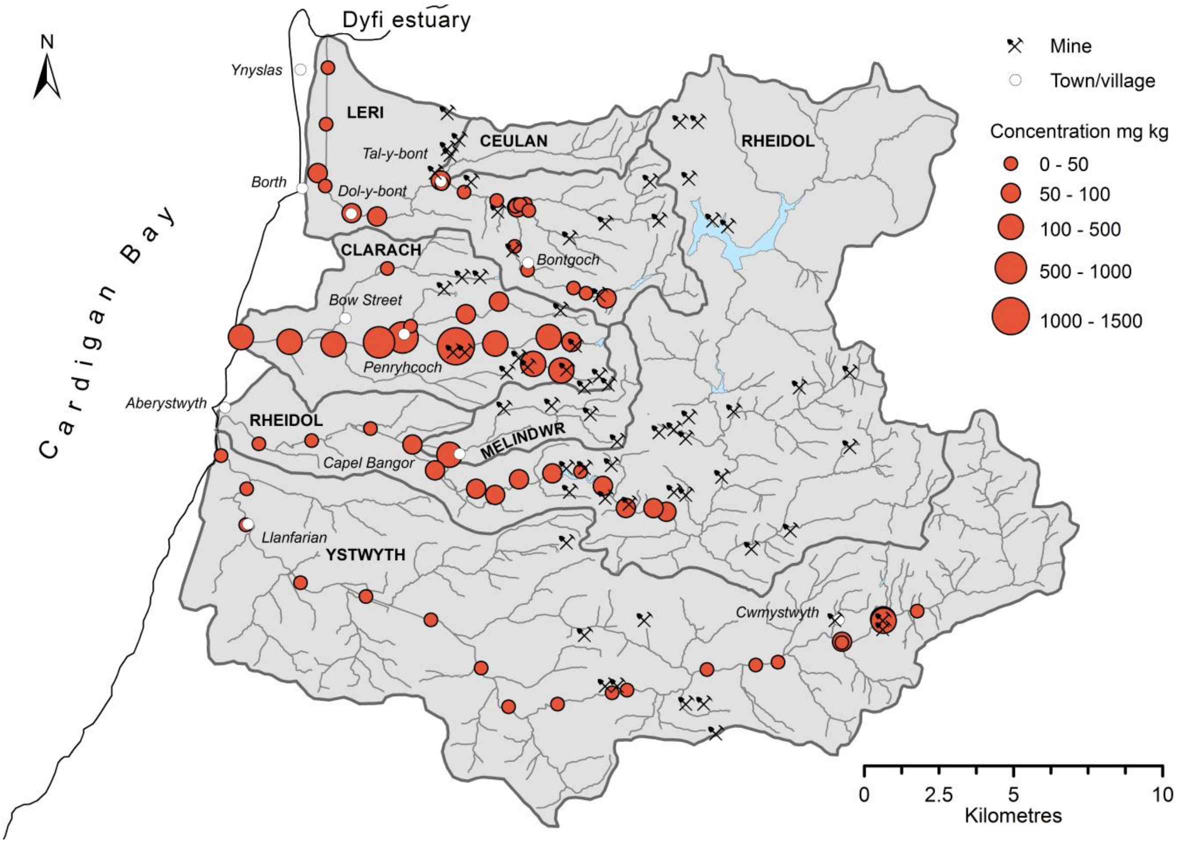

Figure 15. Cu concentrations in June 2012 flood sediment.

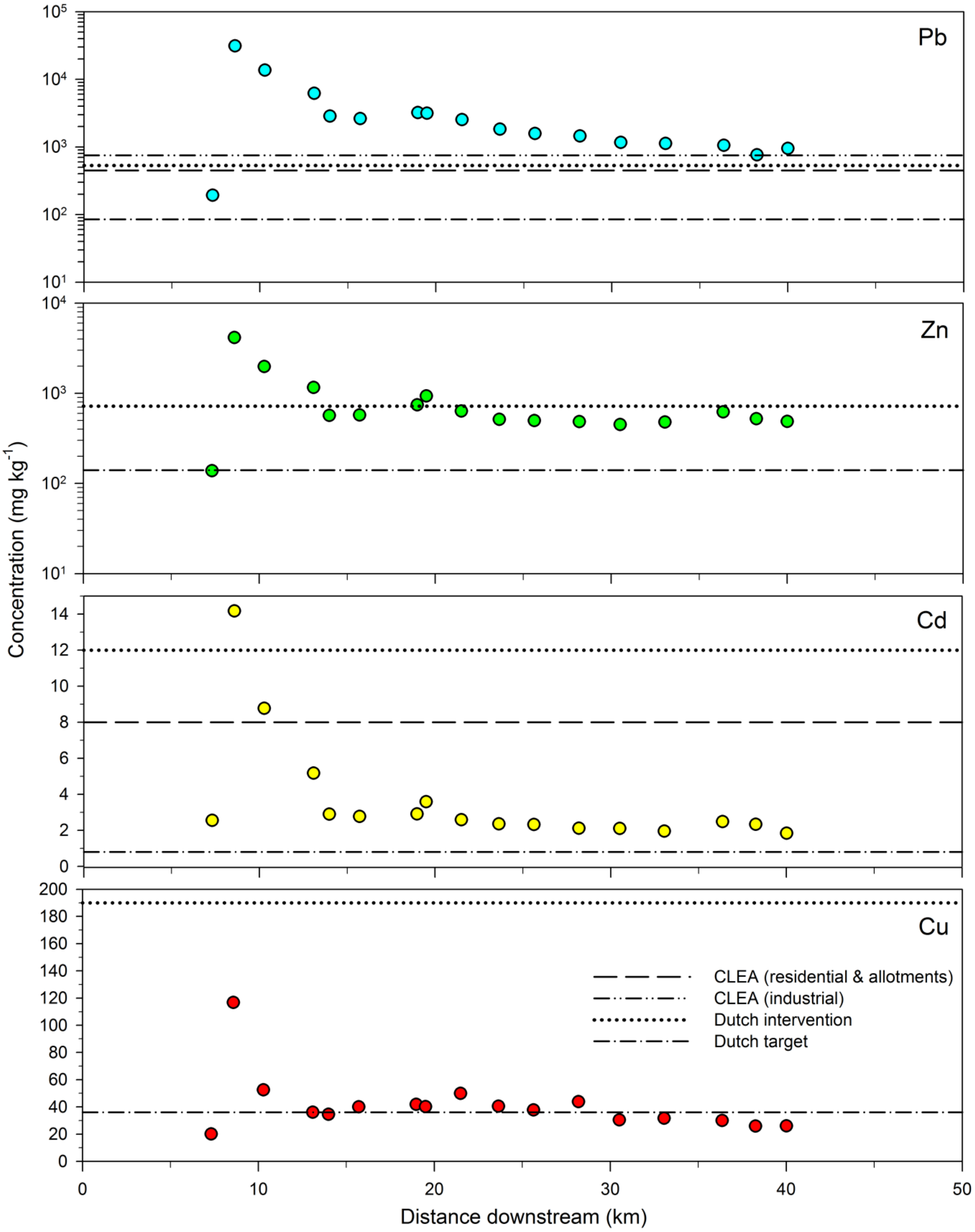

Figure 16. Downstream variation in heavy metal concentrations on the River Ystwyth, June 2012. Selected UK and European threshold values are also shown. Note that because of the extreme range of Pb and Zn values, log graph paper has been used.

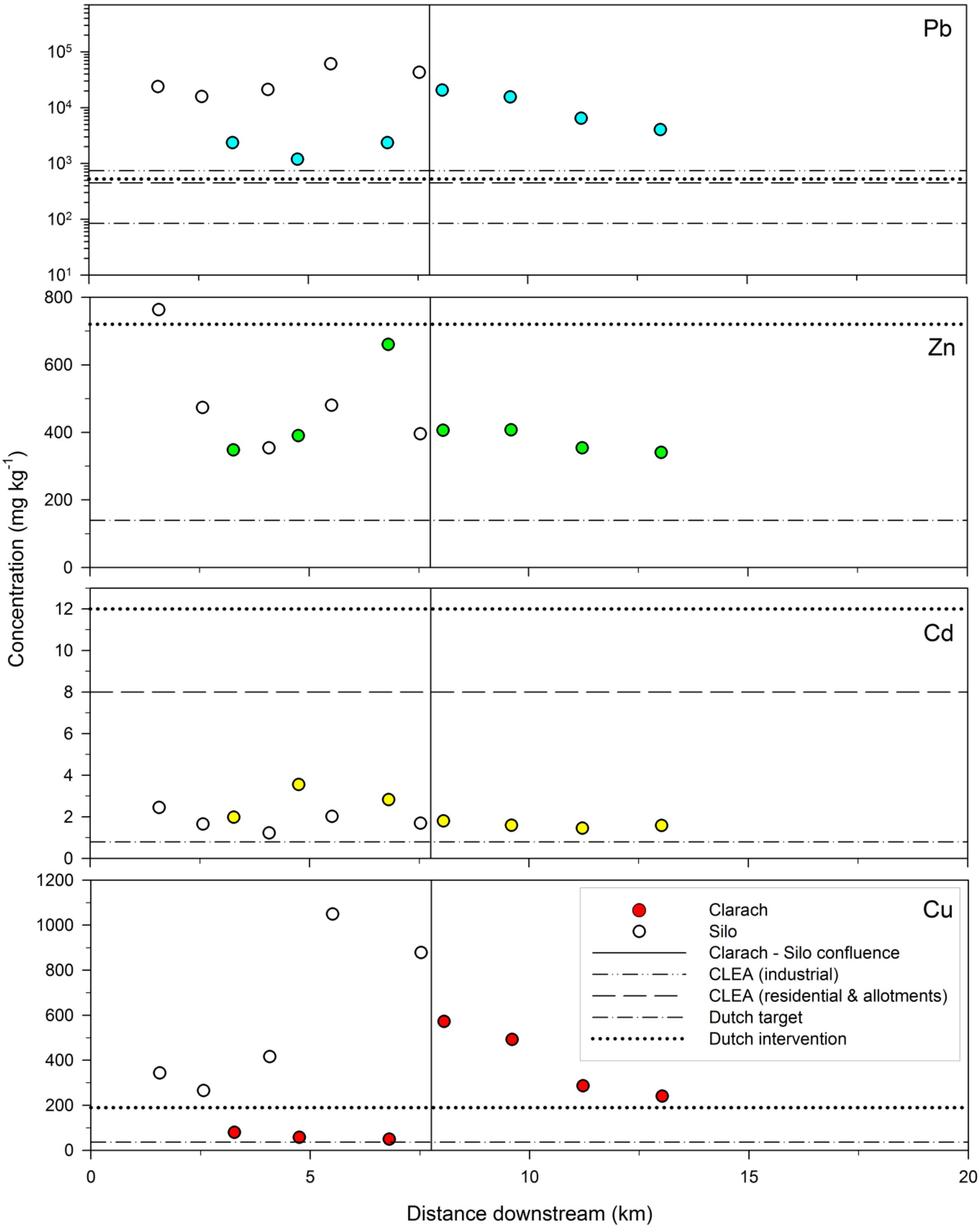

Figure 17. Downstream variation in heavy metal concentrations on the River Clarach, June 2012. Selected UK and European threshold values are also shown. Note that because of the extreme range of Pb values log graph paper has been used.

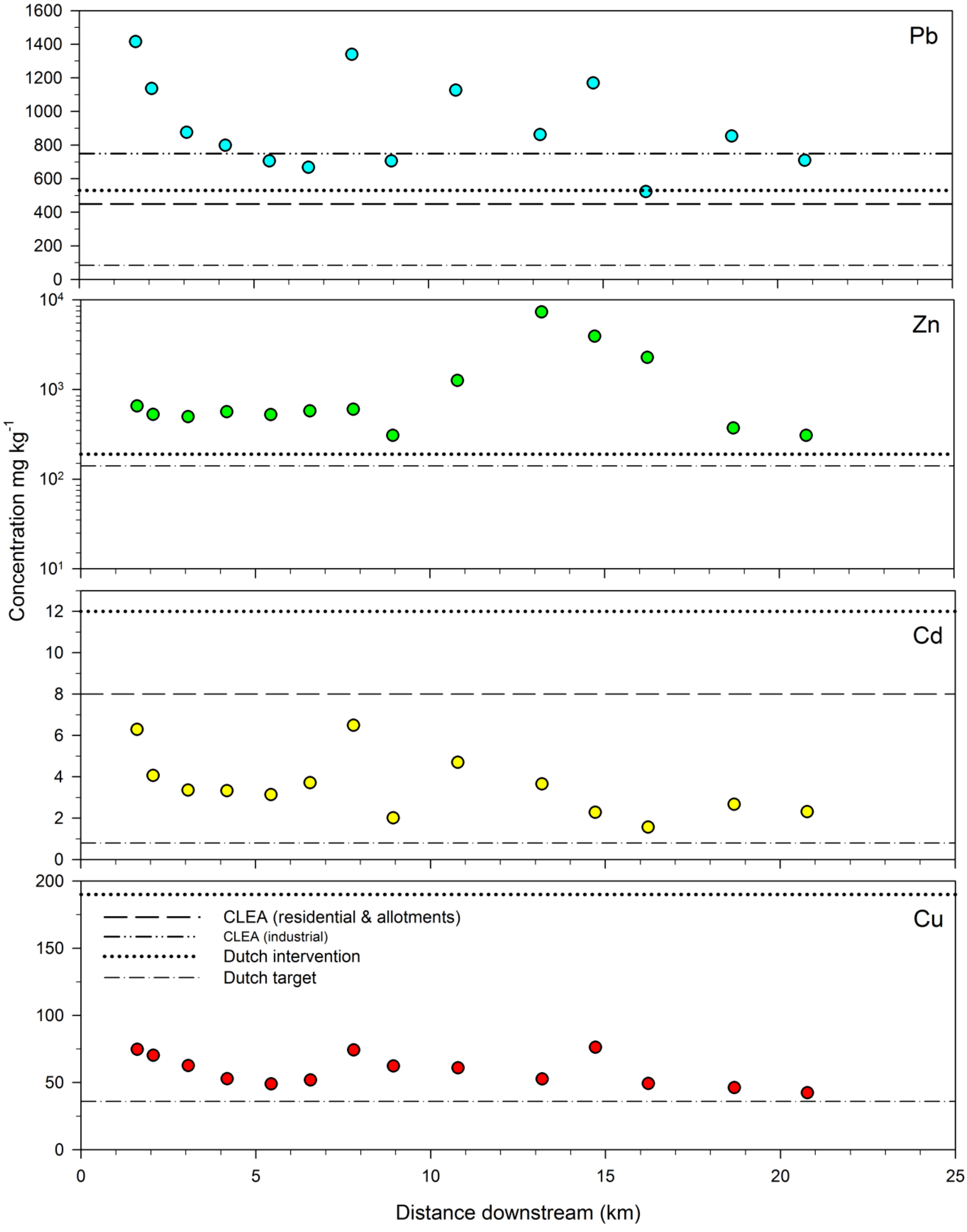

Figure 18. Downstream variation in heavy metal concentrations on the River Rheidol, June 2012. Selected UK and European threshold values are also shown. Note that because of the extreme range of Zn values log graph paper has been used.

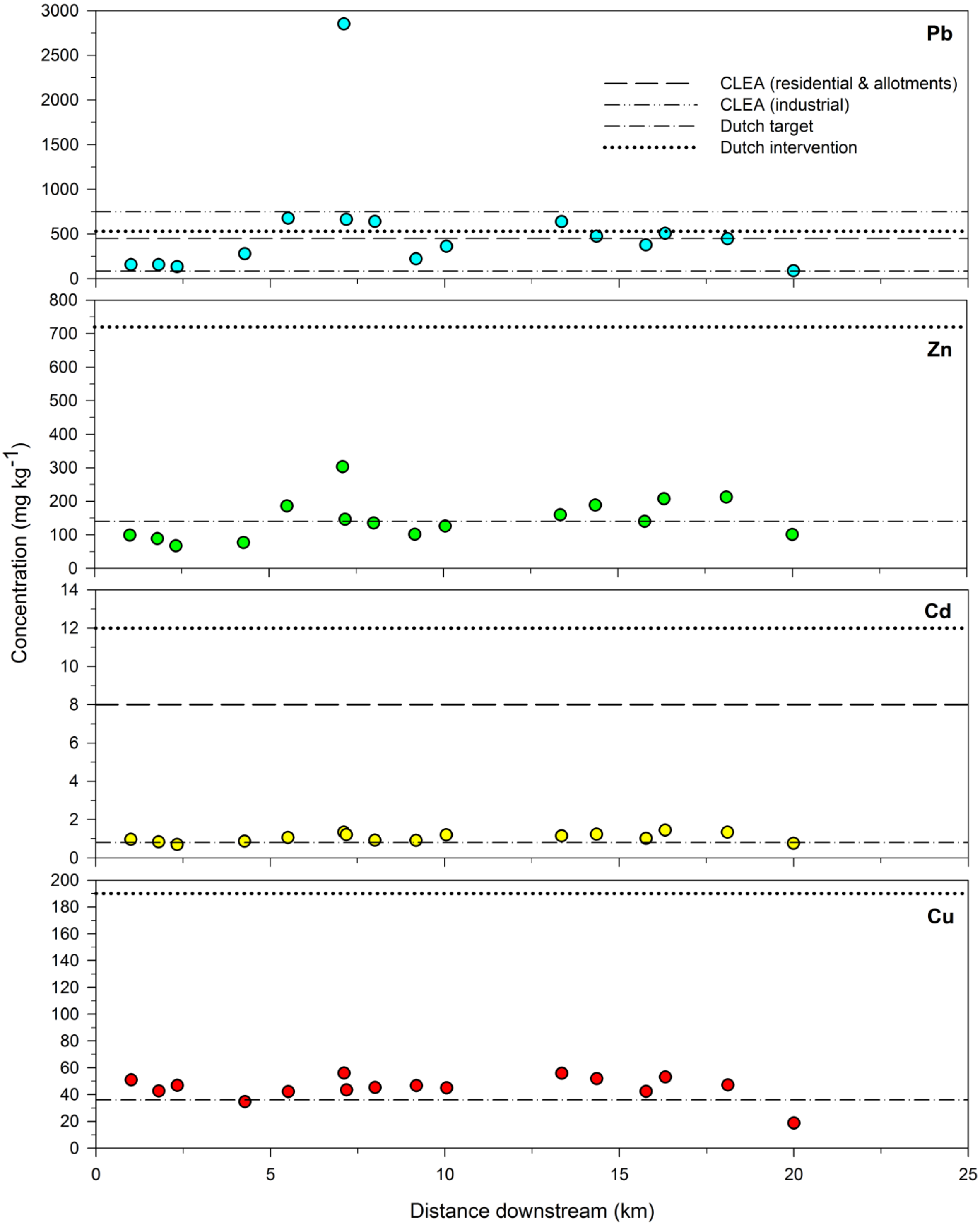

Figure 19. Downstream variation in heavy metal concentrations on the River Leri, June 2012. Selected UK and European threshold values are also shown.

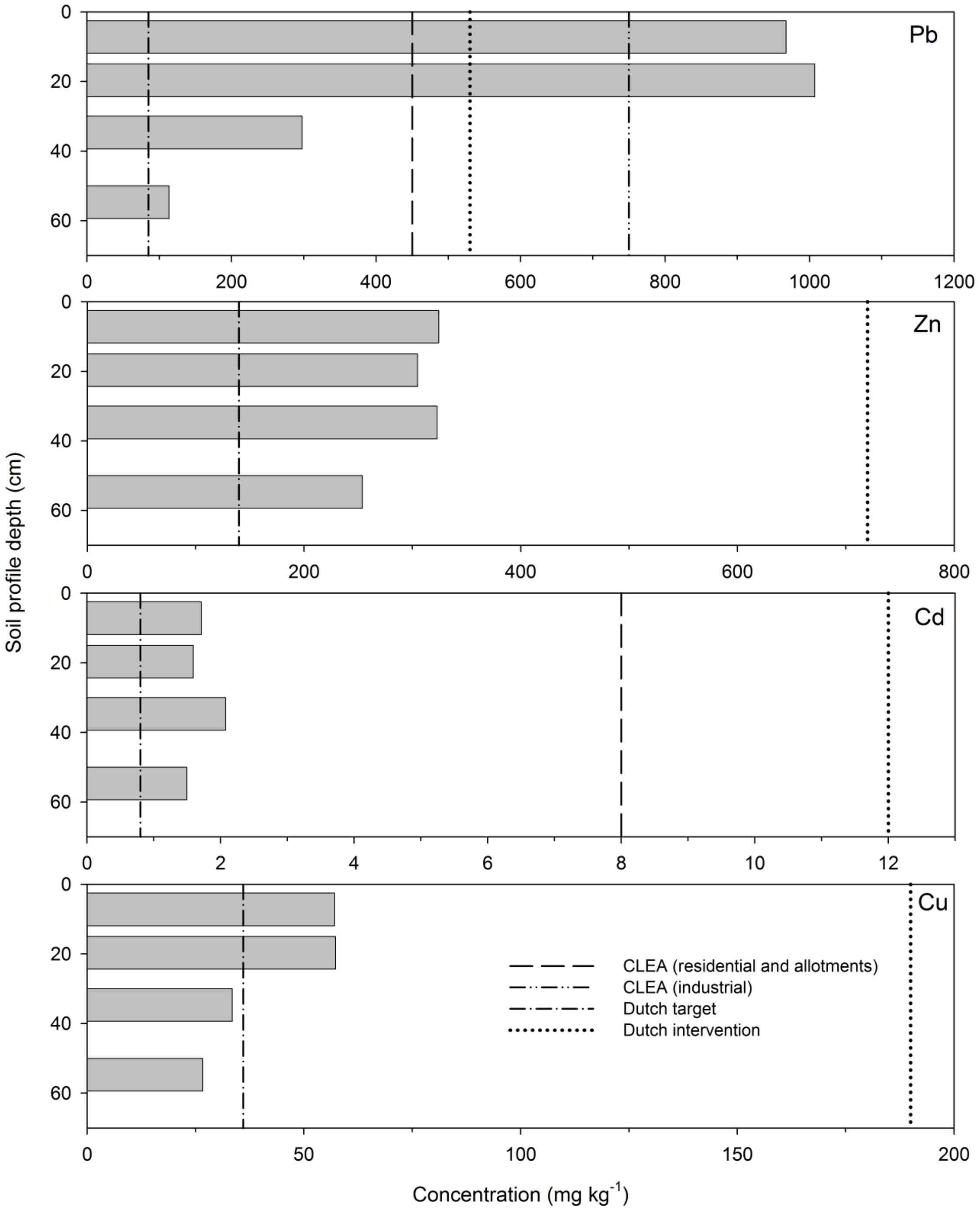

Figure 20. Metal concentration profiles of floodplain allotment soils in the Rheidol catchment. Selected UK and European threshold values are also shown.

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