**THE UNIVERSITY
OF BIRMINGHAM**

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**M.Sc. DISSERTATION
RIVER ENVIRONMENTS and their MANAGEMENT**

O. J. CLEGG

LONG-TERM DRAINAGE DITCH HYDROGEOMORPHOLOGICAL RESPONSE TO PLOT-SCALE TIMBER HARVESTING IN THE NANT TANLLWYTH CATCHMENT ON PLYNLIMON, MID-WALES

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ABSTRACT

Accelerated rates of river channel and drainage ditch erosion in response to plot-scale timber harvesting in the Tanllwyth catchment, mid-Wales, have been widely reported. Reduced thermal insulation immediately following canopy removal has been shown to increase bank susceptibility to frost heave and soil desiccation, leading to temporarily heightened vulnerability to erosion and concomitant rises in suspended sediment and bedload yields until vegetation recolonisation. However, longer-term, non-erosional responses – including after riparian buffer strip introduction – are less well known. This Study shows that natural recovery in rates of erosion after plot-scale timber harvesting is followed by differential rates of aggradation within drainage ditches. An apparent binary system of 'open' (free-flowing with no superficial vegetational layers) and 'closed' (colonised by surficial *Sphagnum* mosses) drainage ditch types has established itself in the Tanllwyth catchment, and sediment distributions from each suggest subtle differences in depositional circumstances likely influenced by forestry-related activities. Furthermore, Tanllwyth drainage ditches have also been shown to be important sediment stores and may represent >16% of total sediment flux with implications for catchment hydrogeomorphological development dominated by low sediment entrainment competence within ditches. The findings in this Study demonstrate how increased drainage ditch erosion and sediment yields are not the only response stimulated by plot-scale timber harvesting, and that a longer-term perspective is warranted. Further research focused on more detailed investigations between how 'open' and 'closed' ditches differ may be prompted by this Study, with larger sediment sample sizes and direct monitoring of ditch water and sediment discharges a prerequisite for detailed comparisons.

ACKNOWLEDGEMENTS

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CHAPTER 1 – INTRODUCTION

1.1 Literature Review

1.1.1 Forestry in Britain

Conversions to forestry largely from marginal improved grassland represented the single biggest land use change in Britain throughout much of the twentieth century (Robinson and Blyth, 1982). Although apparent UK wood consumption in recent years (Forest Research, 2023) has not met projections made by the Forestry Commission in the 1970s (Forestry Commission, 1977), the gaps between domestic production and demand highlighted by the Forestry Commission (ibid.) helped to encourage further expansion of the UK forest estate which in 2022/23 grew by almost 13,000 ha, of which ~63 km^2 comprised new stocks of coniferous woodland (Forest Research, 2023).

Widespread tree planting over large spatial and temporal scales brings with it obvious direct implications for hydrological processes including but not limited to, increased interception (Gash et al., 1980) and evapotranspiration rates (Dunn and Mackay, 1995) and thus decreased catchment water yield compared with grasslands (Calder, 1977); a phenomenon especially true for evergreen species (Nisbet, 2005) and first identified in 1956 (Law, 1956) after initial beliefs that forestry would be *beneficial* to or at least have a neutral impact on UK water resources (e.g. Lloyd, 1950 quoted in Law, 1956). Aside from the influence of conifers themselves on local (Calder, 1977) and regional (Mao and Cherkauer, 2009) hydrology, it is processes ancillary to but not directly involved in tree growth that are also highly influential on local hydrogeomorphological processes.

Cultivation of land prior to afforestation has traditionally involved the construction of networks of plough furrows and drainage ditches (Carling et al., 2001) analogous to the examples shown in Figure 1.1, and these have been shown to have considerable impacts on catchment hydrogeomorphology (Newson, 1980b) alongside the trees whose growth they support. Research in central Scotland has associated forestry drainage operations with increased suspended sediment and bedload yields (Ferguson and Stott, 1987; Johnson, 1993) and erosion rates (Stott, 1997) but little clear, discernible change in rainfall-runoff relationships (Jakeman et al., 1993; Pearce, 2021). Further work conducted in England largely corroborates these general relationships (Robinson, 1980) however there are few locations that have been more intensively researched in this field than Plynlimon, mid-Wales.

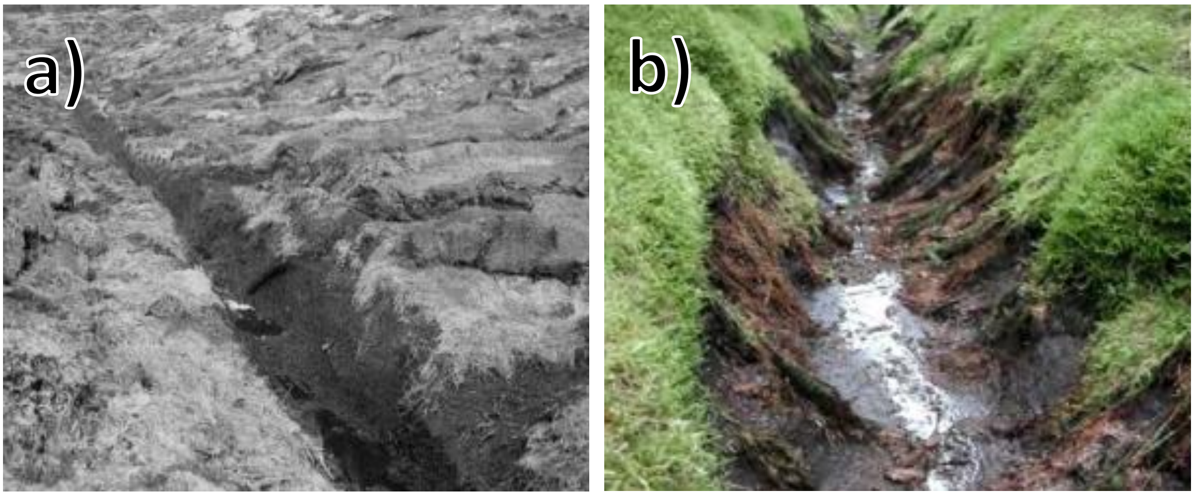

Figure 1.1: Newly excavated drainage ditch perpendicular to smaller plough furrows (Stott and Mount, 2004; a) and an older drainage ditch exhibiting colonisation of vegetation (Forestry Commission, 2019; b).

1.1.2 Overview of the Plynlimon Catchment Experiment

Sound experimental design often relies on the ability to make comparisons between at least one control and impact specimen, and it was in response to the widespread proliferation of UK conifer plantations that the Institute of Hydrology (IH; now the Centre for Ecology and Hydrology, CEH) established the Plynlimon Catchment Experiment in the late 1960s (Hudson and Gilman, 1993) initially to investigate water use by coniferous forests (Kirby et al., 1991). Assessing conifers alone is not enough to gain a comprehensive understanding of their water use however, and so the grassland Wye catchment neighboured by the forested Severn – each separated by the Plynlimon massif with the Severn to the north and Wye to the south – represented an opportunity to compare a control (Wye) with an impact (Severn) catchment. From 1968 onwards the IH furnished the Cyff and Tanllwyth (which was first planted with Sitka Spruce in 1949/50 (Newson, 1980b)) sub-catchments with an array of monitoring equipment to measure, *inter alia*, catchment meteorology, soil moisture, canopy interception, sediment yields and stream discharge to create the longest-running intensive research catchment in the UK (Robinson et al., 2013).

The establishment of a pair of densely-instrumented catchments representative of upland Britain helped to satiate an urgency to study the effects of timber cultivation on water resources, and so it is with a degree of inevitability that after over half a century of study there is an abundance of research emanating from Plynlimon including in areas beyond the original scope of the Experiment.

Work that has been produced as a by-product (that is, well beyond the initial scope of the catchment experiments) of the project includes the creation of a unique time-series of water quality taken at seven-hourly intervals over two years (Neal et al., 2013), comprehensive reviews of the hydrology (Hudson et al., 1997; Shand et al., 2005), vegetation (Brandt et al., 2004; Newson, 1976) and streamwater chemistry (Reynolds et al., 1989; Robson et al., 1993; Stewart et al., 2022) of the catchments, as well as a resource to create a methodology for calibration and uncertainty estimation of hydrological models (Beven and Binley, 1992). Fundamentally, the Plynlimon Catchment Experiment has given succour to a range of environmental science research that covers a great breadth of topics that is an invaluable foundation for contemporary scientific research and understanding, particularly in contexts related to forestry and the freshwater environment.

1.1.3 Forestry and the Freshwater Environment

Research deriving from Plynlimon has shown that trees individually and collectively exert increased resistance to air flow over land surfaces compared with grasslands (Calder, 1977; Finnigan and Brunet, 1995 4) and are responsible for comparatively higher water use through evapotranspiration (Hudson et al., 1997) and thus reduced stream discharge. Whilst increased rates of evapotranspiration over afforested areas clearly play a role in reducing the total volume of rainfall that ultimately reaches the ground surface (Calder, 1977), effects of tree cover on catchment water balances have been shown to be non-straightforward, and macropore networks afforded by tree root structures are effective conduits for water transportation (Mosley, 1982). This is in competition with reduced overland flow rates – even with little understory vegetation and well-compacted soils – imparted by mature conifer trunks (Miyata et al., 2009) but precise catchment hydrological responses to tree felling are unclear and varied (Hornbeck et al., 1993; Pearce, 2021). These works combine with a vast expanse of others (e.g. Calder, 1990; Neal et al., 2004; Neal et al., 2010; Shand et al., 2005) to show that the influence of conifer plantations on the freshwater environment are extensive, including into the biosphere.

Whilst expansive grasslands typical of those found in the sub-catchments of the River Wye are not necessarily associated with substantial tree cover, and despite riparian vegetation being strongly associated with changes to channel shape (Hey and Thorne, 1986), the exact response of channel shapes to different vegetation types are nebulous (Hickin, 1984) and so there are different consequences for stream ecology depending on the types of vegetation that happen to occupy the riparian zone.

Long-running research in Welsh uplands led by Ormerod et al. (2004) coupled with work by Caissie (2006) and Dudgeon et al. (2006) on global freshwaters has shown that broadleaf tree cover proximal to streams plays an important role in providing nutrients and shelter for freshwater macroinvertebrates. Broadleaf trees also mitigate the effects of increased stream temperatures in a warming climate (Reid et al., 2019) and buffer impacts of acidity associated with conifers (Ormerod et al., 2004) – both phenomena which are detrimental to macroinvertebrates (ibid.) and fish (Thomas et al., 2015) populations. The influences of forestry on freshwater ecology therefore are extensive, with management practises having important implications across and beyond the freshwater environment.

1.1.4 Forestry and Fluvial Geomorphology

Attitudes of foresters towards draining soils for tree cultivation have evolved over the course of the twentieth century. The prevailing guidance in the 1960s specified that ditches analogous to those shown in Figure 1.1 should be dug 'considerably deeper' than those dug in the post-war period (Fraser and Henman, 1963 35) in order to lower the water table and maximise drainage. By 1979 consensus had shifted, and Forest Research directed that the lowering of water tables by drainage schemes was no longer expected (Forest Research, 1979) due to water pooling concerns; a concern that has since been superseded over unease of the deleterious influences of over-engineered drains on increased erosion and siltation (Forestry Commission, 2019). Current guidance thus emanates from a pool of research, much of which derives from Plynlimon, that has investigated the links between forestry drainage and fluvial geomorphology.

Malcolm Newson, with others, has been a preeminent scholar on drainage-geomorphology linkages from work on Plynlimon and elsewhere, and much of the work done on Plynlimon in more recent years derives from research by Newson who identified that excessively-sized, exposed open drainage ditches used to drain land for forestry are particularly prone to erosion (Newson, 1980b), with rapid incision down to the coarse glacial deposits and bedrock typical of Plynlimon (Newson and Harrison, 1978). Newson's (1980b) findings have since been supplemented by Stott (1999) who periodically monitored erosion pin protrusion in the Tanllwyth and tributary ditches and found a statistically significant acceleration in bank erosion rates following timber harvesting caused by higher frost incidence associated with loss of insulation afforded by forest canopies (Stott, 1997; Stott, 1999).

Increased channel bank erosivity following timber harvesting coupled with fewer mechanisms for slowing water – such as trees – alongside the presence of drainage ditches in the first place drive improved conditions for higher rates of flow (Trimble and Lund, 1982). This has been shown to manifest itself in the form of a doubling of clast travel distances in the Tanllwyth versus the grassland Cyff (Stott and Sawyer, 2000 395) and thus indicates increased stream power which is itself reflected in significant changes in channel sediment loads. Moore and Newson (1986), when comparing bedload and suspended sediment yields in the Tanllwyth and Cyff, correlated significantly higher suspended sediment yields with the first four years after excavation of drainage ditches, a finding corroborated by Ferguson and Stott (1987) who identified episodic increases in sediment yield in line with streamflow and Stott et al. (2001) whose similar approach found 39% higher suspended sediment concentrations during years of harvesting operations.

Table 1.1, taken from Stott and Mount (2004), summarises the differing responses by river channels to water and sediment dynamics. Where there is general consensus on forestry operations (including forestry road construction and use (Duck, 1985; Moffat, 1988)) playing a fundamental role in upland geomorphology, links to *down*stream changes are less clear (Mount et al., 2005; Trimble, 2009). Trimble (1997; 2009) showed that fluvial environments can be investigated by assessing catchment sediment, and soils can represent important indicators of geomorphological development.

Table 1.1: Simplified summary of expected channel responses to relative changes to water and sediment discharge. From Stott and Mount (2004).

Change in water and sediment discharge	Channel response
Sediment+ Water=	Aggradation: channel instability, channel widens and shallows
Sediment- Water=	Incision: channel instability, channel narrows and deepens
Water+ Sediment=	Incision: channel instability, channel widens and deepens
Water- Sediment=	Aggradation: channel instability, channel narrows and shallows
Sediment+ Water-	Significant aggradation
Sediment+ Water+	All morphological activity intensified
Sediment- Water-	Decreased level of morphological activity
Sediment- Water+	Significant incision: channel instability, channel deepens, width change uncertain

1.1.5 Reconstructing Fluvial Environments

The final aspect of research that needs to be visited in order to address the Aims and Objectives of this study is that relating to the reconstruction of past environments *via* sediment analyses. Environmental discrimination (the process of inferring characteristics of relict environments (Greenwood, 1969)) was traditionally attempted in the context of fluvial environments through qualitative assessments of large geomorphological features (ibid.) and not until the early part of the twentieth century (e.g. Sherzer, 1910; Wentworth, 1919; Cox, 1927; Campbell 1929) did requisite attention get paid to clues left by physically smaller component geomorphological features and their origins, like sediments. Wentworth (1922) developed a scale for the classification of sediment types based on their sizes and it is through grain size compositions and how they fit into the Wentworth Scale (a modified example of which can be found in Appendix 1) that the processes that led to the deposition of different sediments can begin to be determined.

Simple logic dictates that the finest, lightest grains will be those that are most easily entrained and therefore it is an abundance of those grains that may be indicative of more lentic, low-energy fluvial environments (Dobkins and Folk, 1970). The opposite (e.g., larger sediments require more energy to entrain) is also true and so a river that has experienced a range of low and high flows is likely to harbour a reflection of this in its deposits (Folk and Ward, 1957; Allen, 1965). High flow variability and the nature of rising and falling limbs typical of flow time-series' dictate that sediment is likely to be sorted into 'laminations', or layers, and it is on these bases and on the foundations provided by all of the research reviewed in these introductory paragraphs that this study aimed to infer geomorphological activity in the Tanllwyth catchment, mid-Wales.

1.1.6 Research Gaps

This literature review has performed a visitation of each of the components that are fundamental to this project, the understanding of which are vital for its effective completion. Equally important – and key motivators for performing this research – are the research gaps that this literature review has identified. Whilst there is an abundance of work that has been produced on the back of the Plynlimon Catchment Experiment (e.g. Newson 1980a; Newson 1980b; Calder, 1977; Hudson and Gilman, 1993; Hudson et al., 1997; Brandt et al., 2004; Robinson et al., 2013) it is fair to conclude two things. Firstly, the rich repository of research deriving from Plynlimon is now somewhat biased towards that done in previous decades and as such has not been added to at the same rate in more recent years. Second, the abundance of work done investigating channel *erosional* response to timber harvesting is valuable however is in contrast to a relative dearth of investigations into any *aggradation* that has taken place within the Tanllwyth catchment. This project is designed to address this important gap.

1.2 Aims and Objectives

1.2.1 Aims

The *longer-term* forestry drainage ditch response – beyond accelerated rates of erosion and subsequent recovery soon (five years) afterwards – to timber harvesting has not been widely reported. This study aims to achieve a more complete understanding of Tanllwyth ditch sediment characteristics and hydrogeomorphological development following plot-scale timber harvesting by including non-erosional responses in its scope. Study Aims are underpinned by a pursuit of the following Objectives:

1.2.2 Objectives

1. Assess ditch benthic ditch soil characteristics relative to a control to infer sediment origin and likely transportation mechanisms.
2. Estimate the amount of material stored in drainage ditches to understand how much sediment has effectively been removed from the upper reaches of the Nant Tanllwyth.
3. Understand the role of plot-scale timber harvesting on Tanllwyth catchment hydrology.
4. Infer possible future drainage ditch development based on catchment sediment and hydrometeorological characteristics.

CHAPTER 2 – MATERIALS AND METHODS

2.1 Study Site Location

The Plynlimon Catchment Experiment is comprised of the Tanllwyth and Cyff sub-catchments and take their name from Plynlimon Fawr, a nearby summit that lies 752 m AOD (Ordnance Survey, 2024) and forms part of the wider Cambrian Mountains massif. The high elevations characterising the area alongside its situation on the west of the UK make it one that is simultaneously exposed to frontal Atlantic maritime weather systems (Foulds et al., 2014; Thompson et al., 2017), convective summer storms (Newson, 1980a) and subject to increased precipitation *via* orographic enhancement; a phenomenon known to have contributed to flooding in the nearby coastal town of Aberystwyth in June 2012 (Webb, 2013). The combination of these three factors makes the Tanllwyth catchment (Figure 2.1) a particularly wet one, and Figure 2.2 compares mean monthly precipitation in the Tanllwyth with that of the rest of the UK. A clear distinction between the areas can be drawn, with mean monthly rainfall being >79% greater in the Tanllwyth compared with UK as a whole.

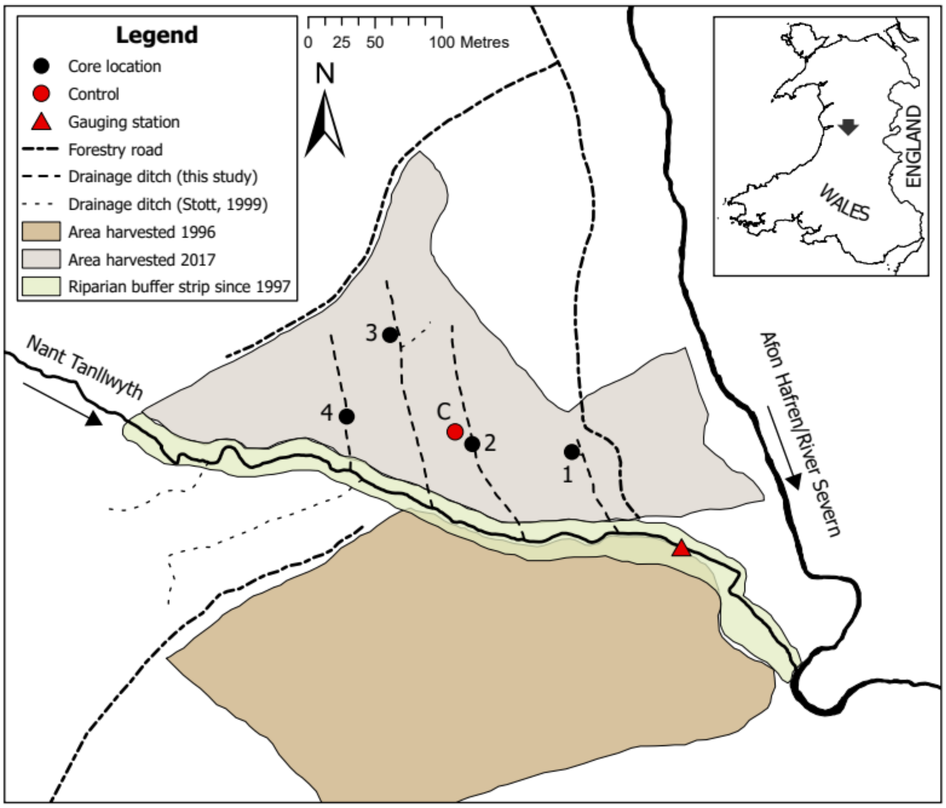

Figure 2.1: Study area within the Nant Tanllwyth catchment. Arrows represent the direction of river flow. Inset: Catchment location within Wales.

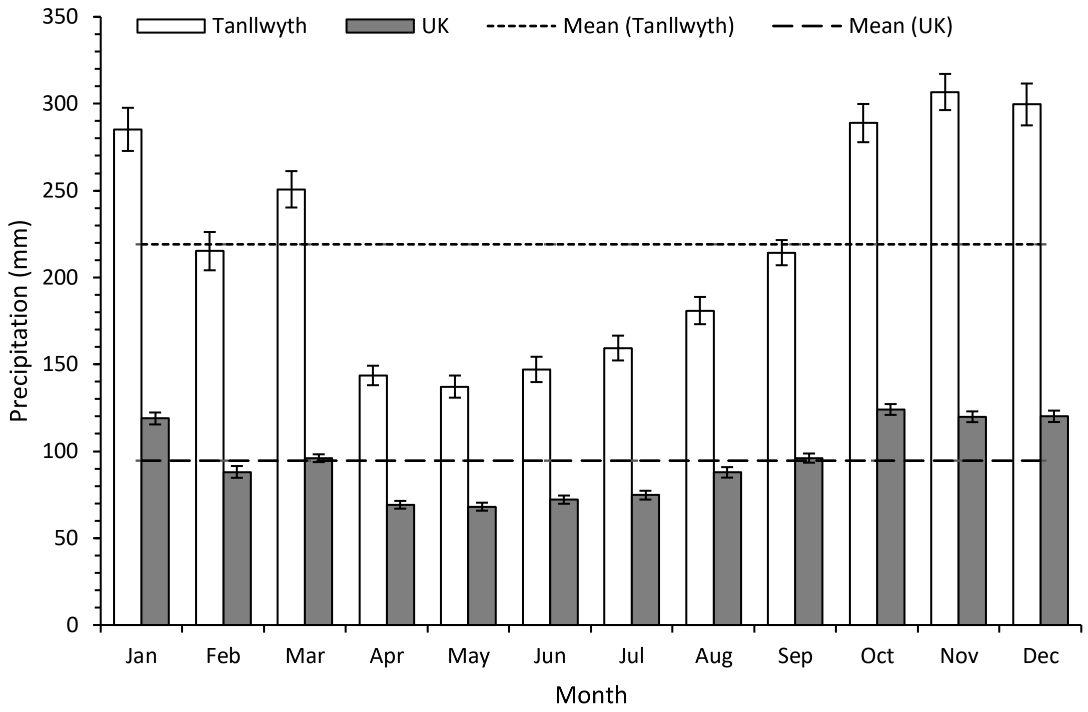

Figure 2.2: Mean monthly precipitation in the Tanllwyth (white bars) and the UK (grey bars). Error bars represent mean standard error. Tanllwyth data from Kirchner et al. (2021), UK data from the Met Office (2024).

Accelerated demand for domestically-grown timber following the First World War saw the establishment of the Forestry Commission in 1919 (Stott and Mount, 2004) who oversaw the single biggest land use change in Britain in the twentieth century as large tracts of marginal improved grassland became afforested (Robinson and Blyth, 1982). That the Tanllwyth catchment is characterised by above-average rainfall, high elevational range and low human population made it an ideal candidate for cultivating timber, and the late 1930s saw the earliest planting in the Severn catchment when plantations of non-native conifer species including Norway Spruce (*Picea abies*) and Sitka Spruce (*Picea sitchensis*) began to punctuate the area (Newson 1976 34) to the extent that some two-thirds of the Severn catchment (within which the Tanllwyth lies) became forested by 1993 to form the Hafren Forest (Hudson and Gilman, 1993).

Where much of the River Severn and its tributaries have been utilised as a source of timber as plantations matured, the neighbouring River Wye catchment has remained one dominated by grassland (Mount, 2000 14; Stott et al., 2001) and so this combination has represented an opportunity to investigate the long-term geomorphological effects of upland timber cultivation by using a paired catchment approach. The Institute of Hydrology (IH; now the

Centre for Ecology and Hydrology, CEH) took advantage of this opportunity and in 1968 began installing an array of monitoring apparatus (Kirby et al., 1991; Hudson and Gilman, 1993) in the Tanllwyth (0.89 km^2; Severn) and Cyff (3.13 km^2; Wye) sub-catchments to act as proxies for the larger rivers they flow into.

2.2 Data Collection and Analysis

2.2.1 Fieldwork

The nature of previous research done on the Tanllwyth and Cyff catchments is varied. This study most specifically builds on work investigating stream channel and forestry drainage ditch geomorphological response to upland forestry activities, namely work done in the late twentieth century in England (e.g. Robinson, 1980), Scotland (e.g. Stott, 1997) and Wales (e.g. Stott, 1999; 2020). Stott (1999) measured geomorphological response to plot-scale timber harvesting in the Tanllwyth that took place in 1997 and 2017 (Stott, 2020). Upon revisiting the catchment in May 2024, it was found that since harvesting in 2017 (Figure 2.3a, b) a significant degree of vegetational growth has taken place including in some of the drainage ditches themselves. Figure 2.3 also shows an example of a *Sphagnum*-covered ditch (c) alongside a photographic representation of the wider catchment from the ground (d).

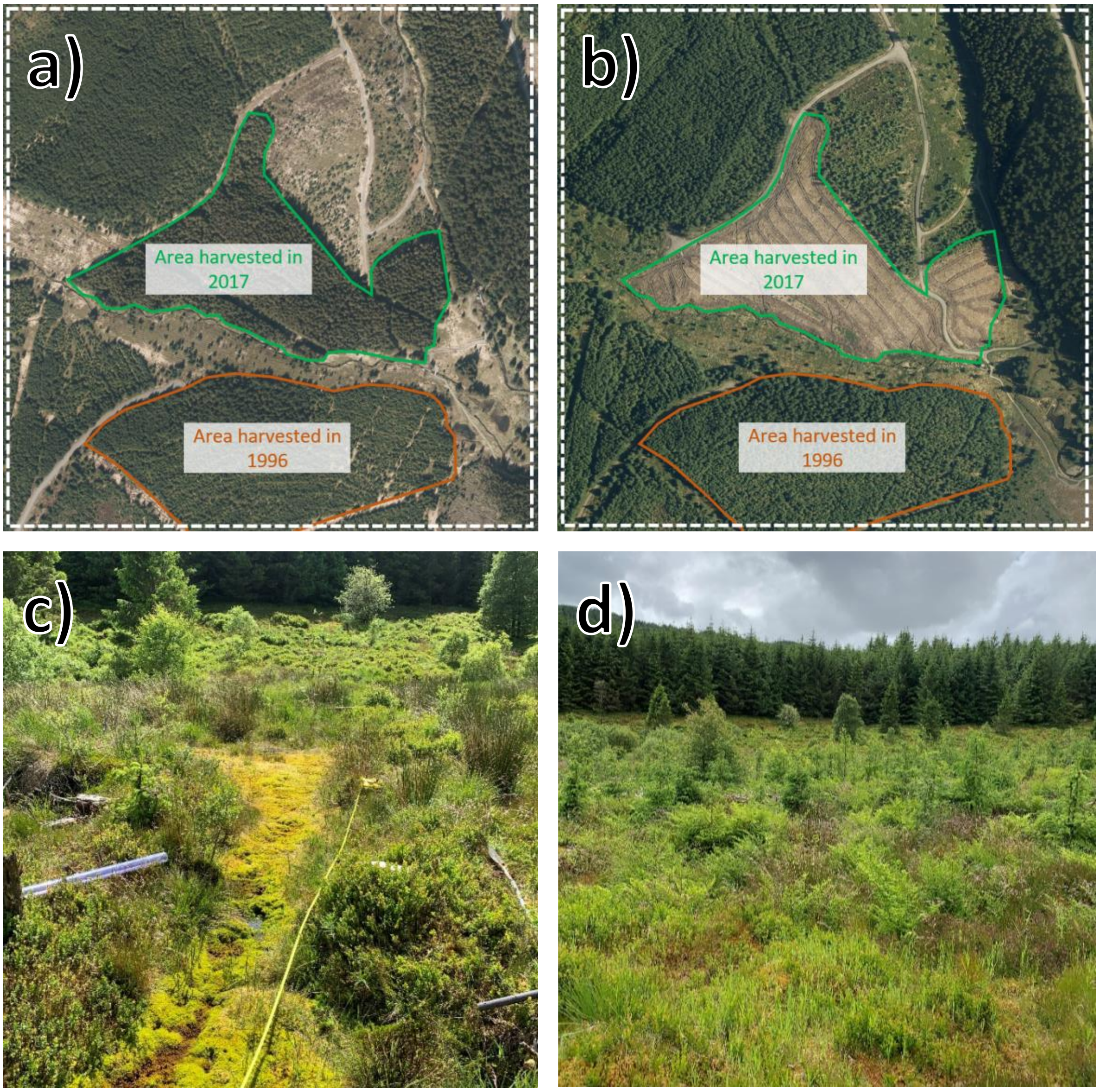

Figure 2.3: The Tanllwyth catchment from above in 2014 (a) and 2018 (b) showing the change of land use following deforestation in 2017. The area shown within dashed outlines is the same as that represented in Figure 2.1 and photographs (a) and (b) derive from Digimap (2014) and Digimap (2018) respectively. Panel (c) shows an example of a drainage ditch exhibiting a layer of Sphagnum *mosses and (d) represents the catchment from the ground. Figure 2.3c was taken from the location of Core 1 shown in Figure 2.1, and Figure 2.3d was taken from the location of Core 3 looking south across the Tanllwyth.*

Here a switch from the increased erosion found by Stott (1999) to ditch aggradation became apparent, and so – where identifiable and reachable – benthic sediment samples down to bedrock were taken from the drainage ditches measured by Stott (ibid.; Figure 2.1) using a Russian corer: two from ditches that were 'open' (Cores 3 & 4) with water flowing freely through them; two from ditches hosting dense superficial layers of upland vegetation and so classed as 'closed' (Cores 1 & 2; Figure 2.3a), and one from soil close to but not in a drainage ditch to act as a control. Coring locations were selected based on a balance between achieving sufficient representation of the whole catchment, accessibility and proximity to locations monitored by Stott (1999). Once cores were extracted, sediment samples were taken at 10 cm depth intervals, transferred to numbered plastic bags and sealed. A total of 26 such samples were taken in this way: ten from Core 1, three from Core 2, five each from Cores 3 and 4, and three from the Control.

Width, depth and length measurements of ditches from which cores were taken were also measured to estimate volume alongside *a*, *b* and *c* axes measurements of certain clasts extracted from them. Finally, translucent PVC tubes of known interior diameter were used to extract sediment samples from ditch beds adjacent to coring locations to obtain samples for bulk density calculations. These calculations were employed to estimate total quantity of material stored in the ditches analogous to Stott's (1997) estimation of sediment removed *via* erosion in central Scotland. Due to difficulties with ground penetration using PVC tubes at the Control Core location, bulk density samples were only taken from ditches (Core locations 1-4; Figure 2.1).

2.2.2 Laboratory Analyses

Once in the laboratory, samples from cores were weighed and then oven-dried to constant mass at 105 °C as stipulated by Gardner (1986 493) to i) establish soil moisture content and ii) prepare samples for further analyses. After drying, samples were again weighed before being visually inspected using a Zeiss Stemi 2000 microscope to qualitatively assess sample makeup. Next, a stack of three soil sieves of 16 mm, 8 mm and 2 mm apertures was used to dry-sieve the samples for nine minutes according to procedures set out by Whalley (1994 130) with a Fritsch sieve shaker, though neither oxidising nor dispersal agents were used for practicality reasons and samples were below the 0.1–0.15 kg recommendation due to limitations in sample sizes obtained with the Russian corer. After sieving the mass of each size fraction was recorded.

Samples were only initially sieved down to an aperture of 2 mm as sizes below that are generally able to be more rapidly and precisely measured with a Malvern Instruments Mastersizer2000, and this was intended for those sub-samples <2 mm in diameter. Ultimately, a small sample size coupled with high buoyancy of the sediment precluded measurement in the Mastersizer2000 (which involves submersion of the sample in deionised water), and so samples <2 mm were re-sieved. For this a further sieve stack comprising apertures 1, 0.425, 0.212, 0.125 and 0.075 mm was used and samples were again processed using the procedure stipulated earlier. These apertures were chosen based on sieve availability and their rough alignment with Wentworth (1922) size classification boundaries. After sieving and weighing, grain size statistics including mean, sorting, skewness and kurtosis values calculated using the Folk and Ward (1957) method were computed using the GRADISTAT programme developed by Blott and Pye (2001).

To determine proportions of organic matter (OM) samples were ground using a pestle and mortar before being transferred to pre-weighed heat resistant crucibles, weighed again, and ignited in a Carbolite chamber furnace at 535 °C; a temperature which has been found to be effective at burning the vast majority of OM (Hoogsteen et al., 2015). Samples were again weighed upon removal from the furnace and cooling to determine OM percentages.

Finally, bulk density was determined by first measuring the depth of the samples within their respective PVC tubes prior to removing them and, as bulk density is oven-dry mass relative to sample volume (Blake and Hartge, 1986 366), samples were weighed following removal before being oven-dried in line with aforementioned drying procedures (Gardner, 1986 493) and weighed once again. Figure 2.4 represents an example of core removal from a PVC tube.

Figure 2.4: Removal process of bulk density sample. Photograph is the author's own.

2.2.3 Desk-based Analyses

To determine impacts of forestry operations on hydrology, hourly hydrometeorological data from 1975-2010 obtained from Kirchner et al. (2021) were analysed and simple linear relationships between Nant Tanllwyth discharge and catchment precipitation calculated. The same was done for data related to the Cyff catchment which acted as a control. Comparisons of precipitation-discharge relationships in different time periods allowed for preliminary investigations into the effects of timber harvesting on catchment hydrology during the harvesting phase of 1997 (Figure 2.1).

Using drainage ditch dimensions that were determined in the field and with mean Tanllwyth slope of 0.054 (Sawyer, 1999 16) being applied to drainage ditches, estimations of ditch bankfull discharge and the discharge required to entrain sediments of various sizes were made for the ditch from which Core 1 was taken with the continuity (Equation 2.1), Manning (1891; Equation 2.2) and Andrews (1983; Equation 2.3) equations. The Manning's roughness coefficient was estimated by using an adaptation of Cowan's (1956) method by Arcement and Schneider (1989) for its simplicity and accessibility in the field. Whilst each equation is imperfect (e.g. Equation 2.2 disregards the increasingly limited influence of bed roughness with higher discharge), each represents an accessible means through which bankfull discharge and sediment entrainment can be estimated and thus possible geomorphological development inferred.

$$Q = wdv \qquad \text{(Equation 2.1)}$$

Where:

Q = Discharge
w = width
d = Depth
v = Velocity

$$U = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{n}$$ (Equation 2.2)

Where:

U = Average downstream velocity
R = Hydraulic radius
S = Slope
n = Manning's roughness coefficient

$$\tau *_c = 0.0834 \left(\frac{D_i}{D_{50}}\right)^{-0.872}$$ (Equation 2.3)

Where:

τ^*_c = Critical dimensionless shear stress
D_i = Particle size
D_{50} = Median particle size

To determine descriptive and inferential statistics, appropriate statistical tests were performed on data where relevant. These tests were performed using the R (R Core Team, 2023) packages car (Fox and Weisberg, 2019) and ggfortify (Yuan et al., 2016) and were selected based on data structures which were investigated using techniques described by Zuur et al. (2010) and Beckerman et al. (2017 118). As an example, a two-way ANOVA to look at the interactive effects of core location and depth (explanatory variables) on median grain size (D_{50}; response variable) was sought. Model validation proved this test inappropriate for data structure however and so significance of differences between D_{50} of different cores were instead determined using one-way ANOVA which is more appropriate for this data structure.

CHAPTER 3 – RESULTS

3.1 Microscope Analysis

3.1.1 Plastics

Chapter 2.2.2 explains that dried core sub-samples were visually assessed under a microscope to gain a basic qualitative understanding of sample makeup. Whilst there is an inherent lack of quantification that comes with techniques such as these they can nevertheless help to identify any apparent trends and/or anomalies that other analyses (such as sieving) will not necessarily highlight. One unexpected discovery was that of blue fibrous plastics, with 8 of the 26 sub-samples across Control and impact cores exhibiting at least one plastic fragment identified from simple microscopic assessments. That >30% of sub-samples taken from a remote upland catchment contained plastic fragments highlights its pervasiveness. Three out of the four impact (non-Control) cores had plastic found within them and Figure 3.1 summarises the number of fragments found within each sub-sample, with a total of 11 particles being found across depths and across the site (Figure 2.1). Figure 3.2 shows a selection of the plastic fibre fragments under the microscope.

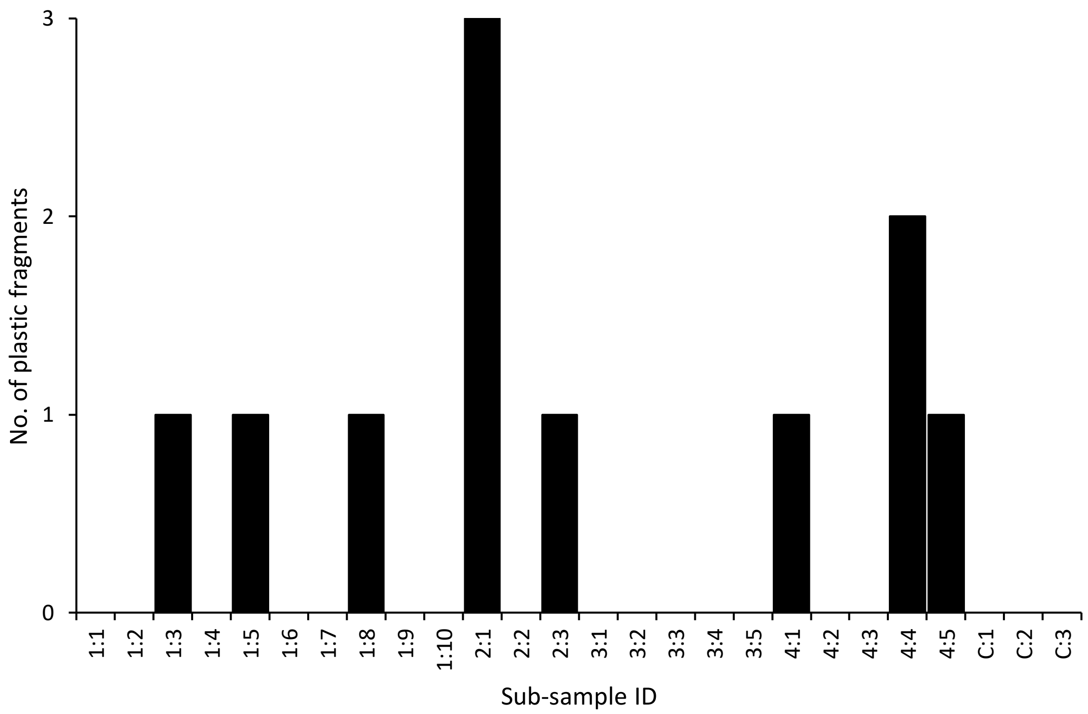

Figure 3.1: Number of individual plastic fibres identified through microscopic analysis, and the sub-samples from which they derive. Sub-samples prefixed with 'C' refer to those from the Control Core.

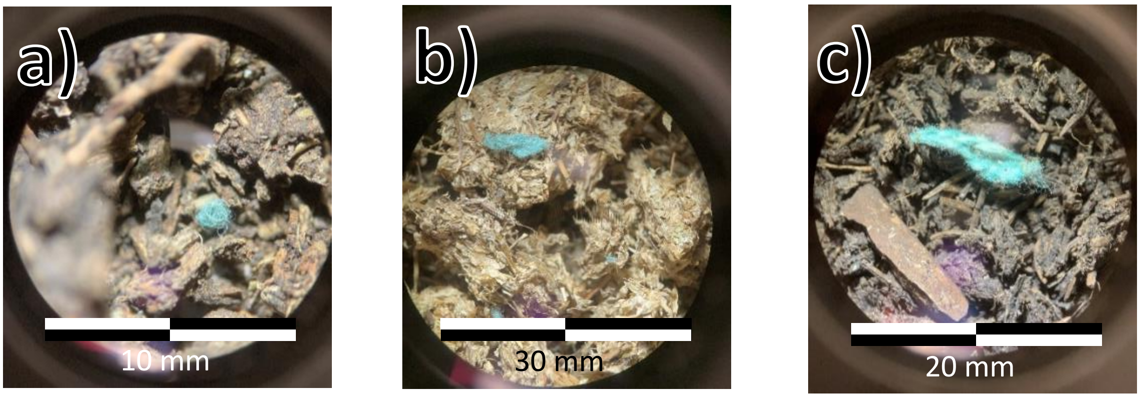

Figure 3.2: Photographs taken through the microscope of plastic fibres found in Core 1:3 (a), Core 2:1 (b) and Core 3:1 (c). Scale bars relate to the images shown within the microscope and do not apply to the components of the microscope itself shown on the edges of photographs. Photographs are the author's own.

3.1.2 Organic Matter

Whilst the discovery of plastics within samples was not expected, their presence represented the only anomaly found in microscope analysis and other notable findings were largely aligned with general expectations. Figure 3.3 shows a series of photographs of sub-samples deriving from Core 1 taken through the microscope, with sample depth from the core surface (e.g. exposed to water flow) progressively increasing from 0-10 cm depth (Figure 3.3a) through 40-50 cm (3.3b) to 90-100 cm (3.3c). Here, cursory examinations of the photographs suggest a somewhat reduced representation of woody organic matter (OM) with increasing depth alongside higher proportions of mineral matter. Fragments of *Sphagnum* moss shown in Figure 3.3c are likely there as a result of being pushed from the surface during coring and are not considered to be a reflection of mosses growing at depth. Apparent increases in mineral matter proportional to depth were consistent across cores with the exception of the Control Core, which seemed to reveal less obvious relationships between depth and OM.

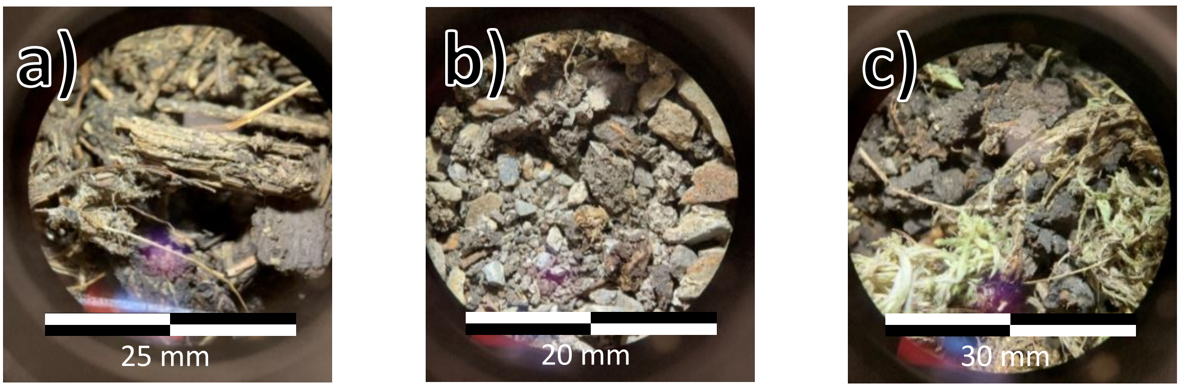

Figure 3.3: Photographs taken through the microscope of Core 1:1 (a; 0-10 cm depth), Core 1:5 (b, 40-50 cm, depth) and Core 1:10 (c; 90-100 cm depth). Photographs are the author's own.

3.2 Physical Analysis

3.2.1 Organic Matter and Depth

Each sub-sample was dry-weighed, ground, ignited and re-weighed according to the procedures outlined in Chapter 2.2.2 following sieving and inspection through the microscope, and this process quantified the OM present in each. Figure 3.4 is the result of this procedure, and shows the relationship between increasing depth from core surface of Impact sub-samples and those from the Control Core. Whilst the relationship is not a particularly strong one (R^2 = 0.34), there are signs of a general reduction in the proportion of OM and corresponding increases in mineral matter with increasing depth. Although Kruskal-Wallis testing (Kruskal and Wallis, 1952) shows no statistically significant difference in OM percentages between cores, OM percentages of 71.5% and 73.7% in the 'open' Cores 3 and 4 respectively are nevertheless higher than 31.7% and 50.0% in Cores 1 and 2. The Control Core exhibits the highest overall OM% at 82.1%.

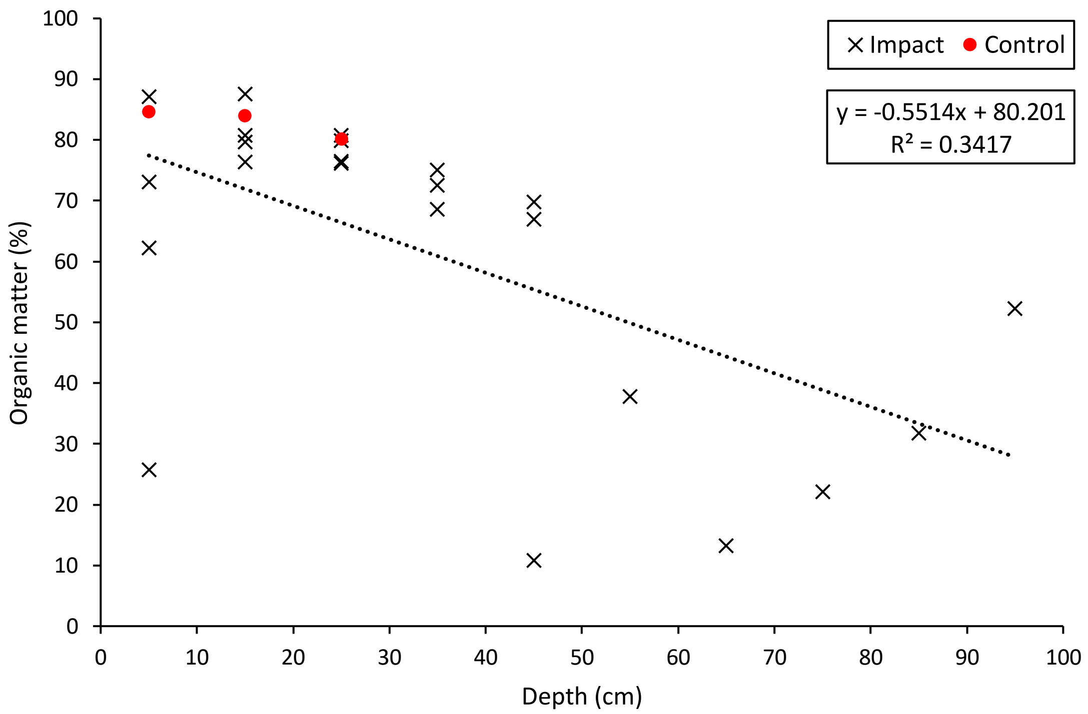

Figure 3.4: Relationship between sub-sample depth and organic matter. A weak negative relationship between increased depth and organic matter can be observed.

3.2.2 Frequency Distributions

Overlap between the size frequency distributions of the Impact and Control cores is demonstrated by Figure 3.5, which shows a higher representation of coarser sediment particles (note negative phi (ϕ) values represent larger particle sizes)) in the Control Core compared with Impact cores as computed by the GRADISTAT software (Blott and Pye, 2001). Higher percentages of large particles in the Control means that proportions of finer diameters in Impact sub-samples are necessarily larger. Table 3.1 summarises descriptive statistics of sediment taken from the cores and similarly shows consistently larger grain sizes in Control vs. Impact cores and statistical testing *via* one-way ANOVA shows median grain size (D_{50}) in the Control Core to be significantly larger against all others (p = 0.001). There are no clear differences between average D_{50} values deriving from 'open' (Cores 1 & 2) and 'closed' (Cores 3 & 4) drainage ditches.

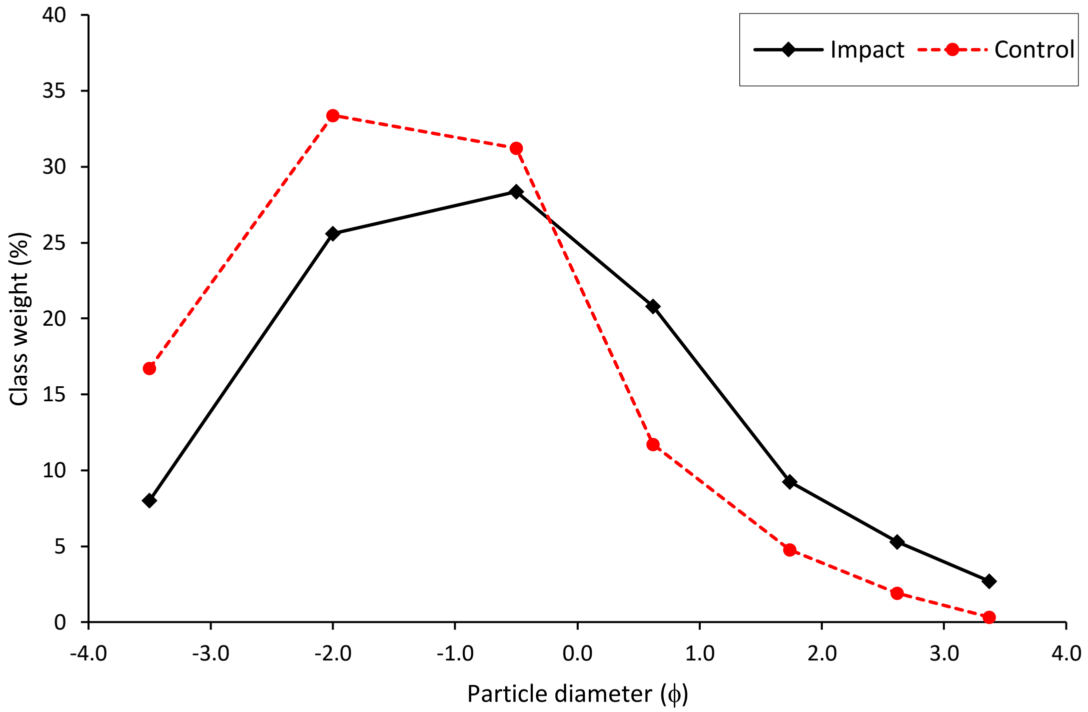

Figure 3.5: Size frequency distributions of sediment taken from Impact and Control cores.

Table 3.1: Descriptive summary statistics of each of the cores taken as part of this study. 'All (-C)' refers to all cores other than the Control Core and core 'C' = Control Core.

Core	Median (D_{50})	Wentworth (1922) descriptor	D_{10} (ϕ)	D_{84} (ϕ)	D_{90} (ϕ)
1	-1.18	Very fine gravel	-3.41	0.86	1.42
2	-0.65	Very coarse sand	-4.04	0.86	1.21
3	-0.31	Very coarse sand	-2.40	1.05	1.53
4	-1.14	Very fine gravel	-2.70	0.69	1.34
All (-C)	-0.89	Very coarse sand	-2.95	0.87	1.45
C	-1.47	Very fine gravel	-3.19	0.00	0.63

3.2.3 Folk and Ward (1957) Graphical Measures

Discrimination of sedimentary environments can also be attempted through analysis of relationships between sediment mean (M_G), sorting (standard deviation; σ_G), skewness (Sk_G) and kurtosis (K_G) characteristics. Table 3.2 summarises these characteristics from each of the cores and trends in data are difficult to identify, with Kruskal-Wallis tests (Kruskal and Wallis, 1952) showing no significant difference in σ_G values between cores. K_G values are similarly aligned, with the 'open' Core 2 exhibiting some deviation from both its 'closed' analogue (Core 1) and other samples, although Kruskal-Wallis testing (ibid.) again shows no significant differences. Finally, in contrast to σ_G and K_G values, Sk_G *is* significantly different among cores according to Kruskal-Wallis (p = <0.05) driven by large differences between Cores 3 and 4. Each of these parameters can also be more easily compared with each other when represented graphically using bivariate plots, shown in Figure 3.6.

Table 3.2: Mean, sorting, skewness and kurtosis values for each of the cores analysed in this Study. All mean values are in phi (ϕ). 'All' refers to all cores other than the Control Core and core 'C' = Control Core. Rounded to 3 significant figures.

Core	Mean (M_G)	Sorting (σ_G)	Skewness (Sk_G)	Kurtosis (K_G)	No. of samples
1	-1.07	1.86	0.0942	0.954	10
2	-0.999	1.63	0.0532	0.534	3
3	-0.416	1.52	-0.0454	0.929	5
4	-0.943	1.55	0.235	0.964	5
All (-C)	-0.861	1.78	0.0383	0.938	23
C	-1.45	1.43	0.0696	0.951	3

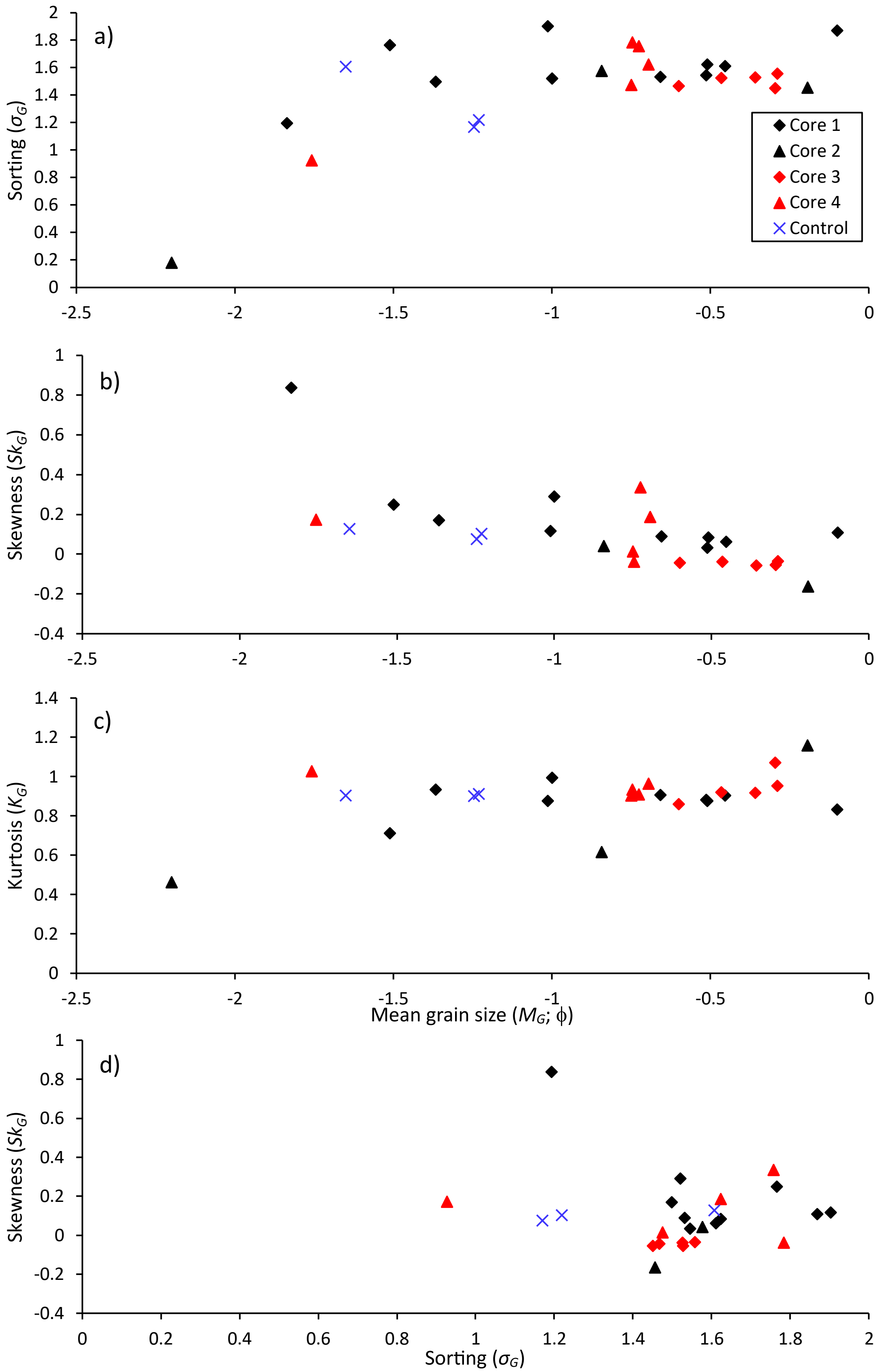

Figure 3.6: Bivariate plots of multivariate statistics from each of the sub-samples taken. Figures 3.6b and 3.6d omit sub-sample 2:1 due to the Sk_G *value being particularly high and thus distorting other data.*

Whole-core values in Table 3.2 are based on aggregate size fraction masses from respective cores entered into GRADISTAT (Blott and Pye, 2001) and thus there are differences between figures presented in Table 3.2 and the sub-sample (e.g. 1:1, 1:2 etc.) figures represented by Figure 3.6. Although Figure 3.6a shows no obvious clustering of sorting (σ_G) values based on whether or not they derive from an 'open' ditch and although there is substantial overlap across categories, there remain small signs of clustering in σ_G of Cores 3 and 4. The slightly higher *mean* σ_G computed based on each of the sub-samples is indicative of more poorly-sorted sediment in the 'open' ditches, although differences are weak.

Skewness (Sk_G), which is the sole graphical metric to show any statistically significant difference amongst cores, again exhibits substantial overlap between Control, 'open' and 'closed' sub-samples (Figure 3.6b). Regardless of the fact that the exceptionally high Sk_G value of 11.11 omitted from Figure 3.6b somewhat drags up overall Sk_G for 'closed' ditches, there are still suggestions of Sk_G from Cores 1 and 2 being generally higher than those from the Control and the 'open' Cores 3 and 4.

Next, Figure 3.6c shows a tighter vertical grouping of K_G among both Control and 'open' samples, with 12 of the 13 sub-samples across the categories being mesokurtic and thus suggestive of insignificant fluctuations in velocity that carry sediment. This is in contrast to the marginally lower and more dispersed K_G values in 'closed' cores, especially in Core 2, which may suggest a slightly higher range of velocity fluctuations that carry material at less time than normal.

No clear distinctions between 'open' and 'closed' ditch samples can be observed through Figure 3.6d (which again omits sub-sample 2:1). One point of difference among sample types is a reduced range of both σ_G (1.17-1.61) and Sk_G (0.075-0.127) deriving from the Control Core, with the Control average σ_G of 1.43 (Table 3.2) the lowest. The omitted sub-sample 2:1 produces by far the lowest σ_G value and the highest Sk_G value (11.11) and so implies good sorting and general lower energy depositional circumstances. The product of sediment deposition in the Tanllwyth, regardless of its origin or mechanisms of its deposition, are a series of drainage ditches that have at least partially filled with material to varying extents.

3.2.4 Bulk Density and Total Ditch Storage

Bulk density (BD) was established following the procedures elucidated in Chapters 2.2.1 and 2.2.2 and combines with ditch dimension measurements taken in the field to produce the results shown in Table 3.3. As there is a lack of data specific to the Control Core this is a comparison between 'closed' (Tubes 1 & 2) and 'open' (Tubes 3 & 4) ditches only. BD data are too limited to reliably perform statistical tests on and so although it cannot be said with certainty that there are differences between 'open' and 'closed' ditches, BD data in Table 3.3 appears to suggest lower BD in Tubes 1 and 2 compared with 3 and 4. These figures can be used alongside others to estimate the total sediment stored in the ditches by multiplying the total volume of material stored in them (itself the product of material depth, mean ditch width and ditch length) by their respective bulk densities. The ultimate product of these calculations is that estimates of mass of material stored in the different drainage ditches investigated ranges from 2.64 t m^{-3} (Tube/Core 2) to 14.84 t m^{-3} (Tube/Core 1) and that the ditches corresponding to Cores 1, 2, 3 and 4 have approximately 88%, 46%, 92% and 45% of their total volumes taken respectively, inevitably impacting their roles as conveyors of water.

Table 3.3: Bulk density (BD) summaries. Each Tube derives from corresponding Core locations (Figure 2.1). Rounded to 4 significant figures.

Tube	Vol. (cm^3)	Moisture content (%)	Dry BD (t m^{-3})	Material depth (m)	Ditch vol. (m^3)	Vol. of material (m^3)	Material stored in ditch (t m^{-3})
1	4797	121.7	0.112	1.0200	150.3	132.2	14.84
2	4665	99.84	0.05561	0.4600	103.4	47.56	2.645
3	2031	50.8	0.146	0.9700	86.52	79.93	11.65
4	3083	77.1	0.134	0.4900	103.6	46.58	6.248

3.3 Hydrogeomorphology

3.3.1 Hydrology

By using hourly hydrometeorological time-series data from Kirchner et al. (2021) that spans pre- and post-clearfelling (Figure 2.3a and Figure 2.3b) periods, and by comparing any changes with a non-clearfelled control catchment, it is possible to assess any changes to the nature of catchment (and drainage ditch) hydrology initiated by timber harvesting. Investigations into approximate catchment lag times (the difference in time between peak rainfall and peak discharge) found that the forested Tanllwyth and grassland Cyff catchments exhibit a rough lag time of three hours, and so by plotting Tanllwyth catchment precipitation against discharge offset by this time, relationships between rainfall and discharge (a proxy for how much moisture reaches the channel e.g. what is not prevented from reaching it by vegetation etc.) can be inferred. Proof of the effectiveness of offsetting discharge figures by three hours is demonstrated by initial linear relationships for the full time-series (April 1975 to December 2010 inclusive) having much poorer correlations in the Tanllwyth prior to offsetting (R^2 = 0.1863) than afterwards (R^2 = 0.4476). A similar response is stimulated by doing the same with data from the Cyff, whose R^2 value shifts from 0.3014 to 0.4556 before and after offsetting.

The relationships developed by using the offset precipitation-discharge data shown in Figure 3.7 can be further developed when considering the time periods of timber harvesting, and the ultimate influence on catchment hydrology can begin to be understood. As a substantial part of the Tanllwyth catchment was clearfelled in spring 1996-summer 1997 (Figure 2.1), the separate linear regression lines shown in Figure 3.7 reflect time periods before (01/04/1975-29/02/1996), during (01/03/1996-30/09/1997) and after (01/10/1997-31/12/2010) harvesting. Adjustments to regression line slope but especially R^2 values are minimal but do exist, with both the Tanllwyth (Figure 3.7a) and Cyff (Figure 3.7b) catchments seeing a slight eventual reduction in relationship strength between pre- and post-harvesting phases.

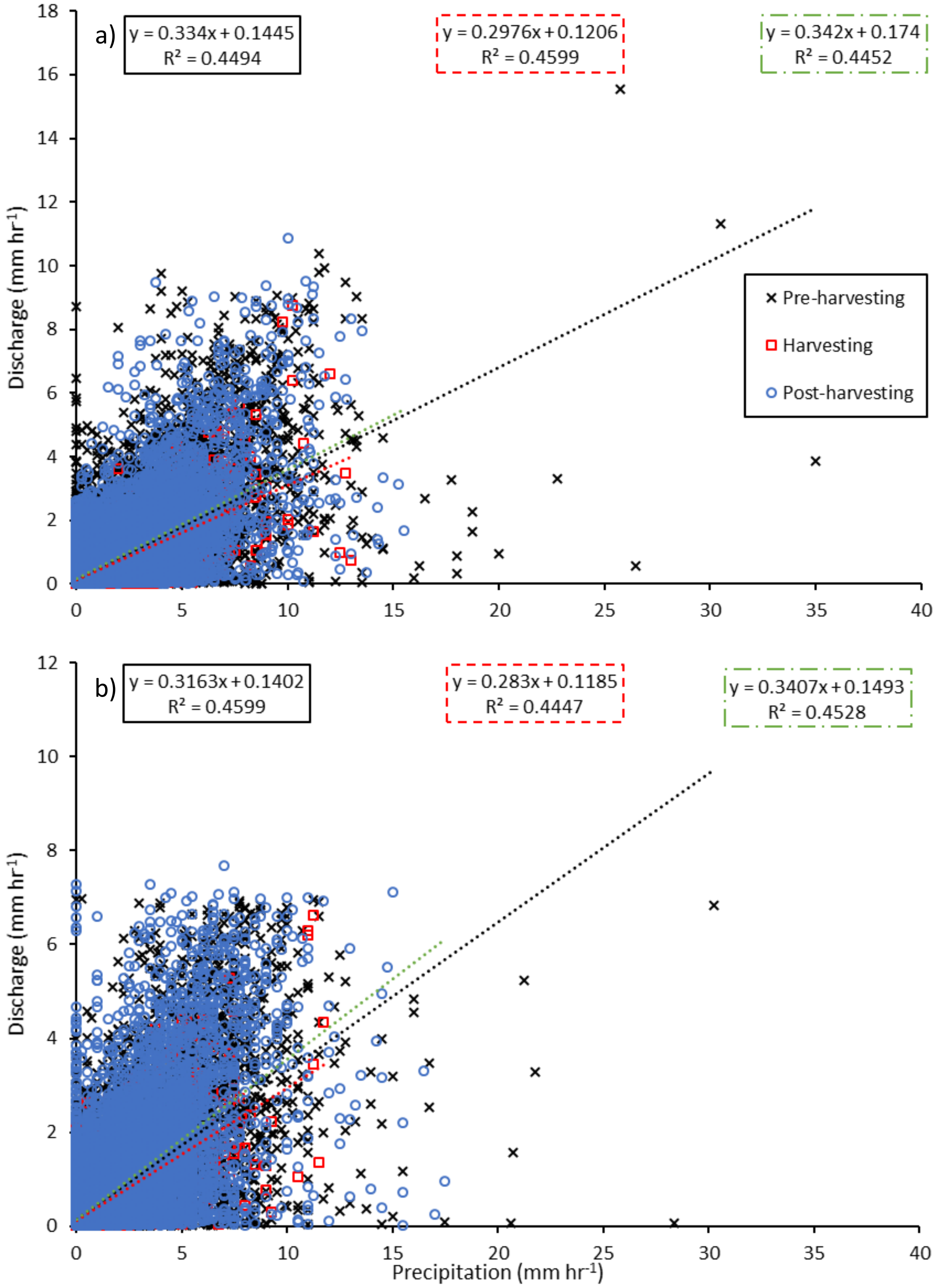

Figure 3.7: Precipitation-discharge plots of the Tanllwyth (a) and Cyff (b) catchments in pre-, during and post-clearfelling phases. Linear regression lines are coloured to reflect their respective slope and R^2 *equations which are shown from left to right in the order pre-, during, and post-harvesting and bordered to match their respective regression lines. Data from Kirchner et al. (2021).*

3.3.2 Ditch Flow and Bedload Entrainment

By using mean drainage ditch dimensions of 1.08 and 1.16 m width and depth respectively, estimated channel slope of 0.054 (Sawyer, 1999), velocity and sediment sizes from the 90th (D_{90}), 50th (D_{50}) and 10th (D_{10}) percentiles along with the maximum sediment size (D_{max}), approximations of likely bedload entrainment and associated discharges can be made. The results of these calculations – specific to the ditch from which Core 1 was taken only – explained in Chapter 2.2.3 are shown in table 3.4.

Almost 5 orders of magnitude separate the depth required to entrain the largest particle found within Core 1 (D_{max}; 9,180 mm) and to move D_{90} (0.1099 mm), with >3 orders of magnitude between depths needed to move D_{max} and D_{10} alone. Differences between levels needed to entrain D_{10} and D_{50} are comparatively much smaller, and differences transition from ~200% between D_{max} and D_{10} to 19.66% between D_{10} and D_{50}. Finally, the 5.785 mm needed to move D_{50} is over 50 times larger than the 0.1099 mm needed for D_{90}. Movement depths for D_{max}, D_{10} and D_{50} all translate to very similar gradients of difference in calculated discharge. The exception to this otherwise almost equal translation is the much larger 3 order-of-magnitude difference between discharges needed to move D_{50} and D_{90}.

Table 3.4: Estimated depth and discharge required to move sediment particles representing different percentiles. Bracketed figures following headings refer to the equations in Chapter 2.2.3 with which they were calculated. Values rounded to 4 significant figures.

	Particle size (mm)	Depth required to move particle (mm) (2.3)	Velocity (m s^{-1}) (2.2)	Discharge (m^3 s^{-1}) (2.1)
D_{max}	83.00	9,180	2.390	23.70
D_{10}	10.60	7.046	2.390	0.01819
D_{50}	2.270	5.785	2.390	0.01493
D_{90}	0.3747	0.1099	2.390	0.00003854

Based on the 35-year Tanllwyth hydrometeorological record (Kirchner et al., 2021), return periods for the flows in the right-most column of Table 3.4 vary substantially. The highest recorded hourly discharge for the Tanllwyth is 3.84 m^3 s^{-1}, making the return period of the estimated 23.70 m^3 s^{-1} needed to entrain D_{max} well over 35 years. Conversely, just 10 percentiles down the grain size distribution, there is a discharge capable of moving a 10.60 mm-sized grain (D_{10}) every 1.50 hours in the Tanllwyth. Next, D_{50} (2.27 mm) can be entrained at similar intervals, with the record suggesting it is moved every 78.6 minutes (1.31 hours). At no point in the 35-year time period investigated in this study has the Nant Tanllwyth discharge been recorded as being beneath the extremely low discharge associated with moving D_{90} and so it is likely to be stationary extremely rarely even in drainage ditches, if at all.

CHAPTER 4 – DISCUSSION

4.1 Objective 1: Ditch Soil Characteristics

4.1.1 Plastics

The discovery of plastics in three out of four non-Control Cores in assessing benthic sediment characteristics from each drainage ditch was unexpected. Although the topic of plastics is outside of the scope of this project and so will only be discussed briefly it is nevertheless an important one that warrants attention.

Whilst the prevalence and pervasiveness of plastics of all sizes in the marine (Andrady, 2017) and urban freshwater (Nel et al., 2018; Tibbetts et al., 2018) environments has been particularly intensively researched during recent years, there is a comparative paucity of research into the extent of its spread and associated consequences in remote, unurbanised upland environments. Each of the particles found in the Tanllwyth catchment (Figure 3.2) aligns with the 'fibre' group described by Helm (2017) which is in opposition to the trend of plastic fibre concentrations becoming generally larger with increasing levels of urbanisation (Tibbetts et al., 2018). Their presence in an area influenced by neither wastewater treatment works (an established source of plastic into freshwaters (ibid.; Murphy et al., 2016)) nor landfill sites from which plastics are prone to being windblown (Barnes et al., 2009) and in a rural location suggests that the likely source of them is the forestry activity that the catchment is primarily utilised for.

Many of the consequences of micro/mesoplastic presence in the environment for ecosystem and human (Mohamed Nor et al., 2021) health are as yet unknown, however the accidental discovery of them in the Tanllwyth setting – nearby the Clywedog Reservoir and so a likely place for ultimate deposition from other nearby streams flowing into it (Tibbetts et al., 2018) and also a source of drinking water and wildlife refuge – is a concern. Ingestion of microplastics by macroinvertebrates (Windsor et al., 2019), waterfowl (Gil-Delgado et al., 2017) and humans (Thompson et al., 2009) amongst other fauna has been identified, making more research into forest drainage ditches as conveyors of plastics into the food web and as influencers on ditch morphology all the more urgent. The Welsh upland environment would therefore benefit from reduced reliance on plastic fibres by forestry operators if indeed this is their source.

4.1.2 Organic Matter

A further way forestry practises have been found to leave physical legacies is through the ways in which they are navigated by the heavy plant machinery typically used for both harvesting and transporting timber from catchments. The decreasing representation of organic matter (OM) with depth suggested by Figure 3.4 may be a reflection of the relatively larger-sized, superficial woody debris shown in Figure 3.3a being deposited during forestry operations – as has previously been identified in the Tanllwyth catchment (Stott and Mount, 2004) – progressively breaking down and washing downstream as it does so. This phenomenon has been found to effect woody debris both deliberately put into channel networks (Krause et al., 2014) and done so unintentionally during forestry operations (Hyatt and Naiman, 2001); with conifer species such as the Sitka Spruce that dominates the Tanllwyth taking longer to break down than deciduous species (ibid.). Core OM figures ranging from 32%-82% *are* high, and range from >6 times to >53 times greater than pond sediment OM figures found by Verstraeten and Poesen (2001), and again may reflect an abundant source of OM in the form of forestry alongside a largely anoxic environment as long as water flows through ditches. Long-term dynamics of OM representation in ditch sediment in line with timber growth and harvesting phases could be measured by taking periodic samples and analysing them, and such a study would further enhance understanding.

Timber harvesting guidelines have evolved over the lifetime of the Plynlimon Catchment Experiment to latterly encourage movement of forestry machinery over only brashings in order to reduce suspended sediment yields and bank erosion (Forestry Commission, 2006; Stott et al., 2001), and from the composition analysis of these cores it is possible that these brash mats represent a source of the superficial woody debris long after cessation of harvesting operations along with the windrows they are eventually constructed into; a known source of nutrient export from peatland forests (Nieminen et al., 2014). The organic-rich layers of *Sphagnum* mosses on 'closed' ditches make the statistically insignificant reductions of OM percentages relative to ones without these layers initially surprising, however it may be that the layers act as a barrier against additions of brashings ever reaching ditch beds. As with use of plastic fibres in harvesting operations, a review of the use of brash mats and windrows could increase understanding of how sediment (organic or otherwise) is deposited into ditches.

4.1.3 Depositional Circumstances

As introduced in Chapter 3.2.3, inferences of the circumstances under which soils have been deposited can be made through analysis of Folk and Ward (1957) graphical measures illustrated by Figure 3.6. Clear demarcation between 'closed' and 'open' ditches for mean grain size (M_G) and standard deviation/sorting (σ_G) is largely absent in Figure 3.6a, however nine of the ten 'open' sub-samples do exhibit σ_G results within 0.33 standard deviations of each other and at higher overall σ_G (e.g. are worse sorted) compared with 'closed' ditches (Table 3.2). Poorer sorting of sediment in cores deriving from 'open' ditches is interesting, and suggests greater discrimination in sediment entrainment in the slower-flowing ditches (Greenwood, 1969) and could indicate relatively low responsiveness to precipitation in 'closed' ones. This is important because variable sediment entrainment dynamics could have implications related to if and how sediment is eroded in the first instance (Stott and Mount, 2004), moves through the catchment (Trimble, 2009) and ultimately enters reservoirs (Newson, 1980b).

Higher skewness (Sk_G) values indicate an excess of smaller particle sizes and thus lower frequency of high energy levels (Greenwood, 1969), and the generally higher Sk_G in Cores 1 and 2 (Figure 3.6b) could be a reflection of this and support the idea of comparatively reduced 'closed' ditch responsiveness to rainfall events and again could be a by-product of ditch 'sheltering' by *Sphagnum* layers. Similarly, kurtosis (K_G) is a reflector of how particle sizes are dispersed and marginally lower K_G values found in 'closed' ditches may reflect a somewhat higher range of water velocity variations that carry a greater range of sediment sizes (ibid.). In reality however K_G values are very similar among cores and so attributing impacts of forestry operations on how and when flows entrain sediment in ditches of different types is difficult, and the fact that each is either mesokurtic or platykurtic implies that grains are entrained under a variety of intermittent flows (Lapointe, 1992).

The lack of *clear* patterns in Folk and Ward (1957) graphical measures between cores and the fact that sub-samples almost exclusively share the same descriptors (e.g. poorly sorted, symmetrical, mesokurtic for σ_G, Sk_G and K_G respectively) does not give much distinction between ditch types and so inferences are made with caution. A future study would benefit from taking sediment samples of sufficient size to be analysed by a laser diffraction particle size analyser to encapsulate smaller grain diameters and thus better infer sediment origin and transport mechanisms.

In spite of the limitations of this analysis, it has nevertheless helped build a case for the likelihood of the forests themselves being sources of benthic ditch sediment, a phenomenon observed by Trimble (1981; 1997; 1999; 2009) and others (e.g. Stott et al., 2001) and the observable differences in particle sizes between Control and non-Control cores (Figure 3.5) suggests that ditch sediment is not composed solely of sediment from the immediate surroundings and may be the product of accelerated ditch erosion rates immediately after harvesting in the Tanllwyth found by Stott (1999; 2005; 2020). Additional research into the dynamics between drainage ditches and the landscapes they are connected to would further enhance understanding of sediment sources, with Newson (1980a; 1980b) identifying upland gullies and burst flushes as sources of bedload into the *Tanllwyth* channel, but not necessarily ditch channels.

4.2 Objective 2: Ditch Storage and Sedimentation

4.2.1 Bulk Density

Chapter 3.2.4 explains that the drainage ditches corresponding to Cores 1, 2, 3 and 4 (Figure 2.1) have around 88%, 46%, 92% and 45% of their respective capacities taken in terms of volume resulting from gradual aggradation. Chapter 3 also presents bulk densities (BD) of samples extracted from these ditches in Table 3.3, and the mean sample BD value of 0.11 t m^{-3} is, compared with other studies of fluvial sediment BD, low and may make it particularly susceptible to erosion (Jepsen et al., 1997). A mean sample D_{50} value of 1,820 μm (converted from phi) would not generally be associated with a BD of this level, with grains of this size being associated with BD of around >1.426 (Trask, 1931 in Verstraeten and Poesen, 2001) and 1.922 t m^{-3} (Hembree et al., 1952 in Verstraeten and Poesen, 2001). Similarly, a BD as low as 0.11 t m^{-3} may be expected to reflect submerged clays (Lara and Pemberton, 1963) rather than the 'very coarse sands' (Wentworth, 1922) found in this study; a reality reinforced by other research on fluvial sediment finding BD over an order of magnitude higher, including in forestry settings in Scotland by Stott (1997; 1.16, 1.04 t m^{-3}) and on Plynlimon itself by Stott et al. (2001; 1.1 t m^{-3}) and Newson (1980b; 0.9, 1.3 t m^{-3}).

This could mean two things: firstly, that samples taken were indeed not big enough and so soil size distributions are not reflective of reality and so larger samples should be taken, or secondly that the BD of Plynlimon benthic drainage ditch sediment truly is particularly low-density relative to grain size, possibly because of high organic matter percentages (e.g., Verstraeten and Poesen, 2001 found higher BD values, but from soils exhibiting between 6 and 53 times lower organic matter compositions than from this study), however this would require further research.

4.2.2 Ditch Storage and Catchment Sediment Yield

By taking the mean depth taken by material stored in the four measured ditches and multiplying this by mean ditch width and length, the average volume of material stored in each ditch is calculated as 74.66 m^3 and this multiplied by the circa 20 ditches in the Tanllwyth catchment (assuming each is of roughly equal mean length, width and depth) gives a rough figure for total sediment volume in the catchment ditches of >1,493 m^3. Finally, combining this volume with a mean bulk density (BD) of 0.11 t m^{-3} equates to a total stored mass of 167.14 t.

Newson (1980b) described how Tanllwyth drainage ditches rapidly eroded down to bedrock after their initial excavation in the 1930s (Appendix 2) before recovering once bedrock was reached and Stott (2005) commented on the fact that water in the ditches continued to flow directly over bedrock in 2001. The presence of sediment at ditch beds in 2024 therefore suggests that at some point during the past 23 years there has been a general switch in the catchment from one governed by erosion to one where aggradation is taking place. Using total stored mass of 167.14 t and dividing it by the years it can be said with confidence that ditches were down to bedrock (2001), mean annual sedimentation rate is computed as 7.27 t yr^{-1} and divided over the catchment area (0.89 km^2) after Van den Wall Bake (1986) annual sediment yield to ditches is 8.17 t km^{-2} yr^{-1}. This, alongside annual Tanllwyth catchment suspended sediment yield (SSY) and bedload yield of 11.8 t km^{-2} yr^{-1} and 38.4 t km^{-2} yr^{-1} respectively found by Moore and Newson (1986), suggests that ditch storage represents 16.27% of Tanllwyth sediment flux.

Mindful that ditch-stored sediment is by no means a perfect reflection of total catchment sediment yield, it nevertheless acts as a supplement to UK sediment yield data collated by Stott and Mount (2004) who found a potential for upland afforestation to increase downstream suspended sediment and bedload yields in the medium-term, although additional work by Mount et al. (2005) found the influence to be negligible. SSY and bedload has been found to rapidly increase immediately following timber harvesting (ibid.; Stott, 1999) before a gradual recovery once insulating canopies become re-established (Stott, 2005), and finally the 50 m deciduous riparian buffer strip adjacent to the Tanllwyth (also covering many of the ditches) was shown by Stott (2020) to significantly reduce SSY just three months post-harvesting when accounting for flow. Therefore it may be that the apparent erosion-aggradation switch in the catchment gradually took hold as the buffer strip established itself, with sediment previously carried by a more responsive water flow slowly deposited.

4.3 Objective 3: Timber Harvesting and Tanllwyth Hydrology

Figure 3.7 shows a shifting R^2 value for the forested Tanllwyth precipitation-discharge relationship from 0.4494 to 0.4599 (relative *increase*) during harvesting operations in conjunction with a change from 0.4599 to 0.4447 (relative *decrease*) in the grassland Cyff. Whilst these are only subtle apparent changes to catchment hydrological behaviour, it does suggest that clearfelling operations in the Tanllwyth does – at least temporarily – strengthen the link between rainfall and flow, and thus suggests that in harvesting the southern plot during 1996 (Figure 2.1) forestry operations increase catchment flashiness. Apparent reduction in relationship strength in the months and years after harvesting may be explained first by the re-colonisation of bankside vegetation afforded by increased light levels (Stott, 2005) and subsequently the establishment of softwood canopies by newly-planted trees.

Tree cover-runoff relationships are not straightforward, with different studies finding differential streamflow responses to changes to tree cover with individual responses not necessarily being attributable to trees (Pearce, 2021). Practical problems with statistical analysis of long time series' (Watson et al., 2001) further complicate the attribution of any hydrological changes to forestry operations and so too does the fact that contemporary harvesting techniques only focus on small plots and so do not affect the whole catchment (Forestry Commission, 2019), making demarcation of discrete harvesting periods for the whole catchment difficult. The inference of a temporarily stronger rainfall-discharge relationship immediately after harvesting is still a useful one, and there may be implications for future geomorphological development.

4.4 Objective 4: Future Ditch Geomorphological Development

This Chapter has sequentially addressed each of the first three Objectives outlined in Chapter 1.2.2, and explorations of Objectives 1, 2 and 3 have helped to build the foundations to be able to explore Objective 4. Findings related to organic matter in drainage ditches (Chapter 4.1.2), of sediment sorting dynamics (4.1.3), of low sediment bulk density and thus high erosivity (4.2.1), of gradual catchment sedimentation (4.2.2) and of temporarily altered catchment hydrological behaviour (4.3) combine to help infer possible future drainage ditch geomorphological development. Figure 4.1 provides a conceptual summary of the geomorphological development cycle of Tanllwyth drainage ditches that has been inferred from the analyses undertaken in this study, and the mechanisms of development that it illustrates are described here.

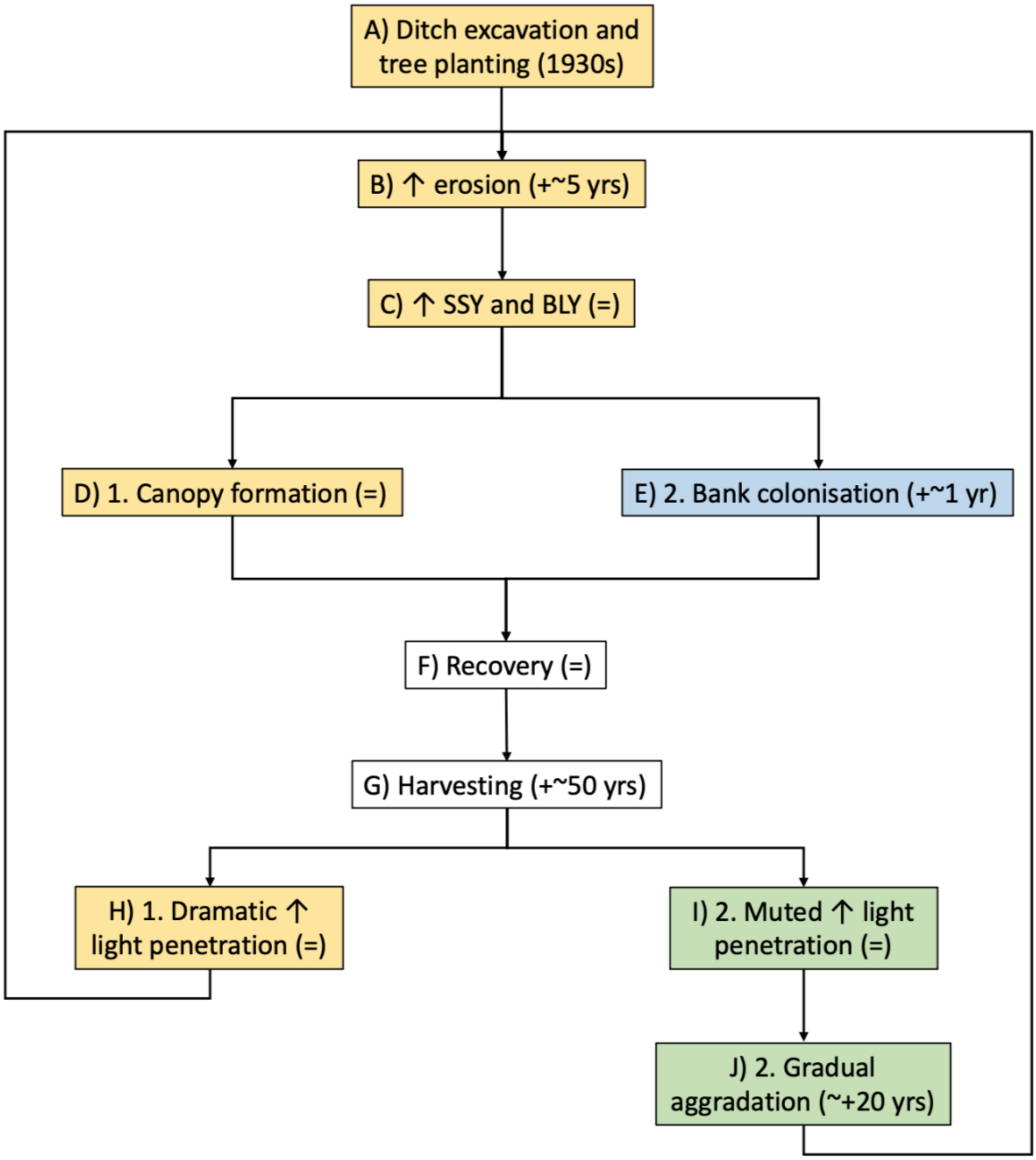

Figure 4.1: Conceptualised fluvial geomorphological development cycle of Tanllwyth drainage ditches. Yellow boxes = first harvesting cycle, pre-riparian buffer strip establishment; blue = second harvesting cycle and beyond, pre-riparian buffer strip establishment; green = second harvesting cycle and beyond, post-riparian buffer strip establishment; white = all harvesting cycles. Numbers 1 and 2 indicate forestry cycles. Values in years refer to rough timescales following the previous step, '=' indicates the same rough timescales as the previous step. 'SSY' = suspended sediment yield, 'BLY' = bed load yield.

Relatively high organic matter (OM) percentages found across sediment samples can be explained firstly by the peatland setting that the Tanllwyth catchment covers and also by the abundant supply of plant matter proximal to ditches, and stage A in Figure 4.1 acts to both disturb the peat-rich soils and establish the plantation and thus source of wood. Specific to the Tanllwyth catchment, rapid increases in rates of erosion resulting from ditch excavation and tree planting shown by Newson (1980b) (stage B) is concomitant with the increased suspended sediment and bedload yields found by Stott (1999; 2020), Stott et al. (2001) and Stott and Mount (2004) represented by stage C. Next, tree canopy closure in the first timber harvesting cycle (D) are associated with natural recoveries in erosion rates in Tanllwyth drainage ditches (F; Stott, 2005). Timber harvesting (G) some fifty years after canopy formation leads to dramatic increases in ground light penetration (H; Stott, 1999) and the beginning of ditch bank colonisation by vegetation in the second forestry cycle (E; Stott, 2005) but not before a return to tree planting, increased erosion, SSY and BLY (A, B and C). Stage F is revisited as erosion rates, SSY and BLY recover (this time through vegetation colonisation and not canopy closure) before harvesting (G), however the riparian buffer strip established during previous forestry cycles means that there is a less dramatic increase in ground light penetration following harvesting (I; Stott, 2020) and so increases in stream power and erosion are similarly less dramatic, meaning there is less sediment carrying capacity and some is therefore deposited (J).

By combining the findings of previous research on Plynlimon with more contemporary observations of the drainage ditches (explained in previous Chapters), the geomorphological sequence shown in Figure 4.1 can be enhanced by catchment hydrological data and estimates of grain entrainment capacities. The calculated discharges required to move particles of different sizes presented in Table 3.4 estimate that a grain/clast typical of those found in ditch bedrock (analogous to D_{max}) will very rarely be moved not only in Tanllwyth drainage ditches, but in the Nant Tanllwyth itself. This is in sharp contrast to the estimated return period of flows that may move D_{10}-sized particles, which occur roughly every 1.5 hours in the Nant Tanllwyth. The fact that these grains are easily moved in the Tanllwyth channel does not necessarily translate to the ease of their entrainment in its non-gauged ditches however, and considerably lower mean flows in ditches mean that return periods are likely far higher. Nevertheless, the relative regularity of flows capable of moving particles sized below D_{50} in the Tanllwyth probably means they are frequently moved in drainage ditches too albeit to a reduced extent.

Although the calculations performed for these analyses (Equations 1-3) bring with them inherent assumptions and other generalisations have been made (e.g. ditch slope, Manning's *n*) these data nevertheless demonstrate how it is perfectly possible for larger grain sizes to be readily deposited and very rarely entrained in the drainage ditches alongside frequent movement of smaller sediments. These dynamics combine to reflect what may be taking place in Tanllwyth drainage ditches, with high representation of (easily deposited) coarser sands and clasts at the expense of low fine-grain compositions; a trend which – especially with the establishment of the riparian buffer strip – may continue depending on catchment hydrological and forestry behaviour.

CHAPTER 5 – CONCLUSION AND RECOMMENDATIONS

The Plynlimon Catchment Experiment has provided a valuable foundation of paired catchment research that covers hydrological (e.g. Hudson and Gilman, 1993; Hudson et al., 1997; Shand et al., 2005) and geomorphological (e.g. Newson, 1976; Newson and Harrison, 1978; Sawyer, 1999; Stott, 2005; Stott, 2020) feedbacks relative to forestry and non-forestry related activities. Despite the rich vein of work that has been undertaken as part of the Experiment including catchment *erosional* response to timber harvesting, a paucity of longer-term investigations into any *aggradational* feedbacks exists and this represents an important gap. This study has aimed to help fill this gap by revisiting the Tanllwyth catchment on Plynlimon some 28 years after the first assessments of drainage ditch response to timber harvesting (Stott, 1999) and assessing ditch sediment characteristics, storage volumes and hydrometeorological behaviours.

This assessment has achieved its aim of gaining a more complete understanding of Tanllwyth drainage ditch soil characteristics and longer-term hydrogeomorphological development to a satisfactory extent. Although not an anticipated aspect of the research, the discovery and brief analysis of plastics in Tanllwyth soil samples nevertheless helped to better understand the impacts of forestry operations on the catchment. The dearth of investigations into plastic distributions across and impacts on unurbanised upland catchments would begin to be addressed by a study on Plynlimon more analogous to Tibbetts et al. (2018) that uses more thorough plastic separation and identification techniques.

A better understanding of both the sources of ditch sediment and the mechanisms for its transport has been gained from the analyses explained in Chapter 2.2, with high organic matter percentages – varying across ditch 'types' – possibly being a reflection of the forestry that characterises the Tanllwyth catchment. Material compositions have implications for their grain size distributions, and the sediment cores taken as part of this research has begun to inform possible sediment entrainment and deposition circumstances. The limited samples sizes extracted by the Russian corer did inhibit the ability to thoroughly assess grain size distributions however, and a future study would benefit from analysis larger samples to get a truer reflection and understanding of Tanllwyth ditch sediment transport dynamics.

Bulk density and characteristics of ditch dimensions also increase understanding of ditch sediment storage capacities and their roles in overall catchment sediment budgets. This aspect of the Study has ultimately given an improved picture of the roles of drainage ditches on Plynlimon as sediment stores, however revisiting the Tanllwyth catchment in a more navigable season (e.g. when vegetation levels are lower, assisting access) to more accurately measure drainage ditch lengths and quantities would increase accuracy of estimations.

Next, suggestions of changing rainfall-runoff relationships stimulated by timber harvesting activities are possibly shown by a long-term time-series dataset obtained from Kirchner et al. (2021), with apparent strengthening of relationships between precipitation and Tanllwyth (not drainage ditch specifically) discharge. Problems with spatial and temporal demarcation of plot-scale timber harvesting events and with statistical analysis of long time-series' (Pearce, 2021) mean that there is no real certainty of the extent to which harvesting activities do alter these relationships. Better understanding would thus be gained through knowledge of precise harvesting start and end times and exact harvesting plots. Further, monitoring ditch discharge specifically would an advantage.

Finally, Objective 4 (Chapter 1.2.2) has also been met to a satisfactory end, and the inferences of low-likelihood of coarse bedload entrainment within drainage ditches made by this Study cannot be ruled out. Although no clear reasons for the selective superficial colonisation by *Sphagnum* layers have been established, some differences in their behaviour have been found. This new research gap of ditch colonisation and reasons for it could be filled by more in-depth work looking at more ditches of different types and comparing their sediment, flow and geographical characteristics. Overall, this Study represents a starting block for the understanding of longer-term drainage ditch response to forestry activities in the Nant Tanllwyth catchment, and presents new ideas for addressing remaining knowledge gaps.

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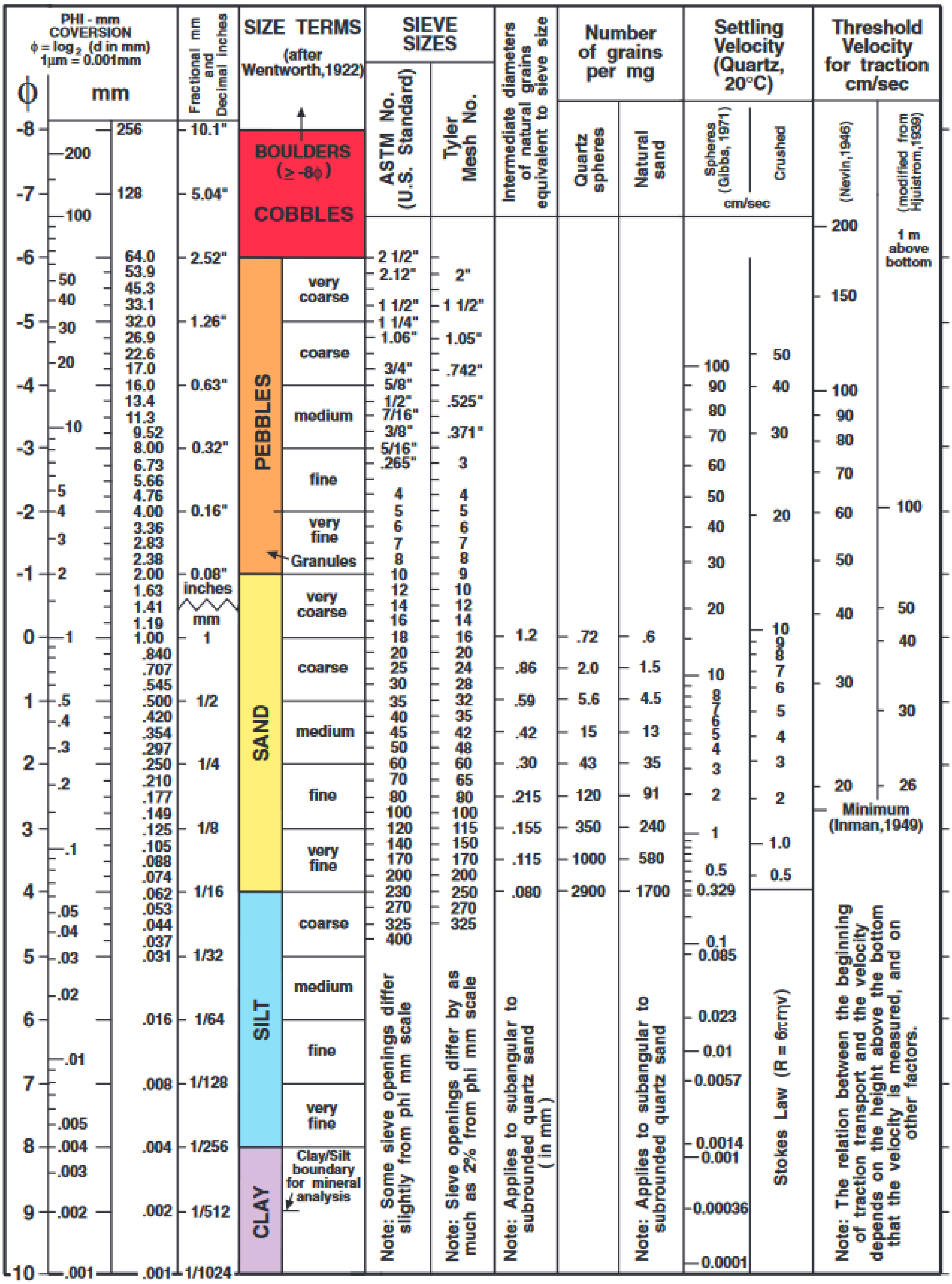
APPENDICES

Appendix 1: Modified version of the Wentworth (1922) Scale. Taken from United States Geological Survey (2020).



Appendix 2: Severely eroded drainage ditch in the Tanllwyth catchment. Taken from Newson (1980b).