The effect of soil bunds as Natural Flood Management features on soil water chemistry and hydraulic conductivity

JEREMY SEBASTIAN TEALE

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Abstract

Nature-based solutions to flooding have drawn growing attention in recent years as climate change models predict a significant increase to flood-risk in the UK and around the world. The lack of systematic empirical evidence to support Natural Flood Management (NFM) initiatives still presents a key barrier to the widespread implementation of NFM techniques.

Both rural and urban areas in the North Pennine Hills in Northeast England have historically been substantially affected by flooding. This study focused on a small-scale pilot installation of five earth bunds designed as temporary storage units for flood water in the upper catchment of the River Wear in Weardale. An upscaled installation of such features on a larger spatial scale may have a significant impact on reducing flood-risk by slowing down flood flows. To assess the effectiveness of the bunds, water sensors were installed in each of the five bunds to record the frequency of flood storage. Changes in soil hydraulic conductivity were measured throughout the study period (December 2021 to June 2022) to assess changes in infiltration capacity as a measure of bund construction quality. Finally, the chemistry of soil water was analysed through Inductively Coupled Plasma Mass Spectrometry (ICP-MS), to establish whether the bunds can act as filters for pollutants in a catchment suffering from heavy metal contamination with possible implications to water quality improvements.

Due to instrument malfunction, no data was recorded on the frequency with which the bunds acted as active storage features. No evidence was found for the bunds' ability to act as sinks for heavy metals, although the data are not conclusive. Hydraulic conductivity measurements found no variation across the five bunds, nor across different areas of each bund, suggesting the bund structure remains stable through time and does not vary in quality. Further research is required to corroborate these results, with more extensive sampling and over a longer time scale.

Department of Earth Science

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Statement of Copyright

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Dedication

To all the many actors in the world of natural flood management and the broader environmental industry. Especially the landowners who are willing to give up their land for research and for the protection of their local communities often with little or no compensation. Also, the contractors and labourers who are often the unsung heroes of environmental restoration but without whom our work would land in no more than drawings and plans. May all your efforts be recognised and our common goals for a fairer and more sustainable future be realised.

Chapter 1: Introduction and literature review

1.1 Introduction

In their natural state, river channels are in constant dynamic interchange with their surroundings, spreading across floodplains and fertilising the land to then shrink away in the summer months. The exploitation of water resources for agriculture, urban development, and industry has dramatically altered the functioning of hydraulic systems (Warner, 2012; Wilkinson et al., 2019). Despite modification however, rivers remain dynamic systems able to flood crops and cities during extreme weather events as shown by recent catastrophes around the world (Bartiko et al., 2019; Hu et al., 2019; Lim & Foo, 2022; Paprotny et al., 2018). In Europe, floods have caused the displacement of around 500,000 people and at least EUR 25 billion in insured economic losses since 2000 (EEA, 2018). In the UK alone, annual claims are approximately £735M, reaching an excess of £1.6Bn in the storms of 2013/14 (Environment Agency, 2022).

According to climate change predictions, flooding is expected to increase in frequency and severity in the UK (Blöschl et al., 2019; Miller & Hutchins, 2017; Watts et al., 2015). Average rainfall has not increased in Britain since records began, but seasonal patterns have changed to become more extreme (Jenkins et al., 2008). Clustering of heavy rainfall has been observed meaning that isolated intense rainfall events have become more frequent (Jones et al., 2013) especially for long duration events with direct implications to increased flood risk (Fowler & Kilsby, 2003). Combined with poorly planned expansion of urban centres onto floodplains over the last two centuries (O'Shea & Lewin, 2020), the result is an increase in flood-risk areas in the UK (Wheater, 2006). Development-induced factors that contribute to enhanced flood-risk are well documented. These include river channel modifications, the installation of impermeable surfaces, woodland clearance, and many other actions related to both urban and agricultural land development (Booth, 1991; Eshtawi et al., 2016; Hamdi et al., 2011; Hollis, 1975; Miller & Hutchins, 2017; Rubinato et al., 2019). A doubling of properties at risk of flooding has been reported in the UK from 2013 to 2017 (Environment Agency, 2022; Rubinato et al., 2019) with a predicted a 10% chance of a catastrophic flood (i.e. one causing £10Bn in damages) happening in the UK before 2030 (Krebs et al., 2014).

1.2 Flood mitigation policy in the UK: from Grey to Green

The UK's response to extreme weather events has historically been reactive in nature. Present management strategies in England are headed by the Environment Agency (EA) under The Department for Environment, Food and Rural Affairs (DEFRA). Typically, grey (i.e. hard engineered) infrastructure has been installed in the form of dams, dikes, and bypass channels to divert water away from vulnerable locations (Rubinato et al., 2019). Moving away from reactive to pre-emptive measures, in 2014 the UK government announced a six-year plan to invest £2.3Bn in capital towards preventive flood mitigation. The plan's central aim was to pre-empt long-term reparation costs of around £30Bn, offering 'better' protection from flooding to 300,000 households by 2021 (DEFRA, 2014). This scheme marked an important change on how flood-risk management is funded in the UK; previously, budgeting was assigned annually based on EA estimations of requirements. The implementation of a six-year strategy now allows the EA to be more efficient in planning and delivering flood mitigation projects. On completion of the 2014-2020 six-year period, DEFRA announced a doubling of the budget to £5.2Bn for the following six years building on the implementation of the previous investment scheme, which reportedly surpassed its targets (DEFRA, 2022). The updated policy statement estimates a reduction of 'up to' 11% in national flood risk by investing in around 2,000 schemes across the country, saving an approximated £32Bn in prevented economic damage by 2027 (DEFRA, 2020, 2021).

Notably, the 2021 plan now includes working with natural processes (WWNP) as a primary objective. This is part of a global push towards more sustainable flood management, which has gained popularity over the last two decades (Bridges et al., 2022; Butler & Parkinson, 1997; Environment Agency et al., 2017; Wilkinson et al., 2019). Working with natural processes and its derivatives are widely discussed in the literature under different nomenclature (Bridges et al., 2021; Wingfield et al., 2019). Natural Flood Management (NFM) has been chosen as a preferred term in this study; it was defined by DEFRA (Environment Agency et al., 2017) and paraphrased by Ellis et al.(2021) as: "protecting, restoring and emulating the natural hydrological and morphological processes, features and characteristics of catchments using environmentally sensitive and beneficial techniques to manage sources and flow pathways of flood waters". Appendix A presents a glossary of terms and definitions used across the literature encompassing NFM. The inclusion of NFM principles in the 2021

DEFRA investment plan is an improvement from the 2014 policy document, where increase to flood-risk due to climate change is only briefly recognised, and the notion of Natural Flood Management (NFM) is not considered at all. This move towards using sustainable and nature-based solutions is an important milestone that has been long in the making since the principle of Sustainable Drainage Systems (SuDS) was introduced in the early 1990s (Butler & Parkinson, 1997; Rubinato et al., 2019), and working with natural processes was proposed as a guiding principle by the EU in 2002 for coastal flood management (Cooper & Mckenna, 2008). SuDS are nature-inspired drainage systems that employ that employ a combination of grey and green infrastructure to reverse the effects of increased flood-risk in urbanised areas caused by the expansion of impermeable surfaces (Davis and Naumann, 2017). It could be argued that SuDS are distinct from NFM, however it is surprising that they are not mentioned in the 2014 flood prevention investment plan considering they were formally introduced to the National Planning Policy Network in 2012. Another important milestone was the 2004 document published by DEFRA on "Making space for water", which recognised the future dangers of climate change and the need for a holistic and sustainable approach to flood management with the added benefits of public amenity and wildlife conservation (DEFRA, 2004; Warner, 2012). The paradigm shift towards sustainable flood-risk management in Britain is discussed further in the following section and is broadly covered by the literature (Cook et al., 2016; Potter, 2012; McKenna Davis and Naumann, 2017; Rouillard et al., 2013; Waylen et al., 2018; Wilkinson et al., 2019).

1.3 NFM ongoing challenges and prospects

There are several reasons for the slow take-up of NFM and nature inspired solutions. The implementation of SuDS for example, is greatly hindered in countries with a prevalence of old infrastructure, where sustainable systems must be retrofitted, which presents extensive logistical difficulties (Lashford et al., 2019). 'Blue-green' infrastructure is being explored around the world as a solution to this problem. For example, green-roof installations that utilise existing roof-space for storm water storage have been suggested to significantly reduce localised flooding in cities (Basu et al., 2021; Costa et al., 2021; Masseroni & Cislaghi, 2016; Mora-Melià et al., 2018). The concept of 'sponge cities', which has been explored in Europe and China (Huang et al., 2020), is another example where improved flood water storage has been achieved through the efficient use of existing infrastructure (Lashford et al., 2019; Zeiser et al., 2022). A recent international study has suggested that a perception change that raises awareness of the broader environmental benefits of blue-green infrastructure is necessary to further encourage its acceptance and implementation (O'Donnell et al., 2021). Along this same vein, Kumar et al. (2021) propose the use of more holistic models in the assessment of NFM interventions, where further benefits to the environment and society are considered an integral part of their value.

Limitation to the funding and implementation of NFM schemes in the past decade can also be attributed to a lack of understanding and evidence of how NFM can be used efficiently and effectively to reduce flood-risk (Dadson et al., 2017; Waylen et al., 2018). In Britain, progress has been made on this front, with a £15M investment across the last 6-year cycle in testing NFM measures (DEFRA, 2021). Building upon this, the 2021 policy statement aims to double the number of government projects employing nature-based solutions. The plan states no dedicated budget for NFM, but it cites the government's £640M Nature for Climate Fund and £25M Nature Recovery Fund as a way of developing NFM solutions delivered through other environmental actions such as peat restoration and tree planting. Importantly, the wider benefits of NFM to water quality, wellbeing, and to the environment are recognised and highlighted in the 2021 policy statement (DEFRA, 2021). The 25-year UK government Environment Plan (2018) also references NFM in its capacity to deliver multiple benefits to society and the environment beyond flood mitigation if integrated with other strategies such as river and wetland restoration. While this is an encouraging prospect, there is a risk of funding priorities hindering NFM when made a 'secondary' goal expected to be covered by other environmental schemes as highlighted by Waylen et al. (2018) in their Scotland case study.

The lack of an empirical evidence base for the effectiveness of NFM is often cited as one of its limitations (Raška et al., 2022; Seddon et al., 2020). Efforts have been made across the world to collate what we do know from smaller scale projects so we can progress towards a new phase of experimentation at catchment scales. As part of the Flood and Coastal Erosion Risk Management Research and Development Programme of DEFRA, the EA published a series of documents on WWNP (Environment Agency et al., 2017). The WWNP initiative includes a collection of 65 case studies from around the UK where different approaches to NFM have been employed (Environment Agency et al., 2017). The Scottish Environment Protection

Agency have also published a manual on NFM guidance based on the work achieved in Scotland since the 2009 Flood Risk Management Act, which operated ahead of the rest of UK in NFM experimentation and implementation (SEPA, 2016). More recently, the U.S. Army Corps of Engineers published the 'International Guidelines for Flood Risk Management' as a product of a collaboration with practitioners and academics from the UK, the Netherlands, and around the world to bring together the state-of-the-art knowledge on NFM (Bridges et al., 2022). Wingfield et al. (2019) makes a good case on 'looking beyond the evidence debate' by capitalising on the multiple ecological and socio-economic benefits of NFM to deliver multi-stakeholder catchment scale interventions. While this is important progress, the evidence gap is something we must continue to work towards closing, and it is worth noting that NFM is not expected replace traditional hard engineering in flood mitigation (Dadson et al., 2017). Current research (Bridges et al., 2022; Y. Huang et al., 2020; Tiggeloven et al., 2022) and policy (DEFRA, 2021; SEPA, 2016) is instead leaning towards the integration of NFM alongside traditional flood mitigation, as hard engineering is also by itself an inadequate solution under current socioenvironmental pressures and the growing threat of climate change (Merz et al., 2010; Wheater, 2006).

Perhaps the greatest hurdle for NFM becoming fully integrated into 'mainstream' policy is the cultural resistance to a paradigm shift in flood management (Cook et al., 2016; Huq & Stubbings, 2015; Seddon et al., 2020). The prevalence of a 'modernist' mentality based around the control of nature, even if unconscious, presents a critical barrier to NFM integration, as nature-based solutions are judged within pre-existing conceptual and policy frameworks for flood management created under the norm of hard-engineered solutions (Harries & Penning-Rowsell, 2011). Furthermore, the coordination of resources required to successfully operate at a catchment scale poses a further difficulty, where good communication between stakeholders and land managers is of paramount importance (Holstead et al., 2017; Wells et al., 2020). Improving communication between the many actors involved in environmental work (policy makers, academics, landowners, practitioners, NGOs, contractors etc.) is a running theme in an industry that is nascent and rapidly growing, pushing the boundaries of science and practical experience beyond our 'comfort zone' (Waylen et al., 2018). In a recent review on the topic, Wingfield et al., (2021) cite institutional and social limitations as the most significant impediments to NFM uptake. Raška et al. (2022) have summarised the perceptions of experts from across Europe on the barriers of NFM citing the following as the most prevalent: a lack of financial incentives and political will in favour of NFM, a lack of institutional frameworks and designated responsibilities in NFM implementation, difficulties in acquiring land for NFM, and the need for a deeper understanding of the effects of particular NFM solutions.

1.4 NFM Strategies and further benefits: a brief summary

As a developing discipline, applications for NFM and the methods it employs vary greatly. Four broad approaches are recognised in the literature: water storage, increased infiltration, slowing the flow of water, and interrupting hydraulic conductivity (Cook et al., 2016; Ellis et al., 2021; Pescott & Wentworth, 2011). This classification varies between authors, but that discussion is beyond the scope of this project; for a more comprehensive review see Environment Agency et al., (2017). An important aspect of this classification is that it is based on the controls that exist in nature to determine how water behaves within a catchment (i.e. transport and storage times). It can therefore also be used to show how different development actions (e.g. industrialisation, urban expansion, land use change etc.) can affect flood risk differently.

Table 1 presents a non-exhaustive list of how different landscape hydrological controls may be related to different development actions, and what NFM mitigation strategies can be employed to counter these effects. The list of NFM strategies in Table 1 is by no means complete and it is worth noting that these factors are intricately related and seldom act in isolation. Table 2 presents a more comprehensive collection of NFM strategies together with their associated further benefits. Note however, that this list is also far from complete and is intended merely to provide examples from the literature on the multiple benefits that can be achieved alongside NFM. Ellis et al. (2021) provides a more detailed assessment on our current understanding of NFM, while encouraging continued research into its further benefits.

Table 1 . *Factors affecting flood risk in a catchment with examples of causes and existing NFM mitigation strategies.*

<table>
<tr><th colspan="2">Mechanisms for increased flood risk and proposed NFM mitigation strategies based on catchment functions[1]</th></tr>
<tr><td colspan="2">Infiltration and runoff
Infiltration is the absorption of water through the soil surface. When the infiltration capacity of soil is exceeded, water is transported overland through the landscape as runoff.</td></tr>
<tr><td>Mechanism for increased flood risk
Reduced infiltration capacity
Increased runoff
Faster runoff velocities</td><td>NFM mitigation
Increasing soil infiltration
Reducing runoff
Slowing runoff velocities</td></tr>
<tr><td>Causes:
-Creation of impermeable surfaces on the landscape (e.g. paving, concrete etc.).
-Land clearance for agriculture (e.g. loss of hedgerows and woodland).
-Loss of soil structure.</td><td>NFM strategies:
- Incorporating sustainable drainage systems to urban expansion (e.g. permeable paving solutions).
- Tree/shrub planting, leaky barrier installations (increasing surface roughness and increasing soil saturation capacity).
- Sustainable land management.</td></tr>
<tr><td colspan="2">Flood Water Storage
As runoff moves through the landscape, it is collected in storage areas such as ponds, lakes, and wetlands. Out of bank flows are also stored in the landscape when the capacity of a river channel is exceeded by flood flows and spills into the flood plain.</td></tr>
<tr><td>Mechanism for increased flood risk
Loss of flood storage areas</td><td>NFM mitigation
Creating flood storage areas</td></tr>
<tr><td>Causes:
- Urban expansion onto floodplains.
- Disconnection of watersheds to the floodplain (e.g. dredging).
- Land reclamation (loss of wetlands).</td><td>NFM strategies:
- Wetland creation and restoration.
- Creation of seasonal ponds (e.g. online earth bunds, scrapes etc.).
- River restoration: reconnecting rivers to the floodplain.</td></tr>
<tr><td colspan="2">Flow conveyance
The rate at which water travels through a catchment is critical to flood-risk. Land drainage and canalised watersheds improve hydraulic connectivity through the catchment, increasing the speed of water as it moves through the landscape</td></tr>
<tr><td>Mechanism for increased flood risk
Faster water transport times (higher peak-flows at ‘bottle neck’ locations)</td><td>NFM mitigation
Re-naturalising flood conveyance</td></tr>
<tr><td>Causes:
- River channel dredging and straightening.
- Agricultural drainage.
- Unregulated land-use change.</td><td>NFM strategies:
- River restoration: re-meandering, substrate restoration, woody debris installations etc.
- Restoring river margins to allow dynamic growth and retraction of watersheds.
- Sustainable agricultural practices: summer/winter crop rotations, landscape farming etc.</td></tr>
</table>

References: 1. Inspired by NFM strategies categorised by hydrological functions as first defined by Pescott & Wentworth, (2011).

Table 2 . *Natural Flood Management strategies and their multiple benefits with examples from the literature.*

NFM Strategy	Societal benefits	Environmental gain	Other benefits
River restoration: - **Re-meandering** - **Substrate restoration** - **Woody debris installation**	-Cultural significance (Anderson et al., 2019) - Ecosystem services (Basak et al., 2021)	- Habitat creation and biodiversity (Lo et al., 2021)	-Sediment regulation (Deane et al., 2021)
Wetland creation	-Green space creation, recreation, education (Mazzotta et al., 2019) -Economic and amenity gain (Richardson et al., 2022)	- Habitat creation and biodiversity gain (Casazza et al., 2021; Tickner et al., 2020)	- Nitrate regulation (Knudson, 2021) - Greenhouse gas emission mitigation (Bartolucci et al., 2021; Hagger et al., 2022)
Peatland restoration	- Welfare benefits and economic gain (Glenk & Martin-Ortega, 2018)	- Habitat creation and bioremediation (Bonn et al., 2016).	- Water quality improvement (Menberu et al., 2017) - Carbon sequestration (Goudarzi et al., 2021)
Sustainable land management: - **Cover crops** - **Afforestation** - **Urban planning**	- Multiple ecosystem services (Stammel et al., 2021) - Agricultural soil nutrient retention (Groffman et al., 1987)	- Pollinator support (Bryan et al., 2021) - Improved mycorrhizal networks (Galvez et al., 1995)	-Soil carbon storage (Kuo et al., 1997) - Improved soil and water quality (Dabney et al., 2007)
Temporary storage features		- Biodiversity gain (Old et al., 2018) -Sediment capture (Robotham et al., 2022)	- Water quality (Old et al., 2018) - Aquifer recharge (Short et al., 2019)

1.4.1 A global perspective on NFM implementation

The specific geography of different locations will determine what NFM strategies can be employed, and which hydrological controls should be targeted to reduce flood-risk. For example, the above classification does not apply to coastal flooding where NFM may take a different form as shown in maritime projects from the USA, the UK, and Vietnam (Pontee et al., 2016). It is also worth noting that the bulk of NFM research has been conducted predominantly in Europe, North America, and more recently China. This reminds us that the lessons learnt although applicable, may not necessarily be directly transferable to catchments around the globe where other societal and economic challenges may present important barriers to NFM (Lechner et al., 2020). Research on the restoration of mangrove forests for coastal flood alleviation in tropical countries, for example, has shown that a multi-criteria analysis is necessary when applying nature-based solutions. This is in order to maximise not only reduction in flood-risk, but also a more even distribution of benefits to the different economic sectors of society (Inácio et al., 2022; Tiggeloven, Buijs, et al., 2022; Tiggeloven, Mortensen, et al., 2022). Similarly, the use of nature-based solutions in sub-Saharan Africa may be of importance to target climate resilience in food and water security, involving the application of traditional practices in combination with 'Western' green-infrastructure technologies (Enu et al., 2022). The review and encouragement of NFM adaptations in countries and regions in the Global South is gaining relevance in the literature, which will hopefully spark the interest of policy makers to invest further into green infrastructure and lead to more extensive research (Contreras et al., 2022; Dhyani & Karki, 2018; Mukherjee et al., 2022; Opperman et al., 2021).

1.5 Study objectives and motivations

1.5.1 Identified research gaps

As discussed above, the evidence base for effectively employing NFM is still growing and in need of further research. There is a particular need for empirical evidence for NFM implementation and success, since a large portion of the existing literature is based on modelling rather than field experiments (Ellis et al., 2021). This bias in the existing body of research can partly be attributed to some of the issues described in section 1.3. Namely, the lack of political will (Cook et al., 2016) and the reluctance to move on from anthropocentric views of progress (Harries & Penning-Rosell, 2011). These factors limit the funding available for empirical investigations which are often more costly than theoretical modelling. The logistical aspects of organising such studies can also be a limitation, because committed collaboration is required of multiple stakeholders over several years (Holstead et al., 2017).

It is evident from review papers such as Dadson et al., (2017), Ellis et al., (2021), and Environment Agency et al., (2017), that NFM empirical research has broadly focused on tree planting, various aspects of river restoration (e.g. re-meandering, LWD installation etc.), wetland restoration, and leaky barrier installations. The study of earth bunds or temporary storage ponds as NFM features is largely neglected in the literature. This is in spite of successful examples of these features in the UK (e.g. Short et al., 2019 and Wilkinson et al., 2010), and of their advantage over other NFM interventions as solutions with a low impact on land use (see section 2.2 for a more in depth discussion).

In an ongoing study in Southern England, Robotham et al. (2022), discusses the use of earth bunds as sediment retention features. The bunds create settlement pools for runoff, collecting sediment before it enters adjacent streams. It is proposed that through a similar mechanism earth bunds may act as 'sinks' for heavy metals in a catchment contaminated with mine refuse material, with important possible applications for water quality improvement. At the time of writing, no other study has been found that examines the use of earth bunds as a means of capturing soil pollution. The motivation for the study of this MScR is to produce ground-based research on the use of earth bunds as a lesser studied technique in NFM interventions. This research will benefit the literature by expanding on our understanding of their effectiveness and exploring the additional benefits of these installations.

1.5.2 Research questions

This study is based on a pilot installation of five earth bunds in the North Pennines. The following research questions are designed to assess the bunds as NFM features on three different aspects: effectiveness, further benefits, and build quality.

1. Are the bunds working as expected to store flood water? If so, how regularly are the bunds acting as active storage?

The first of these questions is directed to assess the bunds in their capacity to perform as flood management features, which is their primary objective. By comparing weather data with data collected in our study, we aim to monitor if the bunds are effectively acting as active storage during storm events or not. The bund's design and mode of operation is described in Section 2.2 in more detail.

2. Are self-manufactured low-cost sensors a practicable solution to record how regularly the bunds act as active storage?

Purpose-built Arduino-based water sensors were designed and manufactured to monitor the capacity of the bunds to act as active storage (see Section 3.1 for details). The objective of this research question is to test the use and reliability of these low-cost sensors as a solution to allow the collection of data in a remote location with no access to a power supply.

Commented [TJS1]: New research question inserted to align better with work done.

3. Do the bunds offer any further benefits as NFM installations?

The third research question is intended to examine potential further benefits of the bunds beyond flood protection, as this is one of the main driving forces in favour of NFM implementation. As mentioned in the previous section, it is proposed that the bunds may act as sinks for metal pollution. By testing the chemistry of soil pore-water in and outside of the bunds, we will assess their ability to capture pollutants as a benefit secondary to flood storage.

4. Does the soil structure of the bunds change as they age and do they differ in build quality?

Finally, the fourth question is intended to assess the bund structures themselves. As further described in Section 2.2, the bunds were constructed at different times and by different people. By using the hydraulic conductivity of the soil as a measure of ground stability, we aim to find how the bunds change through time, and if they differ from each other based on build quality.

Further to the above questions, a secondary aim of this study is to encourage communication between practitioners and academics in the field of NFM, which is paramount in the integration of nature-based solutions to mainstream planning (Bark et al., 2021). To this end, the Environment Agency was involved from the conception of this investigation. Three meetings were held throughout the study period to consider the aspirations of the

Environment Agency and their concerns for the installations with the purpose of producing results that may be valuable to their own internal assessment of the bunds.

Chapter 2: Study Site

2.1 Historical context and project background

The study site is located in the North Pennines along a 1km length of the Middlehope Burn in Weardale, County Durham, England (Figure 1). The area surrounding Middlehope Burn has been heavily modified by mining and farming since the medieval period, although there is evidence for human influence dating back millennia (Mighall et al., 2004). The land was previously occupied by the Weardale Forest, which was progressively cleared and managed as part of a medieval deer park where agisted grazing took place on the lower reaches of the burn (Bowes, 1979). Along with much of the uplands in the UK, areas of Weardale were considered 'wastes', becoming enclosed in the 17th and 18th centuries and converted to rough pasture to increase the productivity of the area (Williams, 1970). This changed the topography of the land with ditching and wall building. The mines are known to have been operated at least from medieval times, hitting a peak in the 1800s with the mining of lead, iron, and later fluorite; the need for wood for tunnelling and the smelting of metals for the mining industry has been suggested to have decimated what remained of the forests of Weardale (Mighall et al., 2004). The peak in the mining industry also brought about a peak in population for the area (Bowes, 1979). The mine in the Middlehope valley operated downstream of the study area (Shaw, 1952), but old spoil heaps of refuse are spread across the fields as far up as the location of the features studied here. The site is best described as a patchy habitat of improved grassland used for sheep grazing all year round and cattle summer grazing. There are clumps of rushes (*Juncus sp.*) in the wetter areas where the land can become waterlogged for extended periods of time, but the area is mostly covered in rough pasture.

Historical flooding of the River Wear has been well recorded since the great flood of 1771 to have caused heavy losses to human lives as well as livestock and infrastructure along Weardale, with particular clustering around Stanhope and Wolsingham (Archer, 1987). Flood frequency and severity seems to have peaked in the 19th century, with decline in recorded floods throughout the 20th century (Wishart, 2004). As discussed above, however, climate change is predicted to bring about high intensity storm events across in northern England, which may result in a new increase to flood risk (Otto et al., 2018).

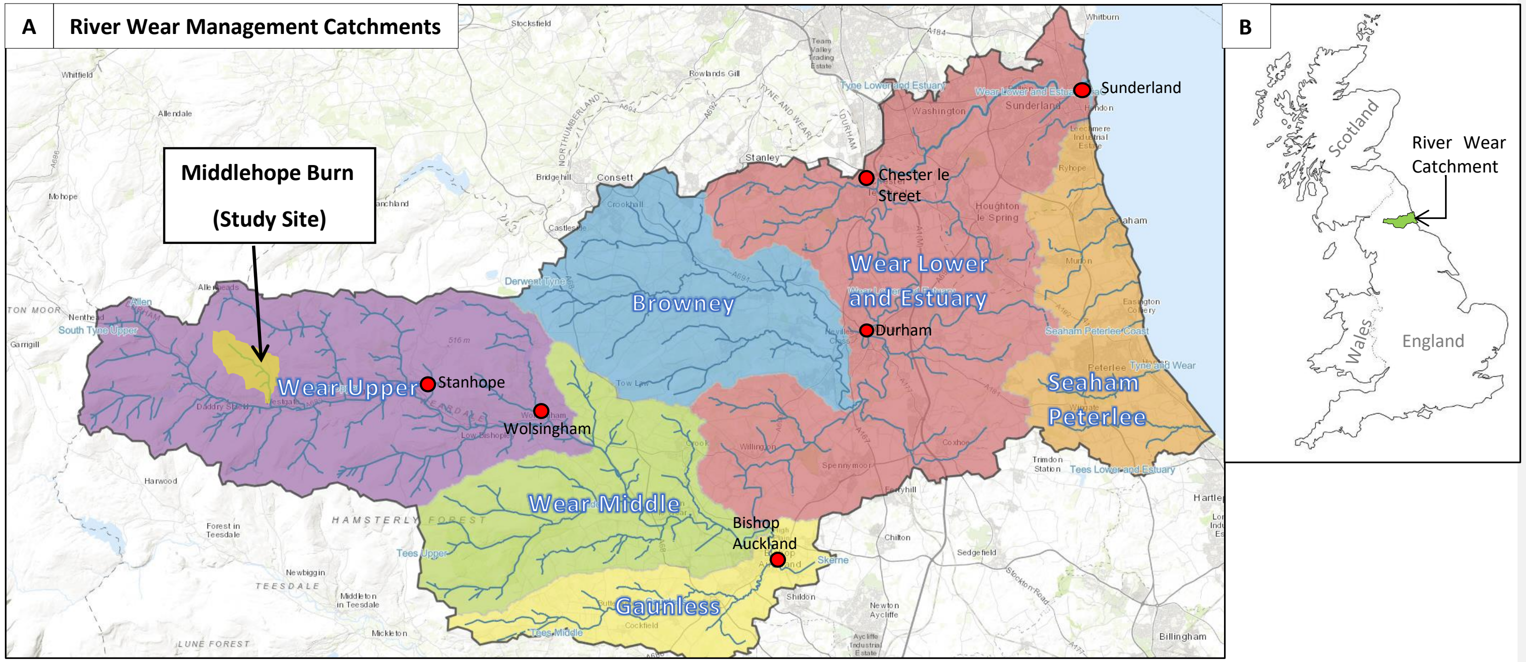


Figure 1. *(A) Catchment of the River Wear showing its operational sub-catchments: Wear Upper (purple), Wear Middle (green), Gaunless (yellow), Browney (blue), Wear Lower and Estuary (red), and Seaham Peterlee Coast (amber). (B) Overview map of Great Britain showing the location of the River Wear Catchment in Northeast England.*

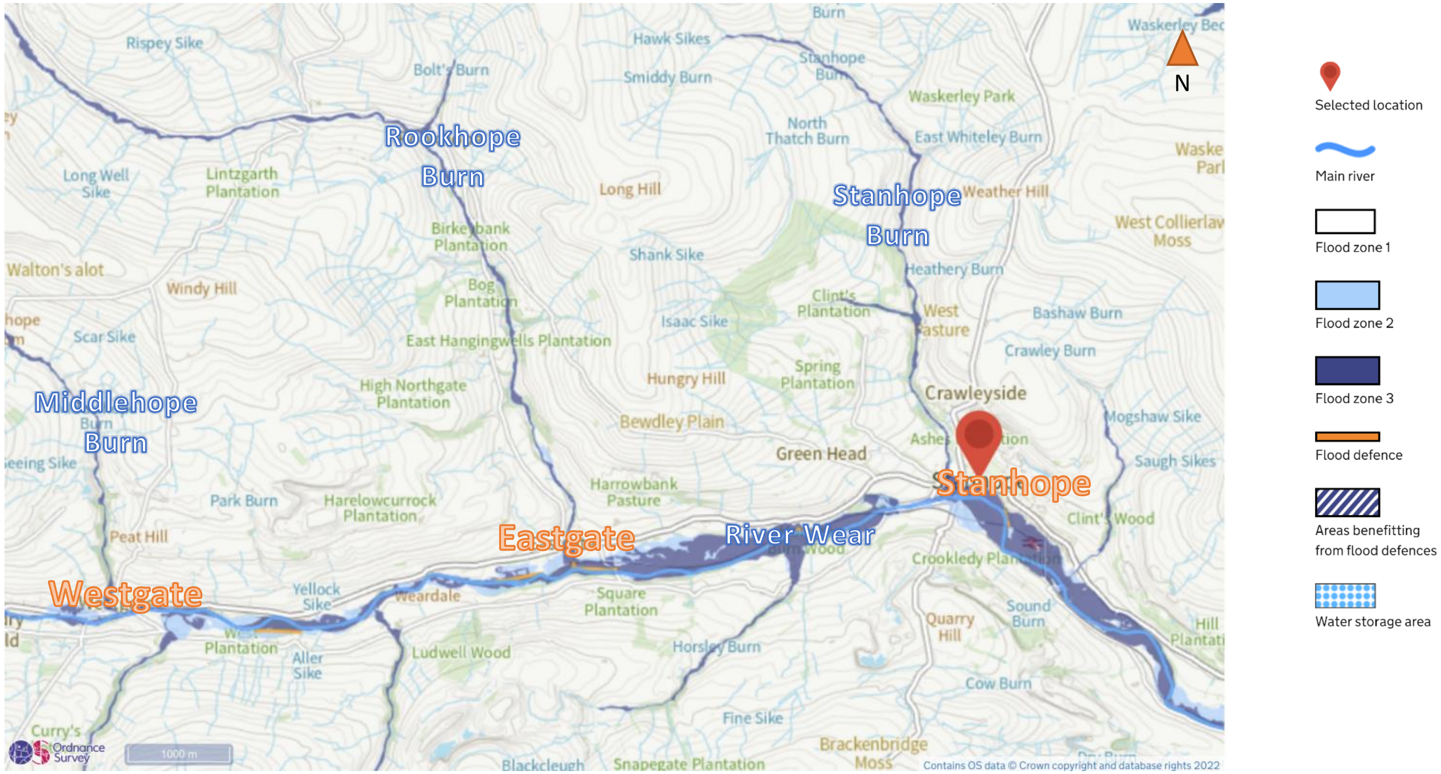


Figure 2. *'Flood map for planning' from Westgate where the Middlehope Burn feeds into the River Wear, to Stanhope, where flood defences have been insufficient in the past to alleviate flooding. Flood zones 1, 2, and 3 are considered to be at low, medium, or high risk of flooding respectively (taken from* Flood-map-for-planning.service.gov.uk, July 2022).

The latest Catchment Flood Management Plan for the River Wear states the various threats that exist across the catchment and proposes mitigating strategies. At present, 4,700 properties are considered to be at risk of flooding, including 40 essential infrastructure assets such as healthcare and power supply installations (Environment Agency, 2009). Weardale is identified as one of three areas in the catchment where flood alleviation is proposed through runoff reduction and increase of flood storage areas (Environment Agency, 2009) with specific focus to five tributaries of the Wear: Kilhope Burn, Ireshope Burn, Middlehope Burn, Rookhope Burn and Stanhope Burn. Within this sub-catchment (Wear-Upper), 73 residential properties and 87 non-residential properties are considered to be at risk of fluvial flooding (Figures 1 and 2). A further 170 properties are at risk between Stanhope and Wolsingham (JBA Consulting, 2020). As part of this greater picture, the EA started the trial installation of an NFM plan that covers a 41km^2 area of the 'Wear Upper' sub-catchment in 2019. With an investment of £2.1 million, the project involves a series of features including timber fences, leaky barriers, and the creation of storage areas (Figure 3). ARUP was commissioned to produce 'off the shelf' designs of these features that could be adapted and employed across the catchment, with modelling completed by JBA Consultants. This study focuses on a trial installation of flood storage features (impermeable earth bunds) along the head waters of Middlehope Burn intended as a pilot to alleviate the pressure on existing flood defences at Stanhope. Figure 2 shows the flood map of the burn where it meets the River Wear at Westgate.

Figure 3. *Example of a leaky barrier (left) and a timber fence (right) installed on the Killhope Burn in upper Weardale (Photograph taken from* Environment Agency et al., 2021*).*

2.2 Site description

The installation consists of five earth bunds constructed in the upper catchment of the Middlehope Burn, designed to act as temporary storage units. Figure 4 shows the locations of the earth bunds along the burn.

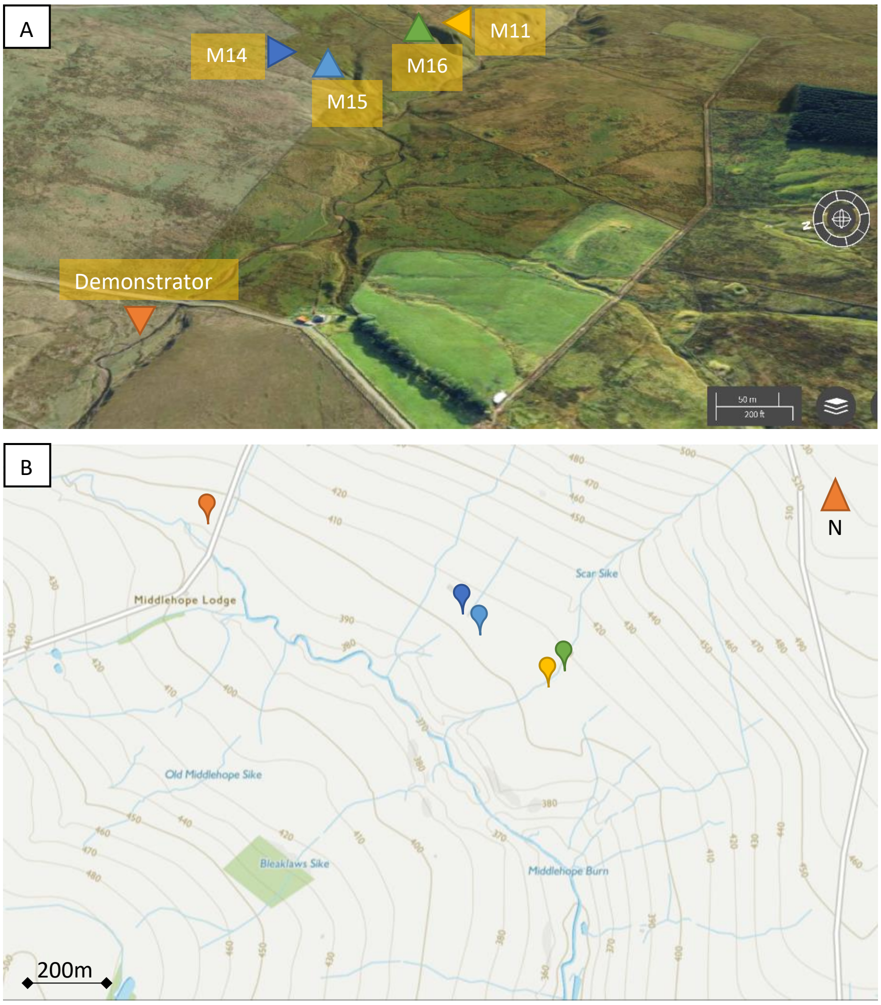


Figure 4. *(A) Aerial overview and (B) map view of the study area. Labels indicating the location of the storage bunds: Demonstrator site (orange), M14 (dark blue), M15 (light blue), M16 (green), and M11 (yellow).*

The bunds vary in size from ~260m^2 to ~750m^2 with an average height of around 1m, meaning they can roughly individually store between 299m^3 to 1,000m^3 of water (Table 3;Environment Agency, 2021). As relatively small storage units, the guiding principle behind this NFM technique is that if spread across the catchment, many of these bunds can act in concert to create enough storage capacity to have a significant impact in slowing down storm flows. For the system to function appropriately, the installations must be in selected key locations where storage during storm flows may be maximised. In this instance, modelling of the topography of the area was conducted by JBA consultants to determine the most appropriate bund locations, and the EA liaised with the landowner to gather their experience and local knowledge of the land. The location of the bunds was then determined by combining these two approaches. A post-construction review of the project is on-going, to assess the bunds functionality and gain insight for future installations. A further four bunds are intended for installation on the Middlehope Burn, with a total potential capacity of 5,150m^3 of water storage (Environment Agency, 2021).

Table 3. *Summary of estimated bund area, storage capacity, and location.*

BUND	AREA	ESTIMATED STORAGE CAPACITY	LOCATION COORDINATES
M11	740m^2	884m^3	54°45'32.0"N 2°09'01.1"W
M14	260m^2	299m^3	54°45'38.5"N 2°09'11.9"W
M15	340m^2	430m^3	54°45'36.4"N 2°09'10.1"W
M16	300m^2	372m^3	54°45'32.6"N 2°08'56.7"W
DEMONSTRATOR	700m^2	1,000m^3	54°45'45.7"N 2°09'49.7"W
TOTAL	2,340m^2	2,985 m^3	

2.2.1 Site considerations to the suitability of earth bunds

As mentioned in Section 2.1, this installation is one of multiple pilot projects conducted by the EA in conjunction with the Wear Rivers Trust. A central reason for employing this particular NFM technique in this site is the low impact of the installation. Other NFM techniques such as tree planting and land-use change require a major commitment from the landowner to renounce to areas of their land. Depending on the specific technique, this commitment may need to extend over many years or may even be permanent. In the case of the bunds, the area covered by the structures is fenced off and therefore excluded from grazing for several months, but once the structures have been fully revegetated, normal gazing practices can resume.

A potential drawback to this type of installation is that a large number of them acting in together is required, for features to significantly reduce flood peaks downstream. This can make installation costly and can potentially generate more disturbance to farmers and grazing regimes. Additionally, the grazing quality of the storage area within the bunds may deteriorate if it remains wet for much of the year. However, adequate adjustable drainage can be installed to ensure the bunds only store water during storm flows. In this instance, the nature of the soil and weather patterns of the catchment mean that much of the area is often waterlogged regardless of the presence of the bunds. For this reason, the wetter areas of the fields were chosen for the installation of the bunds as natural low spots are likely to encourage the bunds to function appropriately; this means that no previously 'dry' areas have now become more prone to being waterlogged.

2.2.2 Demonstrator Site

The demonstrator site was the first feature to be built in the area. It was completed by the EA in 2019 to show landowners what the earth bunds would look like and encourage willingness to allow further installations. The work was carried out by a professional contractor under direction from the EA. The diagram below (Figure 5) shows the placement and intended functioning of the bund.

The bund is an online feature, connected directly to the stream via an overflow channel. During flood flows, the stream spills into the bund which acts as a storage area. The design allows for a controlled ingress and egress of water set by graded sluice gates at either end. The outflow pipe of the bund is set to 300mm, meaning that the bund begins to function (i.e. to store water) when the inflow exceeds the capacity of the outflow pipe. The outflow pipe releases water back into the stream at a rate determined by adjusting the sluice gates fitted at the ingress of water or those fitted at the outflow pipe. The bund is thus not intended for long term storage, but to act as a control point where flood water is slowed down. The other four bunds follow a slightly different design and were installed by the landowners themselves, not by professional contractors.

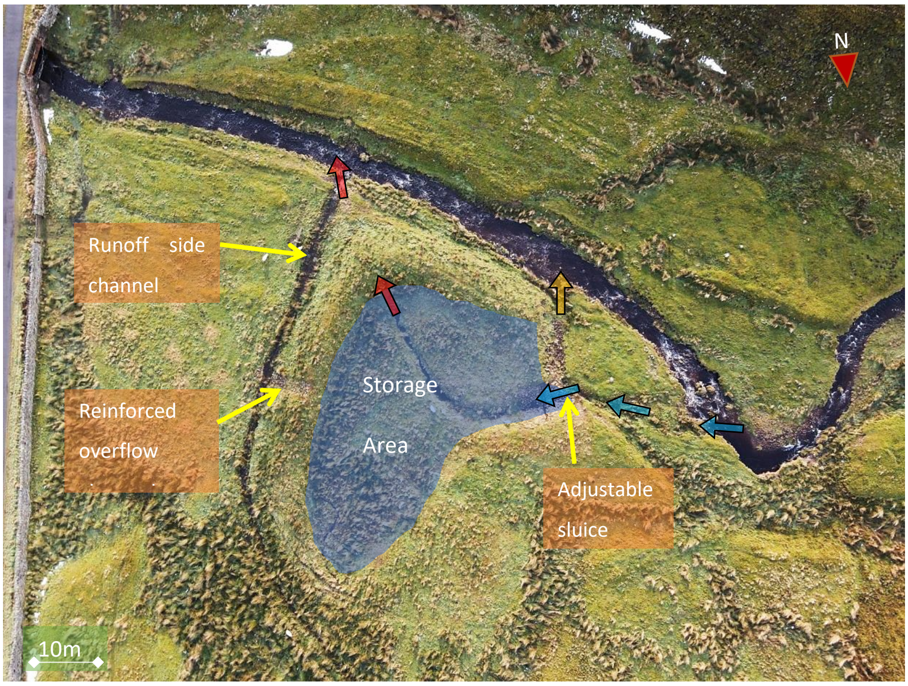


Figure 5. *Diagram of bund function: The stream overflow channel indicated by the blue arrows feeds the storage area (shaded in blue) during storm flows. Flows that exceed the ingress capacity of the bund are redirected back into the stream via the channel marked by the yellow arrow. The bund is slowly drained via the outflow pipe indicated by the red arrows. A reinforced overflow channel is set just below the top hight of the bund in case the capacity of the outflow pipe is exceeded to manage and localise erosion of the structure (Note: Demonstrator bund show; see Fig.4 for location).*

2.2.3 Bund M14

Bund M14 was installed in May 2021 by the landowner. It is located approximately 700m downstream of the demonstrator site, but not directly adjacent to the Burn. It is located ~250m uphill of the stream on the eastern valley slope, on a small seasonal tributary ditch to the Middlehope Burn. This bund is intended to capture runoff from the hillslope as it gathers into this minor stream before it feeds the Middlehope Burn. Figure 6 shows an aerial view of the bund and the drainage ditch that it is intended to intercept. This ditch existed prior to the bund installation and the bund design was adapted to fit this arrangement. A drainage pipe has been installed going down from the ditch, under the wall and into the bund's storage area. A dug channel follows from the pipe to feed the bund's outflow pipe, set with the soffit at ground level. This outflow pipe goes directly under the bund to discharge at the other side. A second outflow pipe is located within the bund with its invert set at ground level. This second pipe only becomes activated when flood flows exceed the level of the first pipe. Unlike the demonstrator site, the pipes have not been fitted with adjustable sluices.

Figure 6. *Aerial view of bund M14 (see Fig.4 for location). As shown, a secondary drainage ditch (indicated by the red arrows) runs parallel to the wall collecting further runoff from the field and discharging it into the main ditch (marked by the blue arrow).*

2.2.4 Bund M15

Bund M15 (Figure 7) was installed together with M14 in 2021 by the landowner. Similar to M14, this bund is intended to capture water from runoff, but unlike M14, it lacks a formalised ingress channel. This bund is located 50m Southwest of M14 and about 240m uphill from the Middlehope Burn. Three land drainage pipes were uncovered during the installation. These were directed towards the newly installed outlet pipe of the bund to avoid permanently wet patches (which can negatively affect grazing) in the storage area. Nonetheless, the area was observed to be wet throughout a large part of the year

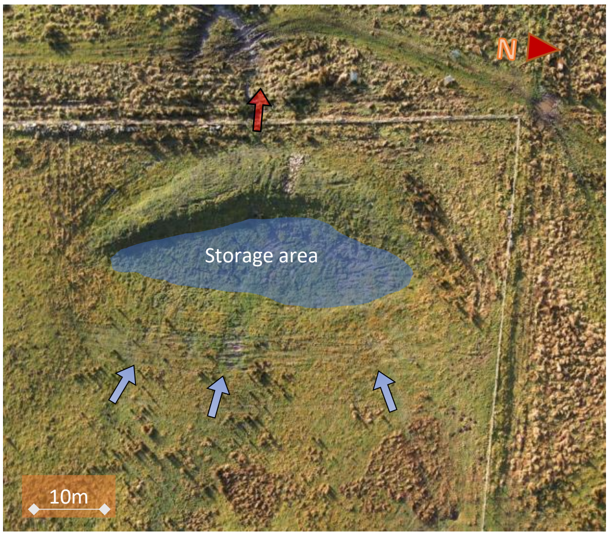


Figure 7. *Aerial view of Bund M15 (see Fig.4 for location). The bund lacks a formalised ingress channel, but is placed to collect direct runoff from the field (Blue arrows). The red arrow indicates the bund outflow to a pre-existing drainage ditch.*

2.2.5 Bund M16

M16 (Figure 8) has a set-up similar to M14 fed from a small tributary of the Middlehope Burn via a drainage ditch. It is located 200m Southeast of M15 and 330m uphill from the Middlehope Burn (also on the eastern slope of the valley). This bund was installed in March 2021 also by the landowner. The system is fed by a drainage ditch at the ingress and has its outlet via a 300mm pipe.

2.2.6 Bund M11

M11 (Figure 8) is placed directly downhill from M16 to receive the outflow. In this way, it acts as a second point where water can be retained and slowed as it feeds into the Middlehope Burn. This bund was the first to be constructed by the landowner in March 2021.

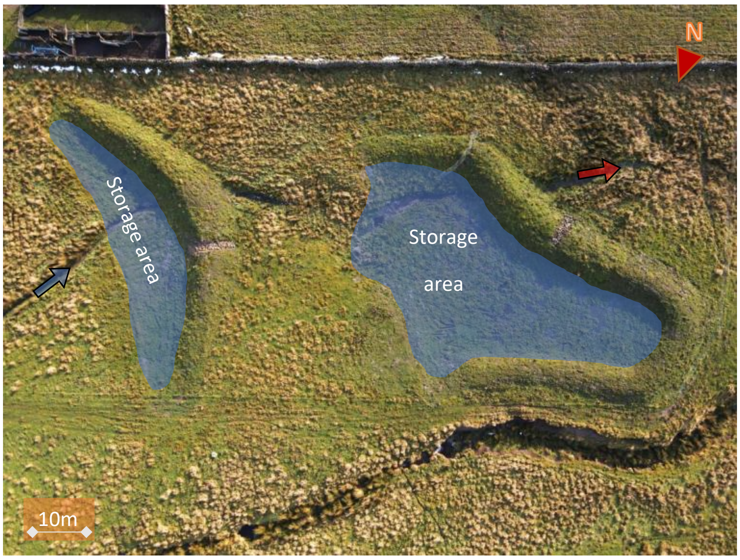


Figure 8. *Aerial view of Bunds M16 (left) and M11 (right) (see Fig.4 for location). The inflow via a drainage ditch is indicated by the blue arrow, and the outflow is indicated by the red arrow.*

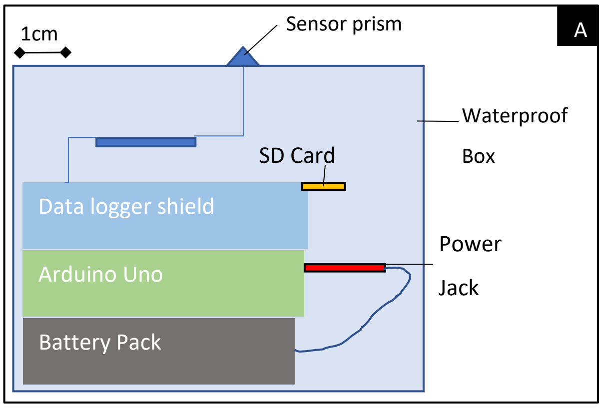
Chapter 3: Methods

3.1 Water storage - Arduino sensors

Five Arduino-based (open-source hardware) water sensors were designed and constructed to record the regularity at which the bunds acted as active storage features (See Appendix B for full list of components). The design is a simplified version of that described by Assendelft and Meerveld (2019). As shown in Figure 9, the instruments consist of an Arduino Uno mounted with a data logger shield that records readings from the digital photoelectric liquid sensor every 15 minutes. All this was encased in an IP65 rated water-resistant box, with the prism of the sensor exposed to the surface. Through changes in light diffraction, the sensor is able to detect if it comes into contact with a liquid, reporting in binary format contact (1) or no contact (0) (i.e. presence or absence of water).

The instruments were tested individually to ensure correct operation and reliability before installation onsite. Testing consisted of two stages. First, each Arduino, powered by a 6V lithium cell battery pack, was programmed to record at 3 second intervals and tested for functionality by randomly dipping the sensor prism into a container with water; second the sensors were set into the boxes and the box was semi submerged to allow the sensor to come into contact with the water and tested for 1 minute, 3 minutes, and then the target 15 minute interval recordings. See Appendix B for detail of the code used to record the data with the sensor and store it in the SD card mounted on the data logger shield.

Two of the instruments were then installed in the field to test the devices in field conditions and for an extended period of time at 15-minute recordings. One day following installation, a preliminary check of the sensors was carried out on site to assess if the Arduino devices were performing as expected in the field. The remaining instruments were installed the following week. Thereafter, the instruments were intended to be checked once a month to extract the data for processing and reinstalled for continued monitoring.



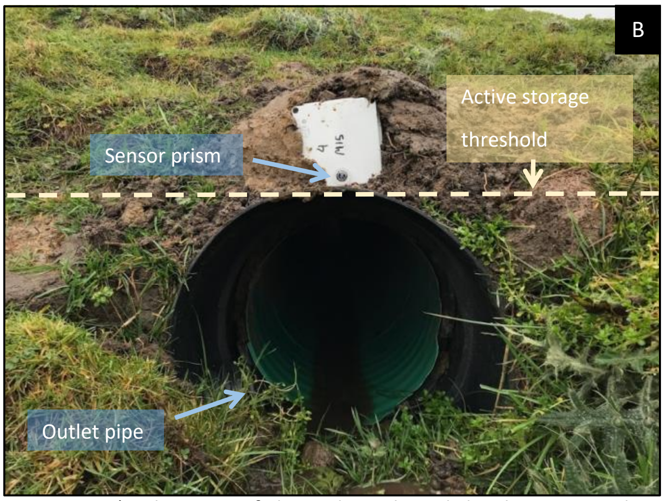


Figure 9. *A) Schematic of the Arduino-based dataloggers used to measure the presence of water in the bunds. B) Arduino data logger as installed on site***.**

The sensors were placed directly above the outlet pipe in each bund (Figure 9), meaning that they would only take positive readings when the capacity of the pipe was exceeded, and water level rose to the height of the sensor (i.e. when the bunds began to act as active storage). The data loggers were also fitted with an inbuilt real time clock that stamped each reading with the precise date and time it was taken, allowing a comparison of readings with weather patterns.

3.2 Soil chemistry and water quality - Suction lysimeters

The chemistry of the soil water was assessed in the Demonstrator site and bund M11. The demonstrator site was built two years prior to M11, allowing a comparison of possible changes to soil chemistry associated with time and the presence of a bund (e.g. the bunds acting as sinks for filtered heavy metals carried by runoff from nearby spoil-heaps). Suction lysimeters of 30cm and 60cm (MMM Tech Support, 2022; SKU: Lys-30 and Lys-60) were used to assess the chemistry of the soil at different depths. A total of six lysimeters were deployed in bund M11: a paired-set of two lysimeters in the bund storage area (labelled as M11-A and M11-B fitted to 30cm and 60cm respectively), and a second paired-set outside of the bund (M11-E and M11-F also at 30cm and 60cm). A replica control-installation was intended for the Demonstrator site, with one paired-set inside the bund and a second set outside. However, the 60cm lysimeters could not be installed at the demonstrator site due to an impenetrable layer of rock deposits found approximately 40cm beneath the surface (The layer of rock is evident in the eroded bank-face of the adjacent stream as shown in Figure 10). The 30cm lysimeters were nevertheless installed at the demonstrator site, one inside of the bund (Dem-A) and one directly outside (Dem-B). The two spare 60cm lysimeters that could not be installed at the demonstrator site were instead placed between the paired set-ups of bund M11 in a 30m transect as shown in Figure 11 (M11-C and M11-D). These additional transect lysimeters were designed to assess any potential gradient across the storage area of the bund, on the bund itself and to the outside of the bund.

Figure 10. *Eroded bank-face of the Middlehope burn adjacent to the demonstrator site.*

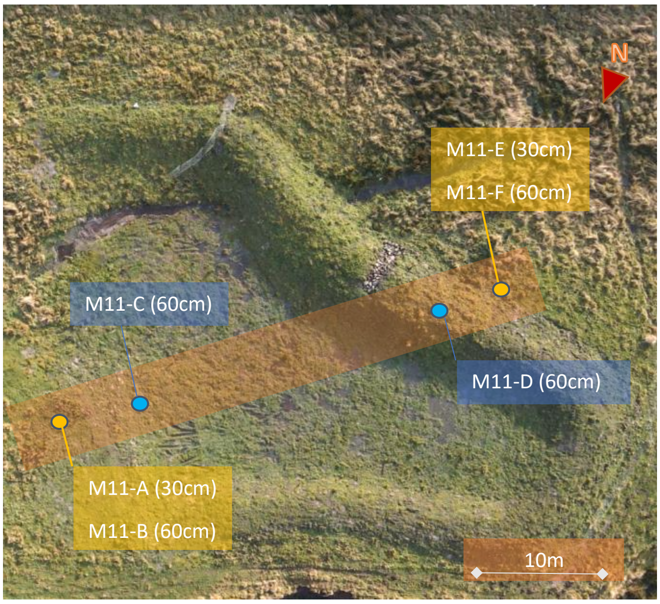


Figure 11. *M11 Lysimeter transect (orange box). The yellow dots indicate 30cm and 60cm lysimeter set-ups. The blue dots indicate 60cm lysimeter set-ups. Demonstrator site and from the Side Stream adjacent to bund M11 and M16 on the first collection in March, and again in April.*

The experimental design consisted of four field campaigns to collect soil water samples from the eight lysimeters across the four seasons: late Autumn 2021, Winter 2022, Spring 2022, and Summer 2022. Due to an extended delay on the delivery of the lysimeters, the instruments were not installed in the field until late January 2022. Installation consisted of drilling a hole in the ground with a hand auger to the required depth (either 30cm or 60cm), whilst keeping the removed soil in a plastic measuring jug. The lysimeters were then slotted into the holes, and packed-in with the soil taken in the previous step. Where necessary, the soil was mixed-in with water from the stream to make it easier to fill the area around the lysimeter and make sure it was packed in tightly (the circumference of the auger was slightly bigger than the lysimeters). The installed lysimeters were then left to rest for a month before extraction to allow the soil to compact around them and re-create conditions as close to 'undisturbed' soil as possible.

For sample extraction, first the lysimeters must be emptied to avoid rainwater contamination. A vacuum of 60-80 centibars is then applied to each lysimeter (as per the instructions manual of the instrument; MMM Tech Support, 2022) using a hand-pump (#1002 – MMM Tech Support) through the extraction tube. Before removing the pump, the extraction tube is clamped to maintain the suction applied by the vacuum. The pore water is then filtered from the soil into the tube via the ceramic tip of the instrument by the force of the vacuum; infiltration time varies with soil type and wetness, from around 4-8h. Following this wait time, the sample can be extracted from the tube using a clean syringe.

The vacuum was applied to all instruments in late February and left for two weeks until the first soil water extraction which took place on the 15th of March 2022. Only four of the eight lysimeters worked as expected (M11-A, B, C, and D) while the rest remained dry. All non-operational lysimeters were re-installed twice in different locations to re-attempt extraction; only one of these attempts was successful: outside of the Demonstrator Site (Dem B). The 'working' lysimeter in the Demonstrator site (Dem-B) was removed, cleaned, and re-installed in place of Dem-A (as it was known to be operational), however, the subsequent extraction which took place in Summer was unsuccessful due to unusually dry weather. The Summer extractions of all other locations were also unsuccessful due to the dryness of the soil. Stream samples were taken directly from the Middlehope Burn by the Demonstrator site and from the side stream adjacent to M11. The first stream water collection took place on the 15th of

March with the other samples, and a second collection took place in April on a further attempt at extraction from the dry lysimeters.

3.2.1 Sample processing and conductivity correction

The collected samples were filtered in the field at 0.45µm and kept in a refrigerated environment until they were submitted for ICP-MS analysis. The mass spectrometer used was an Agilent 7900 ICP-MS, SPS4 with Helium as a reaction cell gas. The elements analysed were Na, Mg, K, Ca, Al, Mn, Fe, Zn (three replicates, one hundred sweeps per replicate). Samples taken from the stream may not be directly comparable to those from the soil water due to rainwater dilution. In order to reduce this sample bias, a data correction was performed by measuring the hydraulic conductivity of the samples. The correction consists of dividing the element concentration values from the ICP-MS analysis by the electric conductivity value of each sample.

3.2.2 Soil water chemistry statistical analysis

All statistical analysis was conducted using R. The overall metal concentration of the soil water collected from the bund was compared with the stream water using a paired T-test. Individual T-tests were also performed for each of the elements analysed comparing the stream and soil water samples. As the stream water is collected from the runoff of the surrounding hills, once corrected for rainwater dilution, it is reasonable to expect soil water and stream water concentration of heavy metals to be broadly similar, except in soil samples taken from locations with unusually high concentrations. For example, a mining spoil heap or as is proposed in this case, a natural 'sink' for runoff to collect would be expected to have disproportionately higher concentrations of heavy metals. A T-test provides a comparison between the two locations (steam vs bund) to assess if there is an unusually high presence of heavy metals in the bund. Finally, an ANOVA comparing all the different locations was intended, but this was not possible due to the problems encountered in data collection (See Section 3.2).

3.3 Soil hydraulic conductivity

The hydraulic conductivity of the soil (*K*) was measured in three zones for each bund: within the storage area (Zone 1), on the bund itself (Zone 2), and on the area directly outside the bund (Zone 3) (Figure 12). To control for seasonal and weather-related changes to conductivity, measurements in all zones and bunds were repeated through winter, spring, and summer over several field campaigns. Table 4 indicates how many samples were taken per bund and per zone.

Table 4. *Hydraulic conductivity measurement sampling distribution. Values in cells refer to the number of samples taken per site.*

BUND/ZONE	1	2	3	TOTAL
M11	6	8	6	20
M14	6	3	4	13
M15	3	7	6	16
M16	7	8	8	23
DEM	6	6	7	19
TOTAL	28	32	31	

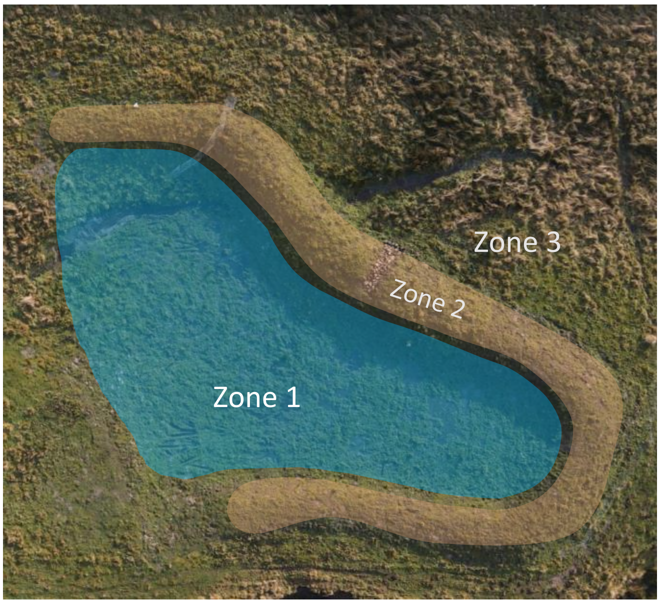


Figure 12. *Example zone distribution for measuring hydraulic conductivity in each bund* (M11 shown). *Zone 1 covers the bund's storage area (Blue), Zone 2 covers the bund itself (Orange); and Zone 3 covers the outside of the bund (not coloured).*

3.3.1 Mini-disk infiltrometer

The hydraulic conductivity of the soil was measured using Mini-Disk tension infiltrometers (METER Group Inc., 2022; Model S SKU: 40300). Mini-Disk infiltrometers were selected over double ring infiltrometers due to their portability in the field and the reduced quantities of water required to carry out measurements in remote locations such as the site selected for this study. It is worth noting that as tension infiltrometers, Mini-Disks measure *unsaturated* hydraulic conductivity. Unsaturated soil conductivity is always less and may be orders of magnitude less than saturated soil conductivity (this is because water is conducted through filled pores where air would otherwise interrupt the flow path making movement more tortuous).

Factors affecting the hydraulic conductivity of the soil include land use, soil porosity, clay and organic matter content, saturation, and various others (Chapuis, 2012; Crawford, 1994; Jarvis et al., 2013). In this study, the hydraulic conductivity of the soil is used as an indirect measure of the bunds' stability. As the bunds were built at different times, it may be expected that changes to the bund structure will be reflected in the hydraulic conductivity of the soil as the bund settles and ages. Additionally, as the Demonstrator site was built by a professional contractor and the rest of the bunds were built by the landowner, the quality of the bund structure may also be reflected in the hydraulic conductivity of the soil and its capacity to retain water.

The instrument consists of a cylindrical plastic container divided by an impermeable seal into an upper (Mariotte) chamber and a lower (reservoir) chamber (Figure 13). To operate the instrument, the reservoir is filled with water to a specified volume, and the mariotte chamber is filled three quarters full allowing the mariotte tube to stand above the water level. The water from the reservoir is then filtered through a sintered stainless-steel disk at the bottom of the instrument to the soil.

The rate at which the water is filtered through to the soil is regulated by an upward suction pull created in the mariotte chamber. The reservoir and the mariotte chamber are connected by a tube (the mariotte tube) that penetrates through the dividing seal; as water permeates through the disk to the soil, the tube allows air from the mariotte chamber into the airtight reservoir compensating for the lost water volume. Likewise, for air to move from the marriotte chamber to the reservoir, the lost volume in the mariotte chamber must be replaced. This is regulated by the 'suction tube', which allows air into the mariotte chamber from the outside. This means that for water to permeate through the disk to the soil, the hydraulic conductivity of the soil must create a downward force strong enough to pull air through the suction tube at the top of the instrument, overcoming the upward suction.

The two opposing factors controlling the movement of water through the membrane are, therefore, the hydraulic conductivity of the soil as determined by the soil characteristics, and the force of the suction applied by the set-up. The force of the suction is controlled by adjusting the suction tube to go deeper into the water-filled section of the mariotte chamber. The deeper the tube goes into the water, the stronger the upward pull, as air entering through the tube will have to exceed a greater water pressure. The tube is graded in cm, with values ranging from 0.5cm as the least powerful suction to 6cm as the most powerful. Due to high saturation of the soil in the winter months, (low conductivity), a suction of 1cm was applied to all measurements taken in this study.

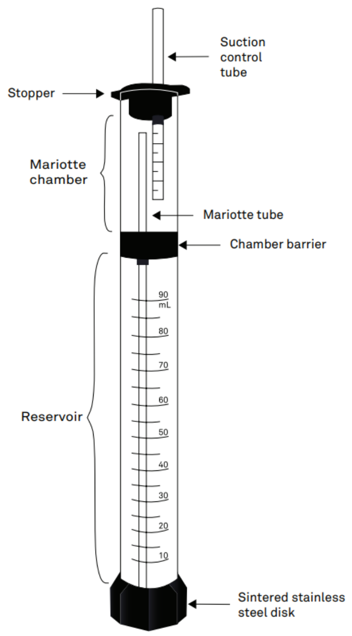


Figure 13. *Diagram of Mini-disk infiltrometer (diagram taken from METER Group, 2020, Mini-Disk Infiltrometer Instructions Manual, METER Group Inc.)*

3.3.2 Instrument operation and data collection

Water level readings are taken at regular time intervals from the reservoir chamber as the water filters through the disk. Cumulative Infiltration was then calculated by plugging the values from the readings into Equation 1, where I is the cumulative infiltration, V_1 is the volume in the reservoir measured in mL at time zero, V_2 is the volume measured at any given subsequent reading, and '*r*' refers to the radius of the disk membrane measured in cm (2.25cm in this case). Note that if volume in Equation 1 is given in cm^3, the resulting unit of measurement for cumulative infiltration is cm.

$$I = \frac{V_1 - V_2}{\pi r^2} \qquad \text{Equation 1}$$

Infiltration (flux of water per area per unit time) is dependent on matric and gravitational forces as it penetrates a soil. Matric forces describe the attraction between liquid and solid phases through capillarity and adsorption (Tuller & Or, 2005); when the soil becomes saturated with water, the matric potential becomes zero leading to hydraulic conductivity to be equal to infiltration ($K = I$).

Zhang et al. (1997), described a method to derive the hydraulic conductivity of a soil (K), when cumulative infiltration over a period of time is known through equations 2 and 3. Equation 2 relates cumulative infiltration (I) to C_1 and C_2, which are parameters for soil sorptivity and hydraulic conductivity respectively. These parameters were tested both theoretically and empirically through field and numerical experiments.

$$I = C_1 t^{1/2} + C_2 t \qquad \text{Equation 2}$$

A_2 is a coefficient determined empirically by the authors that can be treated as a constant. The value of A_2 is derived from retention parameters of different soil types and the pressure head (h_0) of the infiltrometer. Table 1 (Appendix C) indicates the value for A_2 to be used in the estimation of hydraulic conductivity (K) according to soil type and the suction applied to the instrument.

$$K = \frac{C_2}{A_2}$$ Equation 3

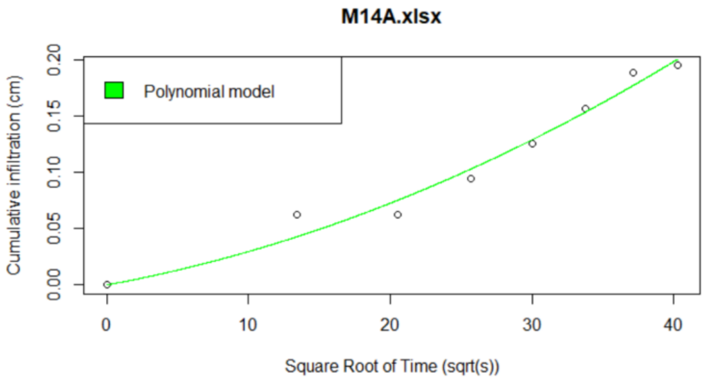


Figure 14. *Sample plot used to estimate hydraulic conductivity of the soil (K). The dots represent the volume of water infiltrated from the Minidisk into the soil through time. The polynomial model is a best-fit approximation of the rate of infiltration based on the scattered dots.*

The Cumulative infiltration can be plotted against the square root of time ($t^{1/2}$) as shown in Figure 14 to produce a scatter plot illustrating the infiltration of the water through time. The polynomial model derived from Equation 2 is then fitted to the data and the parameters of the 'best fit' line make a close approximation to the value of C_2 as the rate at which water infiltrates into the soil.

3.3.3 Statistical methods

Differences in hydraulic conductivity were assessed at three levels: across Zones within each bund, across Zones as averaged from all five bunds, and across bunds disregarding the Zones (i.e. M11 vs M14 vs M15 vs M16 vs Demonstrator). A Shapiro-Wilks test concluded that the data were not normally distributed, meaning that a Kruskal-Wallis test was determined the most appropriate for the analysis.

Chapter 4: Results & Discussion

4.1 Water storage

The Arduino devices installed in the five bunds were inadequate for the intended purpose. The initial laboratory testing and preliminary site testing both showed the instruments were functioning correctly in terms of recording presence and absence of water. However, on the first data extraction attempt post testing, it was discovered that the battery life of the devices only allowed for two to three days of data collection on four 1.5V AA lithium batteries (set in series in a single battery pack, generating 6V). Travelling to site weekly to replace the batteries, was deemed impracticable and costly beyond the scope of the project, so it was decided to remove this aspect of the study and focus on the soil chemistry and hydraulic conductivity experiments. An additional layer of testing during the design phase of the devices to test their power consumption would have detected this problem earlier in this study and provided enough time and resources for correction.

Although this study was unable to test the frequency of flood storage of the bunds, the Environment Agency has collected video evidence of the Demonstrator site in operation. The installations are currently under a post construction internal review by the Environment Agency, meaning that some information on the bund function is yet to become available to the author of this dissertation. This includes an assessment on the size of the outflow culverts, and reporting on motion-triggered trail cameras set on two of the other bunds to record them in operation during storm flows. The literature is very limited concerning the efficiency of earth bunds as flood storage features. Notable mentions include the work carried out by Newcastle University in Belford, Northeast England (Nicholson et al., 2012, 2020; Wilkinson et al., 2010), the Stroud Frome project in Southwest England (Short et al., 2019), and the more recent and ongoing research of Robotham et al. in the Littlestock Brook NFM scheme in Oxfordshire (2022). These studies have shown that earth bunds can effectively be used as flood storage features, especially when employed in conjunction with other NFM interventions.

4.1.1 Improvements to the design of the Arduino sensors for future work

Commented [TJS2]: This subsection title was inserted for clarity and for improved consistency with the added research question on low cost sensors.

The power consumption of sensor-equipped dataloggers varies with the efficiency of the code, the hardware in use, and what the device is instructed to do; in this instance, power consumption was brought down from an estimated 60mA to 44mA. Several approaches were taken to reduce the power consumption of the devices which are widely discussed in the Arduino Forum and Stack Exchange (For detailed description see David, 2021). A USB Amp meter was used to test the power consumption of the Arduino water sensors. Importantly, the Amp meter is only able to measure power consumption if the Arduino is being powered via a USB and not batteries. This means that the power consumption of the devices when powered on batteries via the barrel jack was an approximated value. Described below is the approach that was taken to reduce the power consumption of the devices, together with other proposed amendments which were not carried out due to time restrictions.

4.1.2 Sleep mode

A 'sleep mode' function was added to the code to power down the device in between readings. Two libraries were tested: the Sleep_n0m1.h library (Shibley & Grant, 2017), and the LowPower library(Rocket Stream Electronics, 2021). Both libraries put the Arduino into a sleep mode where power usage drops down to 0.044A. LowPower allows the Arduino to sleep for 8 seconds at a time unless coded to repeatedly put the Arduino to sleep in a longer loop. Sleep_n0m1.h has an in-built loop that allows the Arduino to sleep for longer, with the drawback that it uses slightly more power for a few seconds when waking-up (0.055A) compared to LowPower, with which power consumption remains at 0.044A. Sleep_n0m1.h was used in the final code as it was easier to use and the increased wake-up power consumption was deemed not significant enough to make a difference since the device is only waking up every 15 minutes. Notably, reducing the sampling rate would not make a significant difference to power consumption as taking measurements did not increase power consumption significantly (i.e. most of the power consumption came from the base running of the device).

4.1.3 Processing speed and voltage reduction

Powering the board on a lower voltage is a solution to consume less power, as dictated by Ohm's law which states that power is a result of the voltage times the current. The original design used a voltage of 6V. On this basis, a proposed improvement to the instruments' design would be to use a power bank consisting of two sets of two AA batteries (~3V) set in parallel (Figure 15), provided that the circuitry and components would operate effectively in field temperatures at lower voltage. This proposed update on the battery arrangement may effectively reduce the power consumption of the board by reducing the voltage from the original 6V battery pack and double the capacity of the power bank by arranging two packs in parallel and thereby increase the Ampere hours. David (2021) reported a reduction of 88% in power consumption by lowering the voltage from 9V to 3.3V; another publication (Alex, 2015) reported a reduction in power consumption of 75% by reducing the voltage from 5V to 3.3V. If this is applicable to the board used in this study, this approach could reduce the current from 44mA to ~8.8mA. With the doubled capacity of the proposed battery pack the battery life of the devices could theoretically be extended to ~19 days.

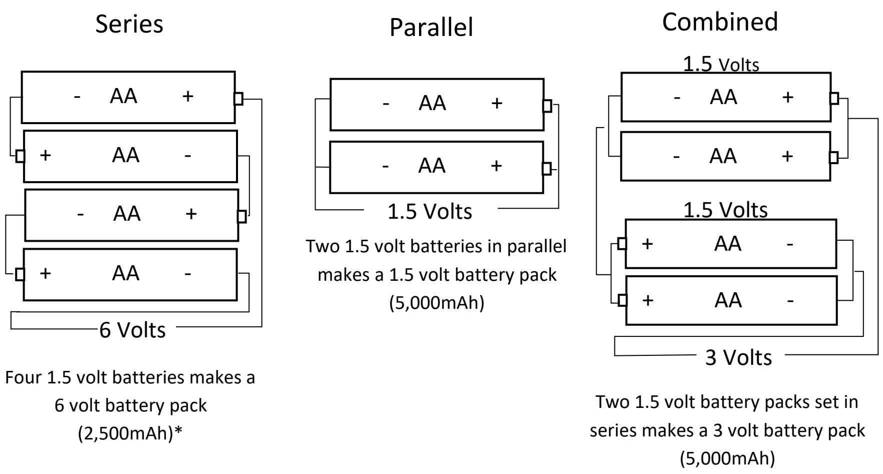


Figure 15. *Simplified diagram comparing a series, parallel, and combined arrangement of AA batteries possible to power the Arduino devices. *Note: When set in series, the voltage of the batteries is added up, but the Ampere hours (battery life) remain the same. When set in parallel, the power remains the same, but the Ampere hours are added up (a standard AA battery produces ~1.5V and is rated to ~2,500mAh).*

Reducing the clock speed of the board is also suggested to have an effect on reducing the power consumption, as the processing speed of the board is reduced from 16MHz to 8MHz (David, 2021). When this was tested however, no change in power consumption was registered. This may be related to the relationship between the Clock speed and the voltage being used (Alex, 2015), but this was not tested as a 3V prototype was not built. It may also be attributed to how effectively the current meter is able to average power consumption during cyclical processes (i.e. the change may not have been registered). Additionally, it is worth noting that running the instrument on a reduced processing speed caused output errors such as missing lines and randomly printing incomprehensible writing. Another common power saving solution is to physically remove the LEDs that are in-built on the board. This solution was not tested due to the time restrictions of the project.

4.1.4 Using an alternative board

For future work, the most significant power saving improvement to the design as proposed by David (2021), is to use an Arduino Nano, or for even longer life, an Arduino Mini Pro instead of the Arduino UNO. Comparatively, an Arduino UNO with all power saving solutions implemented can be brought down to a power consumption of 11.5mA versus 3.4mA and 1.6mA for the Arduino Nano or the Arduino Mini Pro respectively. Assuming a capacity of ~2,500mAh for a standard AA battery, the device could run for a maximum of around 9 days if using an Arduino UNO (2,500mAh/11.5mA = 217.39h) compared to 30 days if using an Arduino Nano (2,500Ah/3.4mA = 735.29h), and 65 days if using and Arduino Mini Pro (2,500Ah/1.6mA = 1,562.5h). If employing the above solution to reduce the voltage and increase the capacity, all these times could potentially be doubled, creating a more reliable device. Power saving measures are summarised on Table 5.

Table 5*. Power saving measures with their respective estimated power consumption and battery life.*

Power saving method	Current	Estimated battery life Using 2,500mAh	Estimated battery life at increased capacity (5,000mAh)
Base power	60mA	41h (~2 Days)	82h (~3 Days)
Sleep mode	44mA	56h (~2 Days)	112h (~4 Days)
Reduced voltage	11mA	227h (~9 Days)	454h - ~19 Days
Alternative board:			
- Arduino Nano	3.4mA	735h (~30 Days)	1,470h (~61 Days)
	1.6mA	1,563h (~65 Days)	3,126h (~130 Days)

-Arduino Mini Pro	

4.2 Soil water chemistry

Due to abnormally dry weather conditions and instrument malfunction, only four soil-water samples were collected together with four in-stream water samples, meaning it is not possible to draw conclusive results on the ability of the bunds to act as sinks for heavy metals carried through runoff from the surrounding spoil heaps.

4.2.1 Pore water samples

There was a wide range of metal concentrations in the soil water samples. Ca was on average the element on highest concentration (84mg/L), while Zn was the lowest (0.06mg/L). The single highest value was for Ca (135mg/L), and the lowest was for Zn (0.007mg/L) both in location M11-D. M11-D also had the highest concentration of Na, Mg, K, and Ca while Al and Zn were highest in M11-C, and Mn and Fe were highest in M11-B. M11-D consequently had the highest average concentration, however this did not correspond with the electric conductivity which was highest in M11-B. Conversely, both the lowest electric conductivity and lowest average metal content were found in M11-C (see Table 6 for detail).

Table 6. *Metal concentration per location***.** *Purple text denotes a measurement performed using an additional 100x dilution of the sample during the ICP-MS analysis; text in green denotes a measurement performed using an additional 10x dilution of the sample during the ICP-MS analysis. Lysimeter depth, sample pH and electric conductivity are shown in the columns to the right.*

Element [mg/l] / Sample	Na	Mg	K	Ca	Al	Mn	Fe	Zn	Depth	pH	Conductivity
M11-A	5.14	11.2	1.34	52.74	0.031	5.359	0.944	0.058	30cm	7.75	311
M11-B	6.65	31.0	3.20	112.4	0.025	17.457	4.300	0.049	60cm	7.63	565
M11-C	3.50	5.9	1.33	38.28	0.051	1.429	0.024	0.145	60cm	7.87	223
M11-D	8.05	42.3	3.28	135.5	0.039	1.504	0.723	0.007	60cm	7.57	514
Side Stream 2	4.44	1.14	0.52	3.73	0.062	0.117	0.228	0.079	N/A	8.07	83.1
Middle Hope Burn 2	2.77	0.71	0.29	2.21	0.131	0.063	0.401	0.016	N/A	8.02	29.4
Side Stream 1	4.82	1.19	0.73	3.45	0.030	0.003	0.131	0.045	N/A	8.07	53.7
Middle Hope Burn 1	2.90	0.64	0.44	2.11	0.092	0.033	0.176	0.024	N/A	8.09	29

Interestingly although adjacent to each other, M11-B (taken at 60cm) had higher concentrations in general than M11-A (taken at 30cm), which is to be expected as metals are known to vary in concentration across soil layers according to the properties of each layer such as pH, particle size, and organic matter (Azeez et al., 2014; Mengel et al., 2001; Minasny et al., 2016). Considering the other two samples taken at 60cm, M11-D also shows a general increase in concentration compared to M11-A, but M11-C does not (except in Al and Zn). This difference may be due to the fact that M11-C was the wettest sampling location, which was observed to be waterlogged for much of the year. This may also explain why it has the lowest concentrations overall and the lowest conductivity, as having more water throughout the year could cause the sample to be comparatively more diluted. The opposite is true for the M11-D sample which was taken from the bund structure itself (Figure 11), meaning it remains less wet than the storage area, allowing for a lower dilution of the pore water.

A higher concentration of Ca in M11-B and D may be due to a higher clay content found deeper in the soil, as Ca is typically high in clay soils (Mengel et al., 2001). The design of the bund included spreading clay in the storage area and the bund itself for improved water retention, covered with a layer of topsoil to preserve grazing. The wide spread of the data in the soil samples (Figure 16-18) and the need to further dilute some but not all of the soil samples further highlights a strong variation of concentrations within the bund. This variation may be due to the mining spoil being mixed with the soil in the building process resulting in 'node-like' locations within the bund with higher concentrations of metals (e.g. note the high concentration of Fe and Mn in sample M11-B in Table 6 in contrast with other locations).

Notably the reduced sample size and the lack of samples from outside of the bund and other locations in the vicinity makes it impossible to draw any hard conclusions regarding the ability of the bund to act as a sink for heavy metals.

4.2.2 Stream water samples

The stream water samples varied less than the soil water, although there was some difference between the samples taken in March vs those taken in April (Table 6). The March Side Stream sample (SS1) had the highest concentration of Na, Mg, and K. The Side Stream sample taken in April, had the highest concentration of Ca, Mn, and Zn. The March Middlehope Burn (MS1) sample had the highest concentration of Al and Fe. The average concentration for the Side Stream remained almost unchanged from March to April (1.29mg/L to 1.30mg/L). This did not hold true for the conductivity of the samples, however, which increased from 53.7µS/cm in March to 83.1 µS/cm in April. This is probably due to changes occurring at individual element level, most significantly in Al, Mn, and Fe. For the Middlehope Burn samples, both conductivity and average concentration remained fairly stable (29µS/cm to 29.4µS/cm and 0.80mg/L to 0.82mg/L respectively). In general, the Side Stream had higher concentrations of all but two of the elements (Al and Fe), and a corresponding higher conductivity. This difference is probably due to the Side Stream coming directly through land polluted with mining waste, whereas the Middlehope Burn is fed by several tributaries, meaning that the heavy metal pollution becomes more diluted.

4.2.3 Pore-water vs Stream water

Metal concentration in the soil were found to be significantly higher than in the stream (Figure 16; T-Test $p<0.05$; $n=64$). However this is unsurprising as stream water may be expected to be more diluted with rainwater than soil water, as much of the stream water may be runoff with short residence time across the landscape. This natural bias is evident in the data corrected for electric conductivity of the sample where the difference in overall heavy metal concentration between the soil and stream samples was not significant (Figure 16; T-Test $p>0.5$; $n=64$). It is worth noting that the soil water samples were collected on the same day as the stream samples (15th of March), however the water in the lysimeters was extracted from the soil and into the tube when the vacuum was applied (25th February), and not the same day as the stream samples. This variation in time may have had an influence on the results, although the weather on the days preceding both dates was similarly dry.

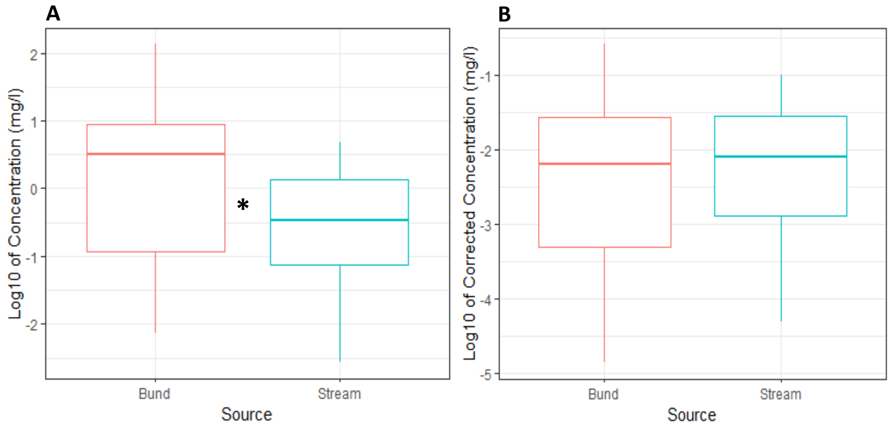


***Figure 16.** Overall metal concentration in stream and bund before (A) and after (B) correcting the data for electric conductivity of the samples. *Indicates a statistically significant difference ($p<0.05$).*

Individual t-tests for each of the eight elements comparing the soil and stream samples before correcting for sample conductivity found a significant difference ($p<0.05$) in the content of Ca and K, but not for Na, Mg, Fe, Al, Zn or Mn (Figure 17). Following the correction for conductivity (detailed in section 3.2.1), a significant difference was found between the stream and the bund in Na, C, and Zn, and no significant difference for Mg, K, Fe, Al, and Mn (Figure

18). See Figure 19 for individual element concentration values in each sampled location. It is worth noting that during the ICP-MS, it was necessary to further dilute some of the samples because the readings on some of the elements were beyond the calibration limits of the instrument (Table 6).

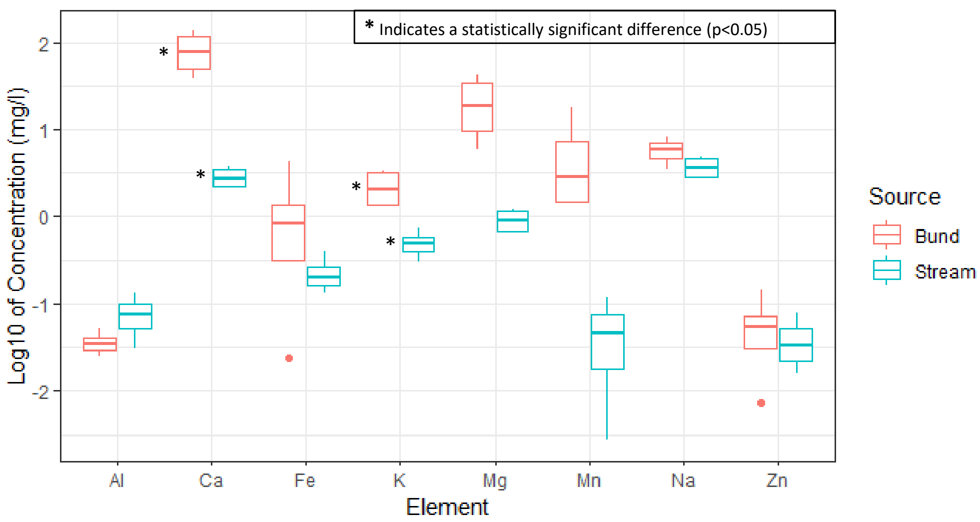


Figure 17. *Log10 of the concentrations of each metal analysed showing the variation between bund (red) and stream (blue).*

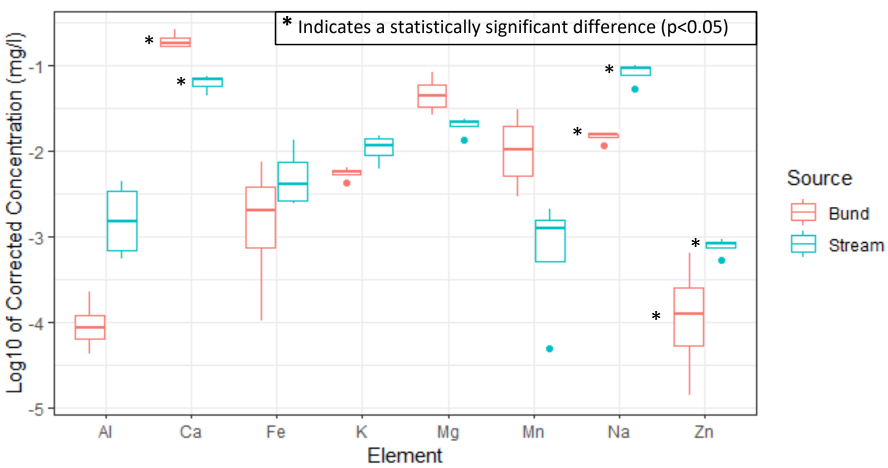


Figure 18. *Log10 of the concentrations of each metal analysed corrected for sample conductivity showing the variation between bund (red) and stream (blue).*

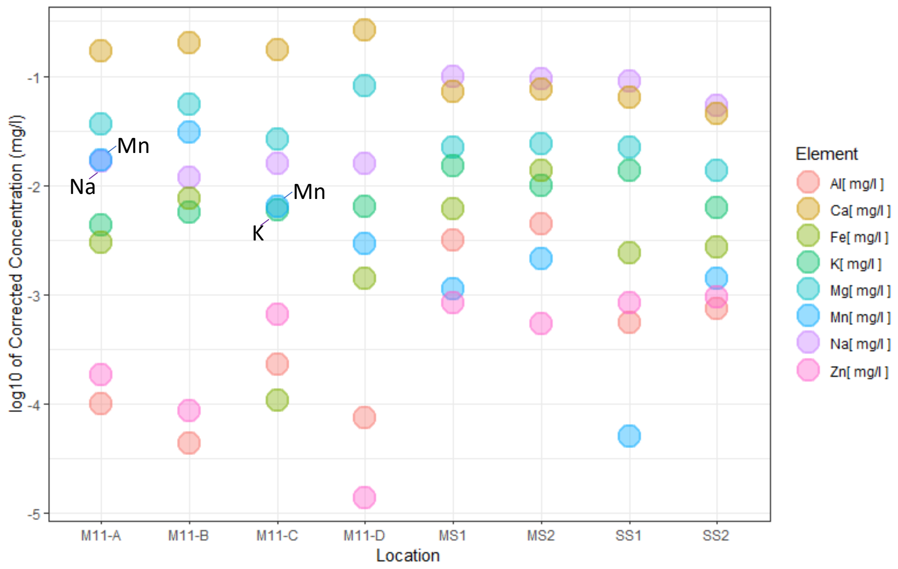


Figure 19. *Log10 of corrected concentration of metals in the four soil water samples (M11A-D) and four stream samples (MS1 – SS2).* Note that M11-A was collected at a 30cm depth, while M11-B, M11-C, and M11-D were collected at a 60cm depth.

If the bunds are able to act as sinks for pollutants, it would be reasonable to expect higher heavy metal concentrations in the soil water compared to the stream water. When considering elements individually, only Ca was found to be at disproportionally higher concentrations in the bund than in the stream after the correction of the data, while Zn and Na were found to be higher in the stream. Heavy metals, particularly Pb and Zn are known to be the main pollutants in historic mining areas of the Pennines and the Yorkshire Dales (Macklin et al., 1997) including the Middlehope Burn (Lord & Morgan, 2003). Floodplains are known to collect heavy metal deposition, which contaminates stream water quality with remobilisation (Bradley & Cox, 1986, 1990; Marron, 1992). The higher levels of Zn found in the stream samples may be indicative of higher heavy metal concentrations in the area up-stream of the bund where old mining spoil heaps can be found. This is in contradiction to the assumption stated above that the bunds would have higher levels of heavy metals, however more data and broader experimentation is required to make a conclusive statement for the ability of bunds to act as sinks. Further, as shown in Table 6, the higher levels of Zinc found in the Side Stream compared to the Middlehope Burn, suggests the input of heavy metals into the main river may come from point sources in the landscape.

4.2.4 Wider catchment relevance

Obtaining conclusive evidence on the bunds' ability to act as sinks for heavy metals may provide insight into where to localise bunds in the future to target water quality improvements. Repairing the damage of the industrial legacy along the River Wear is one of the primary objectives of the Northumbria river basin management plan (Environment Agency, 2016). Figure 20 shows The extent of mining polluted catchments in the area, including the Middlehope Burn. Several projects are ongoing lead by the Environment Agency working with the Wear Rivers Trust, including both green engineering and investigations for water treatment plants (Coal Authority, 2021). Successful application of the Middlehope Burn project would suggest that the green infrastructure approach could be applied in the wider catchment as a solution not only to flooding, but directly to manage metal pollution.

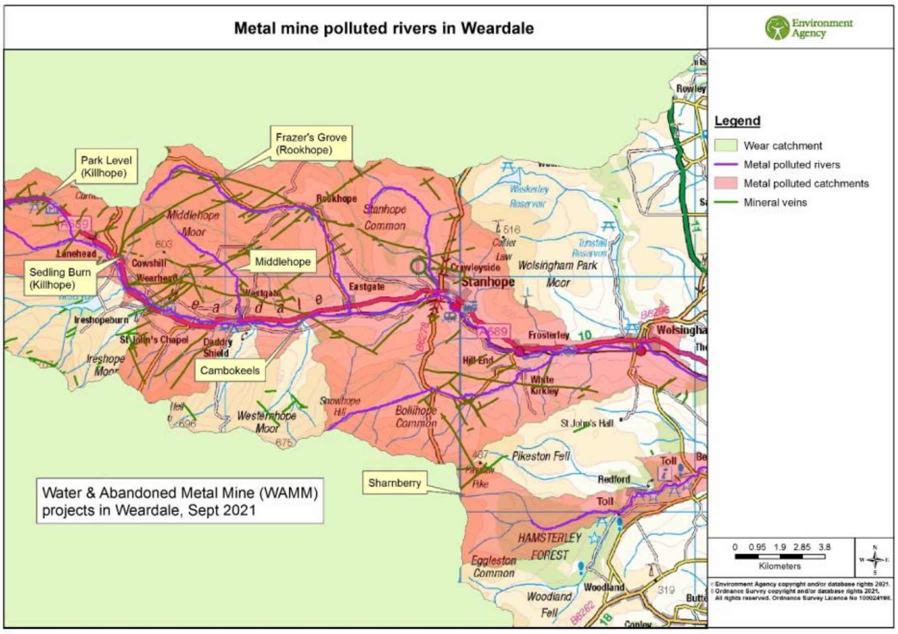


Figure 20. *Map of metal polluted rivers in Weardale (taken from* Environment Agency, 2021a*)*

If it is shown that bunds are able to act as sinks for pollutants, intercepting streams that are known to carry higher levels of pollutants may prove an efficient use of resources by targeting point-source pollution and creating flood water storage at the same time. This proposed benefit derived from earth bunds is based on existing literature on wetlands. Wetlands have been shown to act as natural filters for pollutants ranging from agricultural contaminants such as N (Knudson, 2021), to heavy metals from both atmospheric and point sources (Liu et al., 2018; Rai, 2008; Sheoran & Sheoran, 2006). The emergence of aquatic macrophytes such as rushes (*Juncus spp.*) in the bunds is indicative of the soil being able to support wetland species. Rushes have been shown to have an effect on the chemical properties of soil and to encourage bacterial productivity (Mann & Wetzel, 2000). This is critical, as bacteria are known to play a key role in wetlands acting as pollutant filters both for wastewater (Rehman et al., 2019) and heavy metals specifically (Kosolapov et al., 2004).

4.2.5 Further work

Time limitations were the main constraint for obtaining conclusive results from this experiment. Given that this study was conducted over a one year period, we only had one full cycle of seasons to draw data from with no true baseline for the study. Considering that the bunds are most likely to operate during the wet season, allowing several years for data collection would produce more dependable and relevant results.

A broader spread of sampling locations would also present a more accurate picture of the bund's ability to capture heavy metals. It is key to consider that the bunds were constructed using site-won material and are therefore likely to have mining refuse unevenly mixed into their structure. Having more, well spread sampling locations would reduce the possibility of inadvertently hitting highly contaminated patches by chance. Ensuring the exact same locations are sampled across several years would also eliminate chance skewing of the data due to the patchy nature of the bunds since any changes in soil chemistry would be recorded with a baseline for comparison.

A larger scale study across multiple sites could also add significant depth to our understanding of the further benefits of bunds as filters for pollutants. This could be done in several ways. Sampling water quality downstream of different kinds NFM interventions across several years, for example, could serve to comparatively assess improvements to water quality. Likewise, testing soil pore water across different sites as was done in this study could provide direct evidence of pollutant capture and retention. Another interesting approach could be to look at the ecology of the site. As mentioned in section 4.2.4, the presence of certain plant communities can provide insight into the bacterial communities that can be supported by the site. Plant surveys were considered for this study, but an initial visual assessment of the site found that the plant communities were very uniform and would not significantly add to the findings. Direct analysis of the soil microbiology could also prove to be an interesting approach, but this was beyond the scope of our study.

4.3 Hydraulic conductivity

The data collected for the hydraulic conductivity study were not normally distributed (Shapiro Wilks $P<0.01$; Figure 21), making the non-parametric Kruskal Wallis test the most suitable for analysis (See table 4 for reference; Zone 1 n=28, Zone 2 n=32, Zone 3 n=31; total bunds: M14 n=12 ; M15 n =15 ; M16 n=25; M11 n=20 ; Dem n=18). Given the increased power of a parametric test, a logarithmic normalization of the data was attempted in order to employ an ANOVA. However, the data was too skewed, even if removing outliers (Figure 22), meaning that the normality criteria for employing a parametric test was not met and this option was discarded. Note that a negative value was registered for K in bund M16, which is a physical impossibility; this data point was excluded.

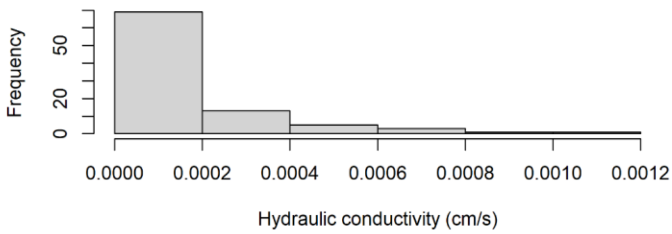


Figure 21. *Histogram of all hydraulic conductivity data.*

4.3.1 Hydraulic conductivity across Zones

Differences in the hydraulic conductivity of the different study Zones were expected given the design of the bunds. The storage area (Zone 1), as a low point designed to retain water (see section 2.2 for construction detail), may be expected to have a lower hydraulic conductivity than Zones 2 and 3. Zone 2 is in a raised position, which may result in a higher conductivity than Zone 1; as part of the bund structure however, it is also designed to retain water. Zone 3, by that logic, which is higher than Zone 1, and not designed to retain water may be expected to have the highest hydraulic conductivity. Contrary to these assumptions, no statistically significant difference was found between the three study zones (Kruskal-Wallis; x^2= 5.53; df =2; p=0.06).

Considering variation in hydraulic conductivity between Zones within each bund produced varying results. Shapiro-Wilks tests for normality found the data are normally distributed in the Demonstrator site (p=0.015) and bund M15 (p=0.013), but not normally distributed in bunds M11, M14 and M16 ($p<0.05$) (Figure 22). Zones 1 and 3 were found to be significantly different in the Demonstrator site when performing an ANOVA (df=2; F=4.78; p=0.024; Tuckey p=0.019). In bund M15, Zone 2 was found to be significantly different from both Zones 1 and 3 (df=2; F=5.55; p=0.018; Tuckey p=0.046 and p=036 respectively). No significant difference was found across Zones in any of the other bunds when conducting individual Kruskal-Wallis tests and Kruskal-Wallis test returned the same results for the Demonstrator Site and bund M15. It is worth noting that when considering the bunds independently, the sample size is much reduced (M14 n=12; M15 n =15 ; M16 n=24; M11 n=20 ; Dem n=18) making any results less robust.

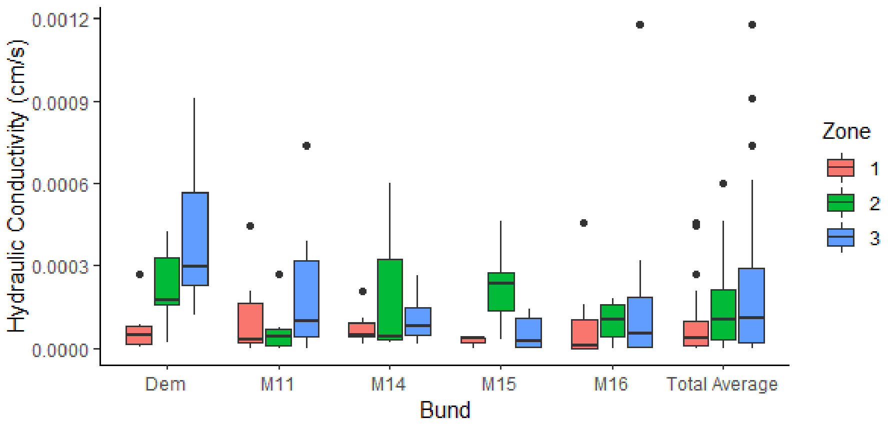


Figure 22. *Hydraulic conductivity plotted against each individual bund across the tree bund zones: Zone 1 = bund storage area, Zone 2 = bund structure, Zone 3 = outside the bund.*

As discussed above Zone 3 differing from Zones 1 and 2 is to be expected, as the bund is packed with clay in order to retain water. This is the case of the Demonstrator site, were Zone 3 had a higher hydraulic conductivity (faster infiltration) than Zones 1 and 2. Contrarywise, in bund M15, Zone 2 had the highest hydraulic conductivity. This may be due to the waterlogged conditions of the soil within and outside of the bund; as Zone 2 is raised from the ground, it is not unexpected that it will contain less water and drain faster than the lower (waterlogged) zones. Additionally, Zone 1 was filled with shallow standing water for much of the year, making measurements impossible until the soil dried out in the summer. This restricted sample distribution which may have a direct impact on skewing the results, reiterating the unreliability of the individual bund results due to sample size and distribution (see Table 4, Chapter 4).

4.3.2 Hydraulic conductivity across bunds

No statistically significant difference was found comparing the hydraulic conductivity of the five bunds (Kruskal-Wallis; x^2= 8.54; df =4 ; p=0.07). Two factors were considered in this study by assessing the hydraulic conductivity of the bunds: bund age and build quality. The bunds were compacted and fitted with clay during construction in order to improve water retention by lowering the bund’s hydraulic conductivity. This means that the hydraulic conductivity of the bunds may increase with age as the soil structure is progressively changed by weathering and ecological activity such as plant growth, burrowing invertebrates, and grazing (Ren et al., 2016; Zimmermann & Elsenbeer, 2008). The Demonstrator Site was built two years before the other four bunds and may have therefore been expected to have a lower hydraulic conductivity. The results of this study suggest that there was no change in bund structure stability within a ~2-year period, as no difference was found.

Finding no significant difference between the Demonstrator site and the other sites may suggest that it is of superior quality as it has not been affected by age. However, this assumption does not consider further factors that may affect the hydraulic conductivity of the bunds such as local variations in clay content and positioning in the landscape which are known to significantly affect hydraulic conductivity (Zeng et al., 2013; Zimmermann & Elsenbeer, 2008). Interestingly, no difference was found in hydraulic conductivity when comparing the other four bunds independently from the demonstrator site. Considering all four bunds were built around the same time (between March and May 2021), observing no differences in hydraulic conductivity may suggest that the spatial distribution of the bunds is not affecting the results.

4.3.3 Sampling considerations and further work

There are multiple explanations to why no differences were found across Zones or across bunds. Sampling error must be considered given the instruments used (mini-disks) arguably require substantially more data collection that other infiltrometers to cover for local variation in an area. This is due to the size of the plate where the measurement actually takes place which is only 2.54cm in diameter. Another explanation could be that the highly waterlogged condition of the soil before the summer months meant that most measurements resulted in a hydraulic conductivity of zero or very close to zero (Benson & Trast, 1995). This skew in the data is evident in Figure 21. Future studies could be improved by conducting more measurements across all Zones, across all seasons, and over several years to yield more reliable data.

Given the inconclusiveness of these results, more research is required to establish the relationship between build quality and bund function. Especially considering the main purpose of these bunds is to act as storage units, which this study was unable to measure (refer to section 4.1 for more details). Future research could address bund quality and bund function through comparative hydraulic modelling of the bunds using detailed topographic survey data. The combination of modelling with real time data collected through improved water sensors discussed in Section 4.1, would allow much deeper insight into the functioning of the bunds.

The question of bund quality related to construction methodology is worth further consideration, given that it may have direct implications on how future NFM interventions are managed. Strong evidence that construction work by landowners is of sufficient quality may lead to the involvement of local communities in NFM and other nature-based solutions, with direct remuneration for services rendered. Empirical evidence that landowners can be relied upon to produce work of sufficient quality could be coupled with a socio-economic study to explore the benefit of NFM to local communities. Such research could provide a valuable expansion to the existing literature where the involvement of local communities is explored as a further benefit of NFM. To the best of our knowledge, this is not considered in any existing academic literature.

4.4 Bridging communication gaps

4.4.1 Environment Agency collaboration

The three meetings held throughout the study period with the EA project leaders were key to frame this study within the greater context of NFM interventions in the UK. As a pilot project, the EA is interested in the application of similar projects elsewhere. One of their priorities include the involvement of the local community, with the aim of creating a 'circular economy'. The purpose of this is that environmental enhancement projects can also bring about an investment in the local community beyond the primary objectives of an installation (e.g. flood regulation, biodiversity gain etc.). In this instance, the landowner was given the opportunity to build four of the bunds himself, receiving payment for his labour; this is of notable importance considering that they received no other compensation or any form of payment for the bunds and his land was used on a 'good-will' basis. This point was raised in the initial project meeting, which resulted in adding the third objective of this study (see section 1.5) to assess bund quality. Further studies assessing the suitability of local communities receiving payment for labour in the installation of future NFM projects would be a valuable contribution to develop this concept of a 'circular economy'.

The desire for continued collaboration with Durham University in future assessments of this project was expressed by the EA. This is an encouraging prospect, as it may allow earlier researcher involvement in pre-installation studies, to the benefit of both academics and practitioners. The time constraints of this particular study did not allow for more in-depth involvement with the community. Collecting the perspectives of the landowner and the residents of the area in future studies could provide useful understanding that may improve stakeholder wiliness to contribute towards NFM interventions.

4.4.2 General observations on bridging communication gaps

As mentioned in the introduction to this dissertation, one of the principal hurdles for NFM widespread implementation is the improvement of communication between the various stakeholders. In discussing communication gaps between practitioners and academics, it is important to recognise that the term 'practitioner' covers many distinct groups of people with varying interests and objectives (Bartunek et al., 2014). In the case of the Middle Hope Burn installations for example, the EA (a public body) hired ARUP (a private consultancy) to produce an NFM design. The work was then completed partly by a specialist contractor and partly by the landowner himself. No defined classification of the various stakeholders is found in the literature (to the best of my knowledge) but the following more specific groups are broadly spoken of in the literature (Bark et al., 2021; Holt & Morris, 2022; I. Y. Huang et al., 2022) under the umbrella term of 'practitioner':

- **Authorities:** includes government bodies (e.g. EA, DEFRA etc) and also local institutions (e.g. county/parish councils) that may be responsible for flood-risk management and project procurement. They often act as the funding source for projects and may become directly involved in this capacity as project managers.
- **Industry**: includes both consultancies and specialist contractors that design and/or build NFM installations. May also act as project managers in conjunction with the relevant authority.
- **Other stakeholders**: includes local initiatives, such as volunteer flood groups, and institutions such as wildlife trusts and other environmental activist groups that may be involved in the procurement, installation, and/or management NFM projects in the interest of their communities.

- **Landowners**: landowners play a key role as facilitators of NFM projects, especially in land management schemes where NFM becomes an active and ongoing practice. For this reason, they have been placed in a category of their own.

This broad distribution of practitioners presents in itself a difficulty in consolidating a communication stream with academia. The fact that projects typically develop over the course of several years, with different practitioner groups becoming involved at different stages adds further difficulty from an academic perspective to design controlled experiments that can be run effectively. For example landowners may change, or responsibilities may be split across different authorities. To allow scientific rigor, academics would ideally be involved throughout the process to have information on sites before, during, and after installations as well as having control sites. This sort of involvement is limited by funding. Considering that end-goal of practitioners and academics in NFM may differ, operating from different funding streams may present a barrier for integrating academic research into NFM projects from start to end.

It is also worth noting that significant research is carried out by practitioners themselves (be it consultancies or authorities) in the planning stages of NFM installations. As in many other disciplines (Bartunek et al., 2014), this is however not always translated into academia and remains as so-called 'grey' literature as it is not submitted to scientific scrutiny (if published at all). A possible explanation for this is a difference in motivations. Broadly speaking, academic research is focused towards developing our understanding of NFM, whereas practitioner motivations might be more case specific; for example reducing flood-risk for a specific site in the case of authorities, growing a business/reputation in the case of industry, or even philanthropic motivations in the case of some landowners. It may also be the case, that practitioners are reticent to receiving academic criticism for a variety of reasons(Sallee & Flood, 2012). At the same time, a 'translational' effort may be required from academics to make research more accessible to practitioners (Faulkner et al., 2007; Sallee & Flood, 2012).

At the same time, it must be highlighted that important efforts have been made in closing this gap which is well acknowledged both by academics and practitioners of all groups. This includes important NFM collaborations such as the aforementioned Stroud Frome project in south-west England (Short et al., 2019), the Littlestock Brook scheme in Oxfordshire (Robotham et al., 2021), and the Belford installations in Northumberland (Nicholson et al., 2012). In England, the annual conference held by the River Restoration Centre also provides a useful platform for communication. There is hope, also, that the post-Brexit environmental land management schemes (ELMs) present an opportunity to develop more integrated catchment management (Klaar et al., 2020). Central in this development is ensuring that new schemes align with landowners' needs (Holt & Morris, 2022; Huang et al., 2022) as they often act out of goodwill (as is the case in this study), and they have not always received the best compensation for their contributions, which in turn can cause reticence to accept future NFM schemes (Bark et al., 2021).

Chapter 5: Concluding Remarks and Further Work

The use of nature-based solutions to address flooding in the UK and around the world is gaining increasing popularity in the form of NFM. This study focused on a trial installation of earth bunds as temporary storage units for flood water, intended to reduce peak flows downstream. No evidence was found for the bunds' ability to act as sinks for heavy metals, although the data are not conclusive to support the opposite. Further research over a longer period of time is required to establish this, with important implications to water quality improvement as a further benefit of the bunds.

Due to the time restrictions inherent in a study undertaken over the period of only a year, several questions remain unanswered regarding the functioning of the bunds. The placement of the bunds, for example, may be tested for optimal storage and further benefits. As reported by Robotham et al. (2022), online bunds performed best at capturing sediment compared with offline bunds. In this study only the Demonstrator site can be described as being directly online. It is proposed that bunds M11 and M16 could be placed as online features to the adjacent Side Stream as opposed to being fed by a drainage ditch to maximise both flood storage and possibly filter heavy metals more effectively. It is understood, however, that this may not be ideal for the landowner, and there may be other considerations to take into account.

Another consideration is optimising pipe diameter, as this is critical for the functioning of the bunds. The drainage pipe fitted beneath M14, for example, may not allow the bund to collect runoff, as it increases the total outflow capacity of the bund, thereby raising the inflow threshold at which it becomes active storage. Only the Demonstrator site is fitted with an adjustable inflow/outflow system, which can be used to increase or lower the active storage threshold. Given the other bunds are offline, and therefore less likely to collect sufficient runoff in smaller storm events to act as active storage; adding an adjustable outflow could be trialled as an improvement to their functioning.

Bund stability could also be monitored over a longer period of time, as breaches could cause the bunds to a) stop functioning as storage features, or b) release stored water in a single event. Along this line, long term studies of the soil water chemistry and ecological assessments of the bunds may also provide valuable insight into their further benefits. Finally, the implementation of habitat improvement initiatives or the addition of further NFM measures could set the scene for an interesting environmental development case study. This could consider the mining history of the site and its present agricultural use, and how it may be adapted to more sustainable practices to the benefit of the environment, the local community, and the landowner.

5.1 Further benefits of Earth bunds as NFM features and further work considerations

The existing literature on earth bunds as NFM features has highlighted their use as effective sediment traps (Adams et al., 2018; Nicholson et al., 2012, 2020). In an agricultural catchment in southern England, earth bunds were shown to be highly effective at capturing sediment carrying agricultural contamination from runoff (Robotham et al., 2022). In that study, 14 of these features trapped a total of 83 tonnes of sediment (15% of the total suspended sediment yield of the catchment), 122kg of phosphorus (10% of the total), and 4.3 tonnes of organic carbon (8% of the total) in the space of 2-3 years. This is remarkable considering the bunds have a footprint covering less than 1% of the 3.2km^2 catchment. The author estimated a required clearance of sediment every ~10 years to maintain the bunds working as both efficient flood storage features and sediment traps. Wilkinson et al. (2010) also noted the maintenance requirement of earth bunds in an earlier example of earth bunds as NFM features in Belford in Northeast England.

Future studies could also focus on other potential benefits of earth bunds. For example, an important benefit that arises from colonisation of macrophytes and bacterial communities due to increased water storage of an area, is the creation of ephemeral pond habitats. These habitats have been shown to be of significant value to biodiversity, having a distinct ecology from perennial ponds (Hill et al., 2017). Habitat creation is an important aspect of all NFM projects, as it not only expands the benefits derived from such interventions, but also makes additional funding streams (e.g. the afore mentioned £640M Nature for Climate Fund and £25M Nature Recovery Fund) available for further NFM implementation and research. Figure 23 shows a schematic depiction of how Earth Bunds might be used as flood alleviation features with multiple benefits such as capturing pollutants from the soil, and creating habitat for a range of species. Further study into the biological communities in the bunds and how they might change through time is key to providing insight into the potential further benefits of the bunds as filters for heavy metals and ephemeral pond habitats.

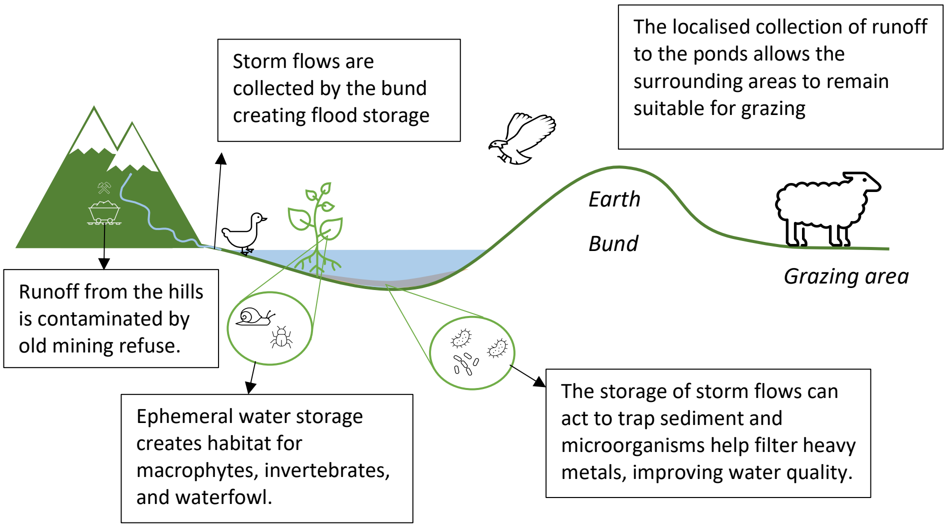


Figure 23. *Schematic representation of how earth bunds used as NFM features may create ephemeral wildlife habitats, capture sediment, and filter pollutants transported with runoff*.

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Appendix A – Glossary of Terms

Term	Definition	Source
Natural Flood Management (NFM)	"Protecting, restoring and emulating the natural hydrological and morphological processes, features and characteristics of catchments using environmentally sensitive and beneficial techniques to manage sources and flow pathways of flood waters."	(Ellis et al., 2021)
Technical Flood Management	"A philosophy guiding flood risk reduction grounded in the physical control of river systems. Measured through quantitative–usually scientific and economic cost-benefit analyses to justify interventions."	(Cook et al., 2016)
Nature-based Solutions (NBS)	"[…] a broad definition covering the conserving, enhancing, and using of biodiversity by society in a sustainable manner, while also integrating social factors such as socio-economic development and effective governance" Note: this definition is not exclusive to flood risk management.	(Short et al., 2019)
Green Infrastructure	"a strategically planned and managed network of natural lands, working landscapes, and other open spaces that conserves ecosystem values and functions and provides associated benefits to human populations, in order to link GI concept closely to its implementation"	(Benedict & McMahon, 2006)
Working with natural processes (WWNP)	"Working with Natural Processes (WWNP) to reduce flood and coastal erosion risk (FCRM) involves implementing measures that help to protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast"	(Environment Agency, 2017)
Sustainable Drainage Systems (SuDS)	"sustainable urban drainage systems aim to slow down and reduce the quantity of surface water runoff in an area in	(McKenna Davis and Sandra

	order to minimize downstream flood risk and reduce the risk of resultant diffuse pollution to urban water bodies”	Naumann, 2017)
Sustainable flood management	“An alternative philosophy to technically focused management, which prioritises risk reduction. Willing to incorporate technical control of river systems, but emphasis on behavioural adaptations”	(Cook et al., 2016)
Natural and Nature-Based Features for Flood Risk Management (NNBF)	“The use of landscape features to produce flood risk management benefits. […] These landscape features may be natural (produced purely by natural processes) or nature based (produced by a combination of natural processes and human engineering) […].”	(Bridges et al., 2021)
Making space for the river	“[…]system-oriented approach […] in which the river is given the room to behave in its natural way and to deal with natural disturbances” and also “a simultaneous move from vertical flood defences to horizontal expansion (widening) of rivers, and from vertical, top-down management to more egalitarian forms of multi-actor network governance”, which takes a holistic approach to water management where flood alleviation is combined with environmental, economic, and societal benefits.	(Warner, 2012)
Ecosystem-based Flood Risk Mangement	“The ecosystem-based approach uses ecosystem services as a strategy to adapt to the adverse effects of climate change and to reduce flood risk”	(Huq & Stubbings, 2015) See also (Todorova, 2017)
Engineering with Nature	“the intentional alignment of naturaland engineering processes to deliver economic, environmental, and social benefits efficiently and sustainably through collaboration”	(Berkowitz & Hurst, n.d.)

Appendix B – Water Sensor Additional Information

Arduino Code

```
//Test code with liquid sensor
//First include libraries
#include <SPI.h>
#include <SD.h>
#include <Wire.h>
#include "RTClib.h"
//#include "LowPower.h"
#include <Sleep_n0m1.h>

//define objects: file, Real Time Clock, data logger, and sensor
File myFile;
RTC_PCF8523 RTC;
int pinCS=10; //written as "const int chipselect=10" in previous
code
int Liquid_level=0;
Sleep sleep;
unsigned long sleepTime;
uint32_t syncTime=0; //time of last sync - used to stamp time
since start
#define ECHO_TO_SERIAL   1 // echo data to serial port - JST
#define WAIT_TO_START    0 // Wait for serial input in setup()-
JST For testing - turn off for running
void setup() {
 CLKPR = 0x80; // (1000 0000) enable change in clock frequency
 CLKPR = 0x01; // (0000 0001) use clock division factor 2 to
reduce the frequency from 16 MHz to 8 MHz
  Serial.begin(9600);
  sleepTime = (900000/2);
  pinMode(5,INPUT); //designates the sensor at pin 5 as an
external input
  pinMode(10,OUTPUT);//designates pin 10 (i.e. the SD) to be an
output destination)
  //connect to the RTC
  Wire.begin();
```

```
  if(!RTC.begin()){// ! indicates "if RTC does not begin"
    myFile.println("RTC failed!");
  if(ECHO_TO_SERIAL){
    Serial.println("RTC Failed");//writes error to serial print
  }
  }
  if(WAIT_TO_START){
    Serial.println("Type any character to start");
    while (!Serial.available());
  }
  else{
    //initialise SD card
    Serial.print("Initialising SD Card...");
  }
  // initialise SD
  if (SD.begin())
  {
    Serial.println("SD card initialised");
  } else
  {
    Serial.println("SD card failed");
    return;
  }
}
void loop() {

  //call rtc
  DateTime now = RTC.now ();
  //create the txt file
  myFile=SD.open("testJST.txt",FILE_WRITE);
  //define liquid level sensor state
  digitalWrite(Liquid_level,HIGH);
  // log milliseconds since starting
  uint32_t m = millis();
```

```
  myFile.print(m);           // milliseconds since start
  myFile.print(", ");
if (ECHO_TO_SERIAL){
  Serial.print(m);         // milliseconds since start
  Serial.print(", ");
}
  //now we write into the file
  if (myFile){
      //Read sensor
      digitalRead(Liquid_level);
      Liquid_level=digitalRead(5);
      //Fetch time
      now=RTC.now();
      //log time
      myFile.print(now.unixtime()); // seconds since 1/1/1970
      myFile.print(",");
      myFile.print('"');
      myFile.print(now.year(), DEC);
      myFile.print("/");
      myFile.print(now.month(), DEC);
      myFile.print("/");
      myFile.print(now.day(), DEC);
      myFile.print(" ");
      myFile.print(now.hour(), DEC);
      myFile.print(":");
      myFile.print(now.minute(), DEC);
      myFile.print(":");
      myFile.print(now.second(), DEC);
      myFile.print('"');
      myFile.print(",");
      myFile.print(Liquid_level, DEC);
      myFile.print("sleeping for ");
      myFile.println();
      myFile.print("sleeping for ");
```

```
    myFile.println(sleepTime);
    myFile.close();//close the file

if( ECHO_TO_SERIAL){
    Serial.print(now.unixtime()); // seconds since 1/1/1970
    Serial.print(",");
    Serial.print('"');
    Serial.print(now.year(), DEC);
    Serial.print("/");
    Serial.print(now.month(), DEC);
    Serial.print("/");
    Serial.print(now.day(), DEC);
    Serial.print(" ");
    Serial.print(now.hour(), DEC);
    Serial.print(":");
    Serial.print(now.minute(), DEC);
    Serial.print(":");
    Serial.print(now.second(), DEC);
    Serial.print('"');
    Serial.print(",");
    Serial.print (Liquid_level, DEC);
    Serial.println();
    Serial.print("sleeping for ");
    Serial.println(sleepTime);
}
//if the file didn't open, print error

else{
  Serial.println("error opening M11.txt");
}
 delay(100/2);
 sleep.pwrDownMode();
 sleep.sleepDelay(sleepTime);
//LowPower.powerDown(SLEEP_8S,ADC_OFF,BOD_OFF);
```

```
}
}
```

Manufactory details

The table below presents the full list of components used for the Arduino device manufacture.

Table 1. Arduino water sensor components

Component	Supplier	Details
Arduino UNO Rev 3	The Pi Hut	SKU: A000066
Data logger shield	The Pi Hut (Adafruit)	SKU: ADA1141
Gravity Photoelectric Water & Liquid Level Sensor for Arduino	OneCall (Farnell)	SKU: SEN0205
SD Card (8GB)	Memoryc.co.uk	SKU: 13913
ABB Junction Box- IP65, 100mm x 100mm x 80mm	RS	SKU: 454-949
Battery Pack (4xAA)	Amazon	ASIN: B07D1JLG3C

Appendix C – Van Genuchten parameters

Table 1. *Van Genuchten parameters for soil texture classes and A values for a 2.25cm disk radius and suction values from 0.5 to 6cm (table taken from METER Group, 2020, Mini Disk Infiltrometer Instructions Manual, METER Group Inc.).*

Soil Texture	α	n/h_o	A						
			−0.5	−1	−2	−3	−4	−5	−6
Sand	0.145	2.68	2.84	2.40	1.73	1.24	0.89	0.64	0.46
Loamy Sand	0.124	2.28	2.99	2.79	2.43	2.12	1.84	1.61	1.40
Sandy Loam	0.075	1.89	3.88	3.89	3.91	3.93	3.95	3.98	4.00
Loam	0.036	1.56	5.46	5.72	6.27	6.87	7.53	8.25	9.05
Silt	0.016	1.37	7.92	8.18	8.71	9.29	9.90	10.55	11.24
Silt Loam	0.020	1.41	7.10	7.37	7.93	8.53	9.19	9.89	10.64
Sandy Clay Loam	0.059	1.48	3.21	3.52	3.24	5.11	6.15	7.41	8.92
Clay Loam	0.019	1.31	5.86	6.11	6.64	7.23	7.86	8.55	9.30
Silty Clay Loam	0.010	1.23	7.89	8.09	8.51	8.95	9.41	9.90	10.41
Sandy Clay	0.027	1.23	3.34	3.57	4.09	4.68	5.36	6.14	7.04
Silty Clay	0.005	1.09	6.08	6.17	6.36	6.56	6.76	6.97	7.18
Clay	0.008	1.09	4.00	4.10	4.30	4.51	4.74	4.98	5.22