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Feasibility Assessment of a Small-Scale Hydropower Scheme at Browsholme Hall, Lancashire, UK

By

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In collaboration with

Browsholme Hall

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Declaration

I hereby declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research. This thesis has not been plagiarised from any unacknowledged sources and has not been previously submitted for another higher degree.

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Abstract

The threat of catastrophic, irreversible climate change is forcing society to change its approach towards energy production. Switching to renewable energy sources is vital to cutting global carbon emissions and mitigating climate change. Small-scale hydropower is a source of renewable energy that is highly efficient, cheap and assumed to have minimal environmental impacts. Small-scale hydropower technologies can utilise flow conditions that would make larger-scale hydropower installations non-viable, such as low flow or head, to generate power. Moreover, the relatively small size of these hydropower schemes enables them to be constructed in remote and difficult-to-reach areas, providing energy security to isolated communities. In this thesis, a small-scale hydropower feasibility assessment was conducted at a rural site, Browsholme Hall, in Lancashire, UK. Browsholme Hall is a Grade I listed building which is operated by its owners as a tourist attraction and a venue for weddings and other events. Feasibility was assessed by conducting hydrological, topographic and ecological surveys. On-site waterbody discharge rates were measured over several months, whilst a long-term rainfall model was also devised to estimate discharge. Ecological surveys were conducted to ascertain whether a proposed hydropower scheme would likely cause harm to protected species on-site. The results of the feasibility assessment deemed the site unsuitable for small-scale hydropower generation. This was primarily caused by the intermittency of significant potential power generation which was due to a combination of low head and flow. From this it is inferred that either head or flow is required to be significant for small-scale hydropower to be viable. Therefore, the UK may not be as feasible for small-scale hydropower generation as previously assumed, and small-scale hydropower may be more appropriate in regions with lower energy demands. Conducting feasibility assessments are important in determining the overall viability of small-scale hydropower in the UK. Ideally, feasibility assessments should be utilised in future to devise a system to accurately and remotely assess feasibility without the requirement of extensive physical measurements.

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- **AMBER** – Adaptive Management of Barriers in European Rivers
- **AONB** – Area of Outstanding Natural Beauty
- **CEH** – Centre for Ecology and Hydrology
- **CHESS** – Climate, Hydrology and Ecology research Support System
- **Defra** – Department for Environment, Food & Rural Affairs.
- **ERN** – European Rivers Network
- **EU** – European Union
- **GHG(s)** – Greenhouse Gas(es)
- **GIS** – Geographic Information System
- **IDW** – Inverse Distance Weighting
- **IPBES** – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
- **IPCC** – Intergovernmental Panel on Climate Change
- **LCOE** - Levelized Cost of Electricity
- **NBN** – National Biodiversity Network
- **ROR** – Run-of-River Hydropower
- **RTK GPS** – Real-Time Kinematic Global Positioning System
- **SR15** – Special Report 15
- **UK** – United Kingdom
- **UN** – United Nations
- **US** – United States
- **US$** – United States Dollar
- **WFD** – European Union Water Framework Directive

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1. Introduction

1.1 Background and Rationale

Climate change is forcing society to readdress its approach towards energy production. The recent United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) Special Report 15 (SR15) (IPCC, 2018) states that society has until 2030 to maintain global temperature levels below 1.5^{o}C above preindustrial levels, or likely face catastrophic, irreversible changes to the environment. The report details that "rapid and far-reaching" changes to all aspects of society are required to limit the progression of climate change (IPCC, 2018, p. 15).

Large-scale investment and development into renewable energy sources is one of the solutions to tackling climate change. According to the *Renewables 2018 Global Status Report* published by Renewable Energy Policy Network for the 21st century (REN21) (2018), renewables generate approximately 20% of global energy production (which also accounts for wood burning technologies). However, although renewables already form a significant portion of the energy sector, investment and development of new renewable infrastructure needs to be implemented at a much faster rate and at a wider scale to curtail rises in global-mean temperatures predicted by the IPCC.

Hydropower has long been an established renewable energy source, utilising a drop in elevation to gravitationally accelerate water to generate electricity. Hydropower exhibits little lifetime carbon release, with the majority confined to the construction phase of the scheme, whilst also having the added benefit of providing flood control measures, irrigation and drinking water. Large-scale hydropower schemes were constructed extensively throughout the 1900s, providing low-cost, efficient electricity to the masses. In the United States (US) notable developments, such as Hoover Dam and the Grand Coulee Dams, helped the hydropower industry to contribute 40% of US energy production by 1940 (IHA, 2018a), with the former development since being enlarged and upgraded to a 2,080MW capacity (United States Bureau of Reclamation, 2018). In 2016, hydropower supplied 16.4% of the world's power generation and 71% of the global renewable energy installed capacity (World Energy Council, 2016), highlighting hydropower's global energy significance and potential.

Hydropower was long considered a clean, environmentally friendly source of energy. However, research emerging throughout the latter half of the 20th century began to outline various, negative environmental impacts relating to large-scale hydropower schemes. The impoundment of river courses to create reservoirs alters flow, regime which can cause a number of environmental changes, such as reduction in water quality, habitat change/degradation, sedimentological changes and alteration to river bed geomorphology (McCartney, 2009). These alterations to flow regime may cause significant environmental harm to river systems and, consequently, large-scale hydropower is no longer considered as green as it once was. This has led to calls to reform the hydropower industry, particularly in western nations, implementing new technologies, mitigation strategies and knowledge to make hydropower more environmentally friendly. Others argue that the environmental impacts of large hydropower are far too extensive and outweigh the benefits. Instead, they believe that construction of new hydropower dams should be halted and existing dams should be removed to restore river systems to their natural state.

Development of smaller-scale hydropower technology may serve to alleviate some of the environmental problems encountered with large-scale hydropower. Small-scale hydropower technologies have the ability to exploit relatively unfavourable flow conditions, such as low head or discharge, to generate electricity (Abbasi & Abbasi, 2011). Large-scale hydropower developments do not have the ability to make use of these flow conditions, which emphasises the utility and potential of small-scale hydropower schemes. Small-scale hydropower comes in a variety of forms and sizes, but generally speaking, it does not require the creation of a large impoundment of water for power generation, potentially alleviating a number of the environmental impacts caused by significant changes to flow regime in large-scale hydropower systems (SSWM, 2019). Moreover, the scale of construction of small-scale hydropower developments tends to be less extensive and significantly cheaper than large-scale hydropower (SSWM, 2019). Coupled with hydropower's high efficiency rates and relative low maintenance costs (IRENA, 2018), small-scale hydropower has become an economically viable, alternative energy source with lower environmental impacts.

The relatively small size of small-scale hydropower enables schemes to be built in more isolated and difficult to reach areas, providing localised energy to communities in the immediate vicinity. Localised energy generation reduces the need for extensive power transmission infrastructure, which subsequently decreases the electrical losses during transmission. Furthermore, small-scale hydropower provides rural and isolated communities with access to electricity, where connections to the national grid are either not available or are unreliable. This may prove to be vital in the future, as it is predicted that climate change and population growth are likely to increase energy insecurity over the coming decades (CII, 2012). Therefore, the development of localised, small-scale hydropower infrastructure may not only be a way of providing clean energy, but may also be key to increasing global energy security.

Small-scale hydropower is also able to make use of existing infrastructure such as weirs and wastewater systems. Weirs, in particular, offer significant potential for hydropower utilisation in the United Kingdom (UK) and the rest of Europe. Prior to the Industrial Revolution, weirs were built extensively in conjunction with watermills throughout Europe. Following the introduction of fossil fuels for power generation, weirs became redundant and currently have little to no importance for the communities that reside by them. An Environment Agency report published in 2010 identifies that approximately 25,000 obsolete weirs existing across England and Wales' waterways have the potential for low-head hydropower generation (Environment Agency, 2010). The Environment Agency estimates that if all obsolete weirs were utilised for hydropower generation, they could collectively generate up to 1% of the UK's energy demands in 2020 (Environment Agency, 2010). Furthermore, the RESTOR Hydro project has identified at least 65,000 former historical hydropower sites (watermills, weirs and other) that could potentially be retrofitted with modern small-scale hydropower technologies. It is estimated that approximately 6.8 TWh/yr of power could be generated if all sites were retrofitted (Punys *et al*., 2019), equivalent to 0.22% of the European Union's (EU) yearly power generation (Eurostat, 2018).

However, the credibility of small-scale hydropower alleged environmental impact has raised questions. It is assumed that, due to the smaller size of small-scale hydropower schemes, the environmental impact will be considerably less significant, but these assumptions have little to no scientific literature to back up their claims, because in actuality, there is little research within the field of small-scale hydropower environmental impacts (Abbasi & Abbasi, 2011). Part of the problem stems from defining "small-scale hydropower". Small-scale hydropower's definition is imprecise and often depends entirely on the country or region where the development is being proposed. For example, in Europe, it has now become widely accepted that small-scale hydropower is up to a generation capacity of 10MW, whereas in India, the Ministry of New and Renewable Energy defines small-scale hydropower as schemes with a generation capacity up to 25MW (Abbasi & Abbasi, 2011). This raises concerns when attempting to quantify the environmental impact of small-scale hydropower. For example, it is unclear whether a 10MW scheme has the same or similar environmental impact as 25MW scheme, nor is there any research which indicates findings can be generalised across generation capacities. Recent studies from China, Norway and Spain have all shown that small-scale hydropower does have significant impacts, with all of them concluding that small-scale hydropower has a larger impact per MW than large-scale hydropower (Bakken *et* al., 2012; Kibler & Tullos, 2013; Mayor *et al*., 2017). However, Zeleňáková *et al*., (2018) maintain that with thorough environmental impact assessment procedures during the screening phase of a hydropower scheme, the environmental impact of a small-scale hydropower scheme may be greatly reduced, allowing appropriate mitigation strategies to be employed during construction and operation. Overall, there appears to be a great deal of uncertainty regarding the potential impact that small-scale hydropower may have on the environment.

Despite uncertainty surrounding small-scale hydropower's environmental impact, the potential benefits of small-scale hydropower remain high. Small-scale hydropower can generate power at a low cost, increase energy security, encourage private ownership of energy infrastructure. The potential increase in energy security is particularly pertinent, especially to those in remote and/or rural communities, most notably in the developing world where small-scale hydropower schemes are becoming increasingly popular, often acting as the sole source of electricity. Moreover, despite potentially having a relatively small contribution to global GHG emissions reductions, scale-scale hydropower can, nevertheless, help to mitigate against climate change as it is a low-carbon technology. The benefits of small-scale hydropower may outweigh the potential environmental impacts, but this, however, will need to be quantified with further research.

This thesis explores the feasibility of a proposed small-scale hydropower scheme at a rural establishment in Lancashire, UK. Site characteristics such as discharge, head and rainfall were measured and derived, then compared against potential environmental impacts to ascertain whether an environmentally friendly small-scale hydropower scheme was possible on-site.

1.1.1 Browsholme Hall

The study site is at Browsholme Hall located in Lancashire, UK. Browsholme Hall is a Grade I listed historic Tudor house, dating back to 1507, which has been in possession of the Parker family since its construction. Browsholme Hall operates both as a family home and a business, which consists of a corporate events/wedding venue, farming and tourism.

Sustainable practices are embedded in the daily workings at Browsholme Hall. Heating for the Hall and adjacent Tithe Barn are wholly served by a ground source heat pump and a biomass boiler. Woodchip for the biomass boiler is produced on-site from the 120 acres of woodland. The woodland is under a sustainable management scheme, which primarily promotes the regeneration of existing trees, rather than importing transplants. The personal water supply is sourced from an on-site spring, whilst rainwater is collected for gardening and cleaning purposes. Estate management, the planting schedule and lake/pond maintenance are based in-part on annual ecological surveys of species such as bats, birds, hedgehogs, moths and wildflowers.

The owners are continually looking to further their sustainable practices and are currently seeking to install a form of renewable energy to power part of the property. However, the Grade I listed building status of Browsholme Hall poses a number of problems. Grade I listed buildings are considered national heritage and subsequently have extra legal protections within the planning system. Restrictions apply to changes made to a Grade I listed building's interior and exterior features. This includes planned structures separate from a listed building but within the building's vicinity, which may affect the building's overall appearance. As all listed building vary structurally and in appearance, the terms of acceptable alterations are highly subjective and dictated by the local planning authority. Depending on the leniency of the specific planning department, this may either work for or against the applicant.

Wind power is particularly popular in Lancashire, but the owners state that due to strict regulations imposed by the local planning authority, installing a wind turbine on-site would cause significant harm to Browsholme Hall's heritage, despite potentially being located a fair distance away from the property. For the same reason, the planning authority will not permit solar power panels to be installed on Browsholme Hall's roof. Rejection of solar and wind power installation projects considerably limits the possibility of adopting renewables at Browsholme Hall. However, as the premises contains various waterbodies and experiences high levels of rainfall, the owners believe there may be potential for hydropower generation.

Additionally, the owners at Browsholme Hall are keen to have their own source of energy generation to increase their personal energy security. Due to Browsholme Hall's rural location, it has often played second fiddle to urban centres during power outages. As power is prioritised for urban centres during shortages, short time-frame power restoration in rural areas is not necessarily guaranteed. Installing a privately-owned power generation system would ensure Browsholme Hall had access to electricity even during blackouts, allowing the family to maintain their on-site business practices and power their home.

Finally, undertaking a hydropower feasibility assessment at Browsholme Hall would enable the Parker family to advise about the viability of small-scale hydropower at other stately homes and/or similar rural businesses.

1.2 Aims & Objectives

The overall aims of this project were to:

- Determine if a small-scale hydropower scheme is feasible at Browsholme Hall.
- Estimate the hydropower scheme's potential power output.
- If feasible, establish the ideal location for a hydropower scheme.
- Assess the potential environmental impact of installing a hydropower scheme and develop mitigation strategies if necessary.

The project would meet these aims by achieving the specific objectives below:

- Measure and derive discharge rates of various waterbodies over a range of flow conditions.
- Take topographic measurements to measure head and to create a digital elevation map in order to model flow dynamics.
- Measure and model rainfall over an extended period to estimate frequency, variability and intensity of flow discharge events.
- Estimate the potential power output of the proposed hydropower development using collected data.
- Determine whether seasonality significantly alters hydropower output throughout the year.
- Conduct ecological surveys to ascertain the potential impact of the proposed hydropower installation.

2. Literature Review

2.1 Climate Change

A climate crisis is facing society, requiring prompt global changes to avoid adverse consequences. The IPCC (2018) SR15 highlights the scale of global warming and emphasises the importance and urgency to reduce global greenhouse gas (GHG) emissions to avoid catastrophic, irreversible changes to the environment. SR15 reports that average global temperatures are currently $1^{o}C$ higher than preindustrial levels, and that society has until 2030 to maintain global temperature levels below $1.5^{o}C$ above preindustrial levels. This would require 45% of carbon dioxide emissions to be cut by 2030. Beyond this threshold, the risk of intensifying natural disasters such as drought, floods and wildfires are likely to increase (NASA, 2019). This could, potentially, have severe detrimental, socioeconomic effects, as populations may experience food, energy and social insecurity, subsequently leading to poverty and conflict over resources. There are several potential environmental impacts if temperatures rise to $1.5^{o}C$ above preindustrial levels; however, SR15 states that past emissions alone are unlikely to raise average global temperature above the $1.5^{o}C$ limit. Hypothetically, if all anthropogenic GHG emissions were immediately decreased to zero, it is likely that warming would not exceed another $0.5^{o}C$ within the next few decades. Therefore, SR15 stresses the importance of "rapid and far reaching" changes to all aspects of society such as agriculture, energy production and transport to limit the progression of climate change (IPCC, 2018, p. 15).

Moreover, the importance to transition to a carbon neutral society is emphasised by population growth projections, as continued population growth will increase global energy demand, potentially exacerbating climate change. SR15 highlighted population growth as one the four key impediments to curtailing climate change, arguing that the common assertion that population is likely to plateau is incorrect. The UN World Population Prospects (2019) states with 95% certainty that global population will range between 9.4-10.2 billion in 2050 and between 9.6-13.2 billion in 2100. Recent research has indicated that avoiding having a child saves more than 20 times the carbon emissions per year than the next most effective measure, going car free (Murtaugh & Schlax, 2009; Wynes & Nicholas, 2017). Changes need to be implemented immediately to ensure population growth does not accelerate climate change.

The energy sector is the largest source of carbon emissions globally, accounting for 42% of emissions in 2016 (IEA, 2019). Switching to renewable energy sources would significantly reduce global carbon emissions, making the targets set out in SR15 more achievable. Renewables use naturally - replenishing sources such as sunlight, wind, tides and geothermal heat to generate electricity. The range of available renewable technologies enables renewables to be installed in varying environments and climates. Several countries are leading the way with renewables investment, demonstrating that it is possible to meet national energy demands with renewables. Costa Rica and Iceland both produce approximately 99% of their electricity using renewables (IEA, 2018; NEA, 2019), whilst Scottish wind farms produced 98% of the nation's energy demand in October 2018 (WWF, 2018). More impressively, Uruguay has been able to increase its electricity production via renewables from 40% to 95% in less than 10 years. Uruguay invested heavily in wind and solar power, with the increase in renewable investment being attributed to a supportive regulatory environment and excellent cooperation between the public and private sector, which was achieved without government subsidies or a rise in consumer costs (The Guardian, 2015). Hydropower is often a key provider of electricity, particularly in countries where renewable energy generation is high. For example, Costa Rica, Iceland and Norway, who produce the majority of their electricity using renewables, use hydropower to generate 75%, 71% and 95% of their electricity respectively (IHA, 2017a; IHA 2017b, NEA, 2019). Hydropower accounts for 72.6% of global renewable electricity generation (EIA, 2018) and, consequently, is responsible for the greatest proportion of GHG emissions reductions within the renewable energy sector. Implementation of hydropower globally will help society become carbon neutral, mitigating the effects of climate change.

2.2 Hydropower Overview

Hydropower is a highly efficient, low carbon energy production technology that uses flowing water to generate electricity. Hydropower does not actively produce polluting emissions during power generation, serving to mitigate climate change and improve air quality. Furthermore, hydropower development can also be used for flood control, irrigation and water supply (Killingtveit, 2019). The storage capacity of reservoirs allows hydropower developments to manage power generation flexibly to meet energy demands. Hydropower provides more energy security than other renewables, such as wind or solar power, which often produce variable or intermittent power generation. Despite relatively high construction costs, hydropower provides low-cost electricity, with a global average electricity cost of US$0.047 per kWh, making hydropower the cheapest source of electricity globally (IRENA, 2019). Moreover, hydropower is exceptionally economical in the long-term due to its lengthy life span, which averages 50-100 years (Renewables First, 2015a).

Hydropower can trace its origins to early water-powered technology used in China during the Han Dynasty, where tilt hammers powered by waterwheels were used in producing flour, ore and paper. The first electrification project dates to 1878, and was used to power a single light bulb at Cragside House, Northumberland, England. In the early twentieth century, rapid technological innovations paved the way towards widespread hydropower adoption worldwide throughout the twentieth century. Global hydropower installed capacity growth stagnated and fell from the late 1980s to 1990s due to financial constraints and concerns surrounding the socioeconomic and environmental impacts of hydropower (IHA, 2018a). However, hydropower has experienced renewed growth in the developing world from the start of the twenty-first century, particularly in Brazil and China, with the latter quadrupling its installed capacity between 2000-2017, accounting for over 50% of global installed hydropower capacity growth, and has led to China becoming the leading producer of hydropower globally (IHA, 2018b). The world's hydropower installed capacity currently stands at 1,292GW, producing a record 4,200TWh in 2018 (IHA, 2019).

2.3 Environmental Impact of Large Hydropower

Research published in the late 1900s began to highlight that large-scale hydropower projects cause considerable environmental impacts. The impounding of water courses to create reservoirs causes significant changes to flow regime, which can give rise to numerous environmental impacts such as a loss of biodiversity, a reduction in water quality and alterations in riverbed geomorphology.

The physical barrier imposed by dam structures prevents the flow of sediment downstream. Over time, sediments become trapped behind dams and may exhibit toxic properties. For example, anthropogenic heavy metal pollution released into waterways often binds to suspended sediments. When sediments accumulate behind impoundments, they can become highly concentrated with heavy metals (Yi *et al.*, 2011). Depending on the heavy metal concentration and mobilisation, sediment-bound heavy metals may become highly ecotoxic, potentially causing significant deterioration of water quality and/or local aquatic ecology (Baran & Tarnawski, 2015). This is particularly problematic for benthic organisms residing in hydropower reservoirs, as their habitat is within channel bottom sediments (Elias *et al.*, 2018). However, as heavy metals bioaccumulate in tissues, organisms throughout the trophic system will likely be affected by heavy metal pollution (Khan *et al*., 2018). Moreover, water quality issues are not confined to the hydropower reservoirs. Releases of poor-quality water through the hydropower scheme may cause significant environmental impacts downstream.

Alterations to flow regime and sediment transport can activate significant fluvial geomorphological changes, which subsequently may cause aquatic and terrestrial ecological harm (Magilligan & Nislow, 2005). Sediment, which becomes trapped behind dams, can deprive local ecosystems of key sediments vital for environmental processes. The Glen Canyon Dam on the Colorado River deprives downstream sandbars of sediment recharge, making their future uncertain. Sandbars on the Colorado River provide a low-velocity flow habitat which is vital for juvenile endemic fish, as well as providing a suitable substrate for rare riparian vegetation (Wright *et al*., 2008). The disappearance of these sandbars is likely to cause a significant shift in local ecological community structure and assemblages. Mitigation measures typically focus on the implementation of fish passes to avoid impact to migratory fish. However, as dams present a number of impacts to aquatic organisms, not all issues can be resolved with a fish pass. Furthermore, alteration to natural flow regime, particularly the introduction of turbulent flow downstream of dams, increases the erosion rate resulting in deepening and widening of the channel (NSW Department of Primary Industries, 2006).

The creation of reservoirs can significantly affect ecological communities by altering the thermal regime. Deep reservoirs typically experience thermal stratification where warm surface layers form over cold, dense layers deeper in the reservoirs (Xie *et al*., 2017). This can be particularly problematic in warmer countries such as Australia, where cold-water pollution may significantly affect local aquatic ecology. As hydropower intakes tend to be located towards the bottom of the dam structure, unusually cold water can be released from the reservoir, which can impact several kilometres downstream (NSW Department of Primary Industries, 2006). Water temperature is particularly important for native fish breeding in the water, as it is acts as a thermal cue for spawning and larval development. Cold-water pollution has also been shown to affect a wide array of physiological and biological processes of aquatic organisms such as ventilation, metabolic and growth rates (Lugg & Copeland, 2014). Moreover, decaying organic matter within the cold, dense layer of reservoirs is decomposed by oxygen-depleting bacteria, which can cause the water to become anoxic or hypoxic. This may lead to the release of anoxic/hypoxic water downstream, which can disrupt oxygen-sensitive aquatic organisms in the river (NSW Department of Primary Industries, 2006).

Recent research has shown that the flooding of land to create reservoirs releases large quantities of methane emissions, as vegetation submerged in the reservoir begins to decompose (Deemer *et al*., 2016). Methane emissions are more prevalent in tropical hydropower reservoirs, which until recently have been considerably underestimated (Fearnside, 2015). Deemer *et al*., (2016) estimates that hydroelectric schemes emit approximately a billion tonnes of GHGs, which constitutes 1.3% of global anthropogenic GHG emissions. This is highly problematic and contradictory for a renewable energy source, particularly when one considers the volume of methane being released, which has global warming potential that is 25 times higher than that of carbon dioxide (Gunkel, 2009). The GHG emissions released by reservoirs form a significant proportion of the global anthropogenic GHG emissions, and therefore, hinders the fight against climate change.

Despite recent research highlighting the environmental issues associated with large-scale hydropower schemes, the use of hydropower is on the rise (REN21, 2018). The growth of hydropower is most apparent in East Asian and Pacific regions (IHA, 2018b), whilst EIA (2015) predicts that hydropower is to form much of the newly installed renewable energy capacity until 2050. The adoption is being driven by the prospect of cheap, efficient energy and global renewable energy targets. This may help mitigate climate change in the long run but raises concerns regarding other environmental impacts such as habitat degradation.

2.4 Alternatives to Large-Scale Hydropower

The environmental impacts of large-scale hydropower are well documented, and new research continues to highlight the varying impacts of large-scale hydropower on the environment. Although there is continued investment into large-scale hydropower development, some in the industry are seeking alternatives to alleviate some of the environmental pressures of large-scale hydropower.

The following section will introduce and evaluate a number of the alternative technologies and measures available to mitigate large-scale hydropower’s environmental impact.

2.4.1 Dam Removal

Problems associated with large-scale hydropower such as ecological degradation, human displacement and safety concerns, has led many to question the future of large hydropower. While many to continue to construct new hydropower developments, particularly in the developing world (Moran *et al*., 2018), others suggest that the reliance on hydropower for energy production should be reduced to minimise environmental degradation (Moran *et al*., 2018). Those who share the latter opinion, often also maintain that removing large hydropower dams is required to effectively remediate the impact caused by the developments over their lifetime (American Rivers, 2017; Gough *et al*., 2018).

Chiefly driven by environmental concerns, dam removal projects are becoming increasingly popular, particularly in the western world (ERN, 2019; WWF, 2019). In the US, the trend of dam removal continues to increase, with a record 86 dams removed during 2017 across 21 states, reconnecting over 550 miles of waterways, amassing to a total of 1275 dam removals over the past 30 years (American Rivers, 2018). Furthermore, others also cite safety and economic concerns, claiming that the repair and maintenance of aging dams is too costly an investment; for example, the American Society of Civil Engineers (2017) estimates that it would cost approximately US$45 billion to repair America's aging, high-risk dam structures.

By removing large dam structures, a river system can be restored to its natural state, providing an opportunity for local fauna and flora to naturally rebound and recover. The fact that only a third of the world's longest rivers remain free flowing indicates the scale of river damming (Grill *et al*., 2019). Moreover, Grill *et al*., (2019) also explain that the primary contributors causing river connectivity loss are river fragmentation and flow regulation. The importance of this is stressed by a recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report (2018), which explicitly states the conservation and restoration of river connectivity is imperative to improve freshwater biodiversity. Within the EU, dam removal could be an effective way for member states to meet the requirements prescribed by the EU Water Framework Directive (WFD). The WFD asserts that all European rivers must be of "good" ecological status, a standard which currently, 40% of rivers do not meet (WWF, 2019).

However, dam removal projects are expensive, and there is much debate as to whether the investment made to restore river courses to a more natural regime is economically viable, and whether dam removal significantly improves or restores conditions to pre-dam construction levels. Moreover, other non-dam related factors may have an environmental impact on dammed waterways, which may not have been previously considered. For example, salmon population decline can be attributed to the estuarine habitat loss and degradation due to industrial development, as these habitats are highly important for juvenile salmon rearing (Simmons *et al*., 2013). Decline in the salmon population on the Columbia River and estuary are well documented. Bottom *et al*., (2001) found that the installation of hydropower and irrigation dams was a key factor in the drop in salmon population, estimating that spawning and rearing was reduced by as much as 55%. However, the study also identified that the destruction of tidal swamp and marshland in the estuary for industrial purposes was just as significant to the declining salmon population, which degrades important salmon rearing grounds as previously stated. Bottom *et al.,* (2001) asserted that a number of contributory factors in salmon population decline, such as estuarine water temperature changes and prey-availability, may or may not be related to the construction of hydroelectric dams. Therefore, it is difficult to quantify the level of environmental remediation that could be achieved by dam removal projects, as there are a number of non-dam related factors potentially causing environmental issues. Moreover, it becomes even more problematic to predict the effect of dam removal projects when there is a lack of historical environmental baseline surveys throughout a river system, which is often the case for smaller rivers and streams.

Furthermore, the negative impact of dam removal may be more extensive than currently reported. Dam removal may mobilise toxic sediment stored behind the impoundment or cause supersaturation (American Rivers, 2005), whereas existing dams can inadvertently be beneficial. This is because barriers in the channel may prevent invasive species from occupying habitats upstream, such as the red swamp crayfish (*Procambarus clarkia*), an invasive species in Spain, which was effectively prevented from expanding its range in upland streams with the use of dams (Dana *et al*., 2011). Supersaturation is the process by which air pressure and flow velocity are greatly increased above water body's natural conditions. Supersaturation can cause significant adverse impacts to organisms downstream, such as gas-bubble disease, which may give rise to gas embolisms in the gills and tissues of fish often leading to death. Supersaturation is generally attributed to draining reservoirs too quickly and tends to only affect ecosystems for a short period after dam removal. Moreover, supersaturation may be avoided with proper planning, ensuring that reservoirs are drained at an appropriate rate (American Rivers, 2005).

Schiermeier (2018) states that greater monitoring of negative impacts is required during dam removal projects to avoid cherry picking data. Carlos Garcia de Leaniz, an ecological researcher at Swansea University, who is part of the EU-funded Adaptive Management of Barriers in European Rivers (AMBER) project, explains that in the past, dam structures were built with little concern for the impact they had on the environmental (Schiermeier, 2018). Garcia de Leaniz stresses that the same mistake must not be made during dam removals, as there is a risk that this may cause harm to our ecosystems, especially if they are not monitored correctly

(Schiermeier, 2018). It is vital not to assume that dam removal projects only provide environmental benefits. Given that there is a general lack of scientifically rigorous "*theory of dam removal impacts*", it is challenging to establish an effective environmental impact assessment prior to dam removal. Part of this stems from the fact that likely impacts are dependent on-site specific characteristics such as sedimentology. For example, water quality response to dam removal is difficult to generalise as water quality trends are dependent on factors such as sedimentology, flow conditions and biogeochemical cycle rates within the river system (Tonitto & Riha, 2016). Furthermore, even when site specific characteristics are known, it can still be difficult to predict the effects. Despite well-established concepts, geomorphologists are unable to accurately predict changes to stream bed geomorphology following dam removal (Pizzuto & Notes, 2002). Nevertheless, post dam removal monitoring efforts are increasing, such as French scientists' plans to monitor the removal of two dams in the Sélune Valley in Normandy commencing in 2019 (Schiermeier, 2018).

Dam removal projects have been shown to significantly improve the quality of water courses, but uncertainty remains surrounding the degree to which negative environmental impacts are caused by hydropower dams as opposed to other industrial processes. Dam removal appears to be an appropriate solution for aging-dams, as the investment required for repair and maintenance is much greater than the cost of removal. However, due to the sheer number of dam or weir structures that presently exist in water bodies, the cost of removing all of these would be immense, likely exceeding the budget for environmental remediation of any local, regional or federal authorities. A lack of research and monitoring of the negative impacts of dam removal creates formidable uncertainty. As the negative environmental impacts of dam removal projects are rarely quantified, dam removal may not be as restorative as proclaimed, which could potentially create significant problems in the future. However, research does indicate that any negative impacts stemming from dam removal are short-lived and lose significance once a river system returns to equilibrium and its natural state. Moreover, with adequate dam removal planning, negative environmental impacts can be mitigated. Similarly, a number of scientists have suggested that with proper environmental impact assessments prior to hydropower construction, site-specific mitigation strategies can be employed through operation which significantly reduces the risk of harm to the environment.

2.4.2 Mitigation

Not all of those seeking to reduce the impact of large-scale hydropower support such a radical approach as dam removal. Others would prefer to invest in mitigation strategy research, reducing the environmental impact and enabling developers to continue to utilise hydropower to produce clean energy. Consequently, developers have invested heavily in mitigation strategies, spanning from the pre-construction to the operational phases of a hydropower scheme.

Mitigation tends to focus primarily on migratory fish, and subsequently, fish passes have been installed widely at hydropower schemes. Most fish passes have been designed to allow passage upstream, particularly for migratory fish such as salmonid species (NHA, 2010). However, mitigation measures for fish that migrate downstream are lacking compared to the mitigation available for upstream migratory fish. Fish usually migrate downstream of channel barriers in one of three ways, as follows: fish are entrained into abstraction intakes and passed through the turbine; fish are redirected into collection channels or directly into the tailrace using bypass screens, or fish pass directly over the barrier in overflowing water (NHA, 2010). A lack of adequate screens in front of abstraction intakes (particularly for juvenile fish) or a general lack of mitigation measures leads to fish being entrained in abstractions intakes. Fish entrained through turbines may be subject to physical stresses which may cause deleterious effects such as rapid pressure changes, turbulence and turbine blade strike. Fish passing through turbines experience an injury/mortality rate of up to 5% in the highest quality conventional turbines, whereas fish passing through other turbines may experience mortalities of 30% or higher. Advanced turbines, currently in development, claim to reduce fish mortality to 2% or less (NHA, 2010). Fish migrating past dams via bypass screens and in overflowing water face additional risks. Weak swimming, juvenile fish may become trapped or injured by bypass screens. Moreover, migratory fish are subject to predatory fish that may reside by the outfalls of collection channels or tailraces. The design and location of such features are imperative to minimise the exposure of migratory fish to predators. Fish passing over high head dams via overflow risk collision with the dam wall and structures below the water’s surface, including those intended to dissipate high energy overflow. Conversely, overflow may reduce the residence time of fish migrating downstream, reducing the potential for predation above the dam in the reservoir. Subsequently, the entire design of hydropower schemes directly and indirectly influences the health and safety of fish migrating downstream (NHA, 2010).

Design flaws in fish passes intended for upstream passage of fish also cause problems. Most fish passes are designed for the specific passage of anadromous salmonid species (NHA, 2010). However, the efficacy may not be as high for other fish species due to their own specific behaviours and physiologies; for example, adult white sturgeon were found to be too large to navigate effectively through certain fish passes designed in North America (NHA, 2010; Thiem *et al*., 2011). Furthermore, the efficacy of existing fish passes for other freshwater species, such as eels and crayfish, are poorly understood. Currently, fish passes do not consider the greater diversity of aquatic organisms in waterways, and rarely consider potamodromous and river-resident species (Dodd *et al*., 2017). The focus on anadromous salmonid species may be driven by their held importance to certain groups such as anglers, or well publicised environmental issues surrounding anadromous salmonid species.

Upstream fish pass design, particularly in Europe, is increasingly becoming what is known as "nature-like bypass". Nature-like bypasses simulate natural flow characteristics, over a range a different flow conditions, using natural materials, which in theory should increase fish attraction, and provide upstream and downstream for a wide variety of species, including non-fish species (NHA, 2010; Dodd *et al*., 2017). Studies have shown that the attraction and passage efficiency of natural-like bypasses are high for anadromous and potamodromous species (Aarestrup *et al*., 2003; Dodd *et al*., 2017; Steffensen *et al*., 2013). Kim *et al*., (2016) showed that some fish spent periods longer than 28 days within natural-like bypasses, indicating that these passes are being used for other purposes than passage. A study of nature-like bypasses in a Portuguese lowland river found that different environmental variables determined variation and diversity of species seen in the pass. Discharge was found to be responsible for the abundance of cyprinid species using the pass, while water temperature was the critical factor driving passage of diadromous species (Santos *et al*., 2005). Consequently, taking control of the environmental characteristics of natural-like bypasses at each site may permit greater species diversity in the pass.

Mitigation measures also focus on natural hydrological flows, attempting to use technology to release varied quantities of water to mimic seasonal variations in flow regime, such as simulated flooding. Natural flooding controls important environmental processes, such as sediment dynamics, riparian habitat maintenance and groundwater recharge in arid areas (NHA, 2010; Zhang *et al*., 2017). Release of simulated flows tends to be straightforward water is either diverted to an outflow channel or, alternatively, allowed to spill over dams, given that flow below the dam is relatively calm. Implementing environmental flows are costly endeavours, as controlled releases result in a loss of generation and subsequent losses in revenue, which can be extremely high especially in large generation capacity schemes (EPRI, 2011) The biggest challenge to implementation stems from determining the quantity, schedule and frequency of releases. The specificity of releases is often site-specific, which usually requires extensive surveys to provide effective mitigation (Cioffi & Gallerano, 2012; NHA, 2010). Given that there tends be a lack of funding, particularly with smaller hydropower schemes, it becomes more difficult to implement mitigation (Grantham, 2014; NHA, 2010). Moreover, there is a great deal of uncertainty surrounding the validity of environmental flow assessments. Hydropower schemes would be more inclined to invest in environmental flow releases if the supposed benefits could be accurately quantified and guaranteed (NHA, 2010).

Common water quality issues such as changes to thermal regime and dissolved oxygen concentrations can be mitigated with emerging technologies. Thermal stratification is commonplace in temperate zone reservoirs. Hypoliminal releases into tailwaters may cause cold-water or warm-water pollution (season dependent), which may cause significant disruption to aquatic ecology downstream of dams. Gray *et al*., (2019) showed that a newly developed thermal curtain was able to significantly mitigate cold water pollution from a dam in Australia. The thermal curtain reduced the mean monthly water temperature difference between an upstream control and downstream site by as much as 3.5°C. Thermal recovery (during the summer), where river temperatures return to within normal ranges, occurred 45km downstream of the dam, compared to 200km without the thermal curtain.

Thermal stratification may also lead to reductions in dissolved oxygen concentration in hypoliminal water. Hypoliminal layers are isolated from atmospheric oxygen diffusion and wind mixing, reducing dissolved oxygen concentration, whilst bacterial decomposition of organic matter at the bottom of the reservoir may further deplete dissolved oxygen concentration. Hypoliminal releases from the reservoir may cause deleterious effects to ecology and undesirable aesthetic qualities. Dissolved oxygen concentration in reservoir and abstracted water can be increased by installing aeration technology in forebays, turbine runners or as weirs in the tailrace (NHA, 2010). The efficacy of dissolved oxygen mitigation measures are clearly determined with appropriate water quality monitoring technology. Dissolved oxygen mitigation measures have proven successful in a number of cases. Additionally, tailrace weirs can also provide secondary benefits, acting as a tool to dissipate turbulence from turbine discharges (NHA, 2010).

This stated, critics of large hydropower state that the environmental impacts of large-scale hydropower schemes are too numerous and far-reaching to be effectively mitigated. For example, mitigation measures cannot restore the sedimentological imbalance cause by dams. Regarding fish passes, they tend to provide passage to a select number of species inhabiting a river system. Although the thermal curtain developed in Gray *et al*., (2019) shows mitigatory promise, the impact of cold-water pollution is still significant. Mitigation strategies may alleviate some of the environmental problems caused by large-scale hydropower, but it is unlikely to adequately provide full restorative benefits.

2.4.3 Small-Scale Hydropower

Small-scale hydropower technologies provide highly efficient, cheap and clean energy. Due to the relatively small size of small-scale hydropower developments, the environmental impact is assumed to be considerably smaller or negligible (Abbasi & Abbasi, 2011). Small-scale hydropower schemes tend to be built for localised energy production, reducing the extent of construction and power transmission infrastructure required. Small-scale hydropower technologies come in a variety of forms, spanning from run-of-river (ROR) to in-stream turbines, with the majority of small-scale hydropower developments typically being the former. ROR systems abstract water from a river or stream without creating a significant impoundment of water, often using weirs to divert a proportion of flow for abstraction. In theory, ROR should minimise the impact of hydropower by enabling much of the flow to assume its natural course, while the abstracted water is returned to the water course downstream following electricity generation. In-stream turbines require no impoundments to generate electricity and are inserted directly into rivers or stream for generation. Small-scale hydropower turbines can generate electricity in localities with low head or flow, making them highly applicable. There is no strict definition of “small-scale hydropower”. The definition varies from place to place but is based on the generation capacity of hydropower turbines; for example, small-scale hydropower can be defined as <10MW in Europe, <25MW in the US and <50MW in China (Mayor *et* al., 2017; SSWM, 2019). Hereinafter, when referring to small-scale hydropower, it will be defined as <10MW, unless otherwise stated. For example, when discussing research, if the author uses an alternative definition for small-scale hydropower, such as <25MW, this will be explicitly stated. Small-scale hydropower can be further divided into the following subcategories dependent on its generation capacity; pico (<5kW), micro (5 kW – 100 kW), mini (100 kW – 1 MW) and small (1 MW – 10 MW) (Renewables First, 2015c).

The construction costs of small-scale hydropower schemes depend on various site-specific characteristics such as geology, flow conditions and ecology, as well as the desired turbine generation capacity. Typically, construction costs range from US$1,000 - 2,000 per kW. Furthermore, maintenance costs tend to be relatively lower than other technologies (Singh, 2009). When compared to technologies with similar maintenance cost (as a percentage of total installed costs), such as wind, the efficiency of small-scale hydropower outcompetes other technologies, providing the former with an additional advantage (IRENA, 2018). Moreover, the lifespan of small-scale hydropower developments can stretch beyond 50 years before requiring a significant upgrade, making small-scale hydropower an enduring, economically worthwhile investment. Research has shown that the economic feasibility of small-scale hydropower in rural developments is high, even if communities are sparsely populated due to the low costs of distributing electricity (Williams & Porter, 2006). Furthermore, installing small-scale hydropower technology into existing infrastructure, particularly drinking water or wastewater infrastructure, can significantly reduce investment costs, enabling existing infrastructure to have multiple uses.

Small-scale hydropower turbines integrated into existing water infrastructure (known as conduit hydropower), provides power generation and reduces the extent of construction by approximately 50%. Conduit hydropower systems have no significant impact as they operate in a completely man-made environment and have continuous rates of discharge through the year as they utilise municipal water works. The generation of electricity in conduit hydropower systems can be used to power the water supply network, whilst excess electricity can be diverted to the grid. The potential for conduit hydropower generation is particularly noteworthy; no land acquisition is required for conduit hydropower installation and there are extensive water supply networks throughout the urbanised world (Kucukali, 2011). Conduit hydropower can be integrated into existing infrastructure in various ways. Within drinking water systems, pressure breakers can be replaced with turbines to make use of excess pressure in pipes to generate electricity. In wastewater systems, wastewater can be diverted through a turbine prior to entering a wastewater treatment plant. Following treatment, wastewater can be diverted through a turbine again to generate electricity, before being discharged into the environment. Conduit hydropower can also be installed within runoff collection systems, acting in a similar way to water supply systems, where pressure is relieved to generate electricity. Conduit hydropower turbines can even be installed in fish passes required by law as mitigation measures. Turbulent discharge produced in fish passes to attract fish can also be installed with turbines to produce electricity. These examples of conduit hydropower installations are not exhaustive; conduit hydropower infrastructure can be installed in numerous technologies such as desalination plants and heating/cooling systems

(San Bruno *et al*., 2010). The potential utilisation of conduit hydropower has not been quantified but appears to be significant. Coupled with no apparent environmental impact, the potential sustainability of conduit hydropower is high.

Small-scale hydropower is becoming increasingly popular in the developing world, particularly within rural communities, where privately-owned hydropower infrastructure can provide access to electricity in areas where grid connections are non-existent; Laos, for example, is one country where small-scale hydropower installation projects are being trialled. One project installed numerous pico-hydropower turbines from 2007-2012, providing electricity to 36 isolated villages in northern Laos. Each family was provided with approximately 1kW of electricity, which covered basic energy demands. The installation of pico-hydropower turbines reduced the monthly cost per family from US$2.88 to US$0.02 compared to previous energy generation systems. This equated to a saving of 2-5% of annual family income. The primary impact of the hydropower installations were improvements to quality of life. For example, a reliable electricity source provided lighting for evening work and social spaces, made household tasks (such as cooking) more straightforward and improved care conditions for doctors visiting the families. At the end of the project, families were interviewed, and the reported satisfaction rate of the installation project was 100%. Due to the success of this project (and similar ones), more small-scale hydropower turbines have since been installed in this region, and further projects are being planned throughout isolated regions in of the country (Descotte, 2016). Localised hydropower installation projects, such as those in Laos, not only provide energy security, but also improve quality of life. The relatively cheap cost of small-scale hydropower may prove to be helpful in delivering energy security in developing countries, which in turn, may help reduce global GHG emissions. Given that many impoverished communities in the developing world lack any extensive GHG emitting energy generation infrastructure, the adoption of renewables is potentially made easier and would bypass any socioeconomic issues related to the replacement of existing infrastructure.

2.4.3.1 Cost of Small-Scale Hydropower

The investment and adoption of small-scale hydropower technology has been slow. Some cite that small-scale hydropower is not as cost effective as alternative power generation technologies. There is great variation in the reported installation costs of building small-scale hydropower schemes. Consultants and construction agencies report costs of US$3,500 – US$15,000 per kW of installed capacity, which equates to US$1,200 to US$5,000 per connection, which is very costly (Practical Action, 2019). Conversely, the World Bank Group (2014) estimates that installation costs range from US$1,300 to US$8,000 per kW, while other research has found that small-scale hydropower installation is inexpensive and only slightly more expensive than its competitors (Practical Action, 2019). Practical Action (2019) found that installation costs of projects in the developing world ranged from US$1,500 to US$3,000 per kW of installed capacity, which equals US$500 to US$1,000 per connection. These costs include all screening assessments, scheme construction and connection to users. Major cost reductions have been attributed in part to sourcing of alternative local materials, components, skills and labour. Locally manufactured equipment can be sourced for 30-50% of the price of imported hydropower infrastructure. Furthermore, when sourcing materials for pico and micro (≤100kW) hydropower schemes, the cost of parts can be found at 20-30% of the price of imported components. This illustrates that costs can simply be reduced by sourcing local material and labour to reduce costs. However, IRENA (2018) states that low, small-scale hydropower installation cost is partly driven by the remaining economic hydropower potential of a country, particularly in the developing world, where there tends to be many undeveloped sites to utilise. As Practical Action's (2019) study sites inspected schemes in the developing world, the reduction in cost may be attributed to the costs and economies associated with developing nations, which may not be able to be generalised to the economically developed nations.

Kosnik (2010) details the cost effectiveness of small-scale hydropower based on installation costs in the US. The study reports that the range of construction cost varies significantly, ranging from US$638 to US$6,103,161 per kW of installed capacity. The data shows that the generator capacity of the hydropower scheme greatly determines the cost effectiveness of the scheme. The study found that micro hydropower was the least cost effective, with average construction costs at US$59,528 per kW, whereas mini (100kW-1MW) and small (1MW-30MW) hydropower were deemed the most cost effective, with average construction costs of US$18,155 and US$8,332 respectively. This demonstrates that increased energy demand in developed nations, such as the US, makes lesser generation capacity schemes too costly. More specifically, it may highlight the cost variability dependent on each country's hydropower industry and resource viability. The study details Norway's average installation costs per kW of installed capacity, with small and mini hydropower projects costing approximately 60% less compared to the US. This may be due to Norway's topography, which has high suitability for hydropower and has subsequently led to Norway regularly producing 95% of its energy production via hydropower (IHA, 2017b).

Analysing median installation costs in Kosnik (2010), reveals the challenge expensive installations cause by skewing data. Over 50% of “small” hydropower installation projects cost less than US$5,000. As the installation cost is greatly dependent on site-specific characteristics, it can be hypothesised that those projects with expensive construction costs are down to installation at less than desirable hydropower sites. This is important to highlight in order to demonstrate that average small-scale installation costs may be reduced if adequate pre-screening processes are carried out.

However, given small-scale hydropower’s relatively long lifespan, low operation/maintenance costs and high efficiency rates, small-scale hydropower has a low levelized cost of electricity (LCOE) (IRENA, 2018). The World Bank Group (2014) estimates that small-scale hydropower’s LCOE is US$0.02 to US$0.27.

2.4.3.2 Environmental Impacts of Small-Scale Hydropower

As previously stated, the majority of small-scale developments are ROR schemes (SSWM, 2019). The reduction of impounded water in ROR schemes is assumed to minimise environmental impact by allowing more water to flow naturally. However, research indicates that changes in flow regime in ROR hydropower systems cause considerable changes to local ecosystems (Anderson *et al*., 2014). Moreover, the environmental impacts of small-scale hydropower development are not as well studied as their larger counterparts. Many of the authors who claim the environmental impact of small-scale hydropower is inconsequential, base their opinions on personally held beliefs as opposed to scientific literature (Abbasi & Abbasi, 2011). This creates significant uncertainty regarding the claimed environmental friendliness of small-scale hydropower. However, Anderson *et al*., (2014) note that as each study site has its own unique scheme size, waterbody condition and native ecological community, the observed impacts related to ROR schemes cannot necessarily be generalised and attributed to *all* ROR schemes; likewise, the absence of mitigation measures at study sites may be driving the observed environmental impacts. Moreover, the lack of long-term data and the limited ability to assess temporal changes following scheme installation hinder ROR environmental impact research. Additional problems may arise when attempting to isolate hydropower-specific impacts in research that analyses schemes that have retrofitted to existing structures, which may actually be attributed to impacts related to existing modifications. This conclusion is not unique to retrofitted hydropower dams, and it is essential to differentiate between impacts caused specifically by hydropower and those due to poor implementation, operation or mitigation strategies.

However, recent research indicates that the environmental impact of small-scale hydropower may, at the very least, be just as significant as large-scale hydropower. Kibler & Tullos' (2013) research comparing the cumulative biophysical impact of small-scale and large-scale hydropower in Nujiang Prefecture, China, revealed that the various impacts of small-scale was greater than that of large-scale hydropower. For example, in terms of habitat loss, higher rates of water depletion related to small dams caused a greater decline in habitat diversity than large dams, by two orders of magnitude. The direct cumulative effect per unit of power to protected conservation areas from small dams was roughly two to six times higher than that of large dams, whereas the indirect cumulative effect per unit of power of small dams was two orders of magnitude higher than large dams. Small dams were also found to cause greater depletion of water during low to moderate flows. Small dams exhibited a higher potential of change to the annual hydrograph per unit of power than large dams by three to four orders of magnitude. On the other hand, in comparison to small dams, large dams had a greater effect on catchment connectivity, landscape stability, sediment modification and water quality.

The greater impact caused by small-scale hydropower over large-scale hydropower was predominantly a measure of impact per unit of power rather than absolute impact, but is nevertheless, important. The results of the study do not indicate that small-scale hydropower has a greater environmental impact than large-scale hydropower but, rather, that small-scale hydropower does have the potential for significant environmental harm. By quantifying the impact small-scale hydropower has per unit of power, it enables researchers to formulate the point at which hydropower schemes impose significant impacts on the environment. However, this may be difficult to undertake as the potential for harm per unit of power may be down to specific hydrological, sedimentological and design characteristics.

It should be noted that small-scale dams in Kibler & Tullos' (2013) study were defined as hydropower schemes with a generation capacity of 50MW or less, rather than 10MW or less than is widely considered small-scale in Europe (SSWM, 2019). It could be argued that these results cannot be generalised to smaller hydropower developments due to the generation capacity, but the study highlights the issue with defining hydropower and the uncertainty surrounding the environmental impact of small-scale hydropower. Moreover, the difference in impact between small and large dams in this study could be due to a number of factors, such as mitigation strategies, hydropower scheme design and site-specific characteristics, all of which are difficult to control.

However, other research conducted in Europe, which defined small-scale as less than 10MW generation capacity, has shown small-scale hydropower has similar effects as identified by Kibler & Tullos (2013). A study comparing large and small dams in the Spanish Duero Basin found that small dams had a more significant impact per unit of power than large dams for all environmental impact indicators including water depletion, length of river affected, habitat loss and river connectivity. The only incidence where small dams had a greater absolute impact was in terms of river connectivity; in all other areas, large dams had a greater absolute environmental impact (Mayor *et al*, 2017). Furthermore, the study highlights the limitations of small-scale hydropower for energy security. Only 20% of small dams' installed capacity was time controllable, with no pumped storage capability, whereas 100% of large dams' installed capacity was time controllable, with 35% of its capacity able to utilise pumped storage. This emphasises the superiority large-scale hydropower has in providing power grid stability, allowing for extra power generation during peak times, which subsequently boosts energy security.

Research published in Norway found that 27 small-scale hydropower schemes had a marginally higher tendency to accumulate more environmental impacts than 3 large hydropower sites (Bakken *et al*., 2012). The study concludes that a reasonable assumption can be made that a small number of large hydropower projects will produce more electricity with a lower environmental cost than numerous small hydropower projects, rejecting the status quo that small-scale hydropower is more environmentally friendly than its large-scale counterpart. However, the authors concede that due to a lack of precision in their data and weaknesses in methodological foundation, their research is prone to uncertainty, throwing the validity of their conclusion into question. Bakken *et* al., (2012) and Mayor *et al*., (2017) show that even with different hydrological regimes and morphologies, the potential environmental impact of small-scale hydropower remains significant.

For smaller hydropower technologies such as pico (<5kW) (which is being considered at Browsholme Hall), there is a general lack of research investigating the environmental impact of pico generators. This is because pico generators are assumed to have a negligible environmental impact as they impart much smaller changes to flow regime compared to large-scale hydropower. However, as is seen with a number of the larger power capacity small-scale hydropower developments, they have marked environmental effects, despite being magnitudes smaller in terms of power generation compared to large-scale hydropower.

In order to maximise the potential of small-scale hydropower, construction of numerous schemes is required. The versatility of small-scale hydropower enables construction throughout the catchment, whereas large-scale hydropower development tends to be built lower in the catchment (Mayor *et al*., 2017). This presents a problem as small-scale hydropower has the potential to create disturbances across longer distances throughout the catchment, reducing connectivity. Large-scale hydropower, on the other hand, has a greater environmental impact but it is confined to a smaller section in the lower reaches of the catchment. Moreover, individual small-scale hydropower developments may not cause the same impact as a large-scale hydropower development, but the cumulative impacts of potentially hundreds or thousands of small-scale hydropower schemes presents a significant problem. It is difficult to quantify which one would be more impactful in the long run, but it must be accepted that small-scale hydropower does have the potential to cause considerable environmental impacts. Mayor *et al*., (2017) recommend that existing single-use non-hydropower reservoirs, dams and weirs should be optimised with hydropower to minimise the environmental impact by providing clean energy production. This pairs nicely with the Environment Agency's (2010) report, which identifies 25,000 obsolete weirs in England and Wales that are suitable for hydropower generation. If these structures already exist in abundance, they are likely causing negative environmental impacts with little to no benefit to society. Retrofitting obsolete weirs in England and Wales would be making the best of a bad situation, increasing clean energy production, whilst offsetting some of the environmental impacts the weirs may already be causing. Furthermore, no new channel obstructions would need to be constructed, lessening the environmental impact.

As previously mentioned, there is no accepted definition of small-scale hydropower. The definition varies from country to country and region to region, but the definition is always based on generation capacity of the turbine, as opposed to the size and scale of the development. For example, the Elwha and the Glines Canyon Dam had a generation capacity of 15MW and 13MW respectively. In the US, both dams would have classified as "small-scale hydropower", but in fact, the size of these dams was substantial, standing at 33m and 64m respectively (Forbes, 2018). The Elwha Dam caused significant environmental effects throughout the region, severely impacting local ecology, such as the salmon population, which experienced substantial decline. Generation capacity of a hydropower scheme is not necessarily the most appropriate way to class dams for the purpose of environmental impact assessment. Research that investigates small-scale hydropower's environment impact based on generation capacity alone does little to help generalise findings across the board. It would perhaps be wiser to investigate and compare environmental impacts of hydropower dams based on shared or similar characteristics, such as size and scale of the development, ecology and bedrock morphology.

There is a great deal of uncertainty surrounding the environmental impacts of small-scale hydro. Many assume that due to the size of small-scale hydropower developments, the impacts are inconsequential. However, recent research indicates the relative impact of small-scale hydropower is high, and when schemes are built in abundance, the cumulative environmental impact is considerable. Nevertheless, it is difficult to generalise results to other small-scale hydropower due to the varying definition of small-scale hydropower, as well as site-specific characteristics such as flow regime, geomorphology and ecology. Moreover, research has not established whether mitigation strategies are able to effectively alleviate the environmental impact small-scale hydropower causes. There is a distinct lack of research in this field, especially when one compares the catalogue of research available investigating the environmental impact of large hydropower. Before extensive implementation of small-scale hydropower development, it may be wise to undertake further research into the potential environmental impacts of small-scale hydropower, taking particular care to control for site-specific variables. Without further research, there is a significant risk of causing further harm to the environment, which is contractionary to the aims of small-scale hydropower.

2.4.3.3 Potential Feasibility of Small-Scale Hydropower

Little research exists analysing the potential feasibility of small-scale hydropower globally. IRENA (2012) states that less than 25% of global hydropower potential is currently being utilised, indicating that potential viability of hydropower is high. It is difficult to estimate how much of the global hydropower potential is comprised of small-scale technologies. However, small-scale hydropower schemes can utilise resources that are more appropriate for large-scale hydropower generation, and subsequently, the potential feasibility of small-scale hydropower may be assumed to be high.

The majority of research investigating the feasibility of small-scale hydropower tends to focus on the potential for the developing world, such as sub-Saharan Africa and southeast Asia, where potential utility is classified as high (Kaunda *et al*., 2012; Korkovelos *et al*., 2018;

Netherlands Enterprise Agency, 2017). In sub-Saharan Africa, research indicates significant hydropower resources are in abundance, yet remain relatively unexploited (Korkovelos *et al.,* 2018). Installation of small-scale hydropower throughout sub-Saharan Africa could provide substantial rural electrification, particularly for isolated communities with no access to electricity (Kaunda *et al*., 2012). Meanwhile, in Laos, small-scale hydropower feasibility is high enough that the government plans to add 18,997MW to its total hydropower generation capacity by 2030 in order to export electricity to neighbouring Thailand, Cambodia and Vietnam (Netherlands Enterprise Agency, 2017). Small-scale hydropower feasibility assessments have been prioritised in Laos, as large-scale hydropower developments are unpopular, primarily due to resistance and awareness applied by local NGOs. Subsequently, the government promotes the development of small-scale hydropower, and this, is why small-scale hydropower feasibility has been widely explored in Laos (Netherlands Enterprise Agency, 2017).

By contrast, in developed nations, studies assessing the viability of small-scale hydropower are less common. This could potentially be due to a number of reasons. Firstly, given that energy demand is higher in developed nations, the lower generation capacity of small-scale hydropower systems may not be considered appropriate, as they will be less cost effective. Moreover, small-scale hydropower technologies are often installed in remote locations to provide localised energy for communities with no prior access to electricity. As access to electricity is more common in the developed world, small-scale hydropower rural electrification projects would only be likely to appeal to a niche market. Stricter environmental regulations, which hydropower schemes are subject to, may also be reason why small-scale hydropower feasibility research is less common in the developed world. The environmental impact of hydropower schemes is often considered in feasibility assessments in developed nations. If the construction of a hydropower scheme is likely to cause significant environmental impacts, it is likely to be deemed unfeasible. The risk of significant environmental impacts may deter feasibility research from being conducted, especially as there are considerable environmental impacts associated with large-scale hydropower.

Furthermore, the falling price of other renewables, such as wind and solar, may be another reason why small-scale hydropower potential has not been largely assessed in developed nations. As the upfront investment costs of small-scale hydropower are relatively high, and as schemes are typically under private ownership, investors may be less inclined to invest, despite the LCOE being low (IRENA, 2018). Finally, the lack of feasibility research may purely be coincidental. By chance, the topographic and hydrological features present in the majority of developed nations may generally be unfavourable for hydropower. Nevertheless, efforts have been made to identify the feasibility of small-scale hydropower in developed nations. Bódis & Szabó (2016), found that additional small-scale hydropower schemes could be installed in European countries such as the UK, Ireland, Spain and Portugal, to complement the ever growing solar and wind power industries. In other countries, which are primarily flat, such as Denmark, Belgium and the Netherlands, small-scale hydropower feasibility was deemed low, especially compared to the feasibility of wind power. However, the authors concede that their research did not adequately consider environmental feasibility, as regulations vary drastically throughout Europe, which complicates an assessment of environmental feasibility. This highlights the difficulty of effectively assessing feasibility in developed nations as more factors tend to be considered in an assessment.

However, to accurately assess feasibility, on-site measurements are usually required. To solve this problem, many researchers have attempted to develop systems which utilise geospatial tools, such as geographic information systems (GIS) and remote sensing, to assess feasibility (Gómez-Llanos *et al*., 2018; Korkovelos *et al*., 2018; Larentis *et al*., 2013). Typically, these studies are only able to assess feasibility in one hydrological unit or country (Dudhani *et al*., 2006; Kling *et al*., 2016; Palomino Cuya *et al*., 2013) which is somewhat limiting. Few studies have attempted to assess feasibility on a grander scale. An example of a study which has attempted to do so is Korkovelos *et al*., (2018), which used open-source geospatial data to identify sites appropriate for small-scale hydropower development along 712,615 km of river network, spanning over 44 countries in sub-Saharan Africa. In total, the study identified 15,599 potential small-scale hydropower sites across the sub-continent, accruing a total potential of generation capacity of 25,221 MW. This is a significant remote assessment of feasibility, showing that it is possible to provide meaningful feasibility data on a large-scale without the need for on-site investigation. However, these remote feasibility studies are prone to uncertainty stemming from the challenge of data acquisition and quality. For example, poor digital elevation model resolution may lead to an inaccurate feasibility assessment, whilst gaps in geospatial data may limit the validity of assessment. Therefore, it is uncertain whether the remote feasibility assessments conducted thus far provide an accurate picture of the feasibility of small-scale hydropower globally.

Overall, the potential feasibility of small-scale hydropower globally has not been accurately quantified and remains unclear. In developed nations, the potential utility is greatly unknown, whereas specific regions in the developing world appear to be feasible for small-scale hydropower generation. However, as assessing feasibility remotely is still in its infancy, the reliability of such an evaluation remains unclear. Moreover, the factors which determine feasibility can change from location to location, which may reduce replicability of results. Nevertheless, as IRENA (2012) states that less than 25% of global hydropower resources have been utilised, small-scale hydropower feasibility may be assumed to be high.

2.5 Conclusion

This literature review has highlighted the scale of the climate change crisis and how renewables may be utilised to mitigate climate change. Hydropower, the renewable technology which produces the majority of renewable electricity generation, is marred by numerous negative environmental impacts. The environmental impact that hydropower imparts is significant enough for scientists to raise questions about the environmental efficacy of hydropower. Mitigation strategies can alleviate a number of the environmental impacts caused by hydropower but, currently, cannot remediate the wide variation of environmental issues that it causes. Alternatively, dam removal, although it appears to be effective in restoring river systems to its natural state, creates uncertainty in quantifying how much damage is caused directly by dams, as opposed to other industrial processes on the river. Moreover, removing dams may restore ecological quality but it does little to limit carbon emissions, and can even increase carbon emissions if the electricity generated by a hydropower scheme is not replaced by renewable sources. Small-scale hydropower may be able to provide substantial, clean energy while minimising the environmental impacts associated with hydropower. Small-scale hydropower projects can be installed in remote areas, providing clean energy to communities who have not previously had access to renewables. However, the research on the impact of small-scale hydropower is limited. Recent research has highlighted that compared to large-scale hydropower, small-scale hydropower causes less absolute environmental impact, but its relative environmental impacts may be greater, with studies showing that when numerous small-scale hydropower schemes are installed on the same river system, the absolute environmental impact is more significant than that of large-scale hydropower. For small-scale hydropower to be effective in mitigating climate change, extensive scheme installation is required, highlighting the potential for deleterious environment impacts. However, as the environmental impacts have not yet been fully quantified, it would be unfair to dismiss small-scale hydropower technologies as environmentally unfriendly, particularly as they show a great deal of potential in mitigating climate change. Nevertheless, before small-scale hydropower is utilised extensively, further research is required to determine the environmental impact of small-scale hydropower. Moreover, given the limited timeframe of the targets set by the IPCC in SR15, a compromise between a reduction in carbon emissions and reduced ecological quality may be required in order to achieve the targets set out by the IPCC.

3. Methodology

3.1 Study Site

The Browsholme Hall estate (53° 54’ 7’’ N, 2° 28’ 55’’ W) lies within Forest of Bowland Area of Outstanding Natural Beauty (AONB), four miles north-west of the nearest town, Clitheroe (location shown in Figures 3.1.1 and 3.1.2). The site comprises mixed woodland, pastureland and watercourses (illustrated in Figures 3.1.3 and 3.1.4). The surrounding area is predominately farmland, with natural landscapes of moorland with significant patches of heather (*Ericaceae*). In wetter areas, there is extensive cover of blanket bog (illustrated in F Figure 3.1.1)

The soil substrate on-site is composed primarily of a low permeability, very acidic, wet soil with a peaty surface. The natural drainage type and natural fertility of the soil are classified as “impeded drainage” and “low fertility” respectively (Defra, 2019). The underlying bedrock is a mixture of limestone and mudstone formations, while superficial deposits consist predominately of diamicton originating from Devensian age till deposits, with less extensive sand, silt, clay and gravel from alluvial fan and river terrace deposits (BGS, 2019). The ground water vulnerability – a measure of the likelihood of contaminants from the water surface reaching a water supply aquifer – at Browsholme Hall is classified as low by Defra (2019).

Browsholme Hall and its associated water bodies are situated in the Hodder and Loud operational catchment. It is classified as a Flood Zone 1 area, indicating that there is a low risk of flooding, and is managed via the Ribble Catchment Flood Management Plan (Environment Agency, 2009). Mill Brook, the main stream which flows through the estate, joins the River Hodder approximately two kilometres downstream at its confluence with Cow Ark Brook.

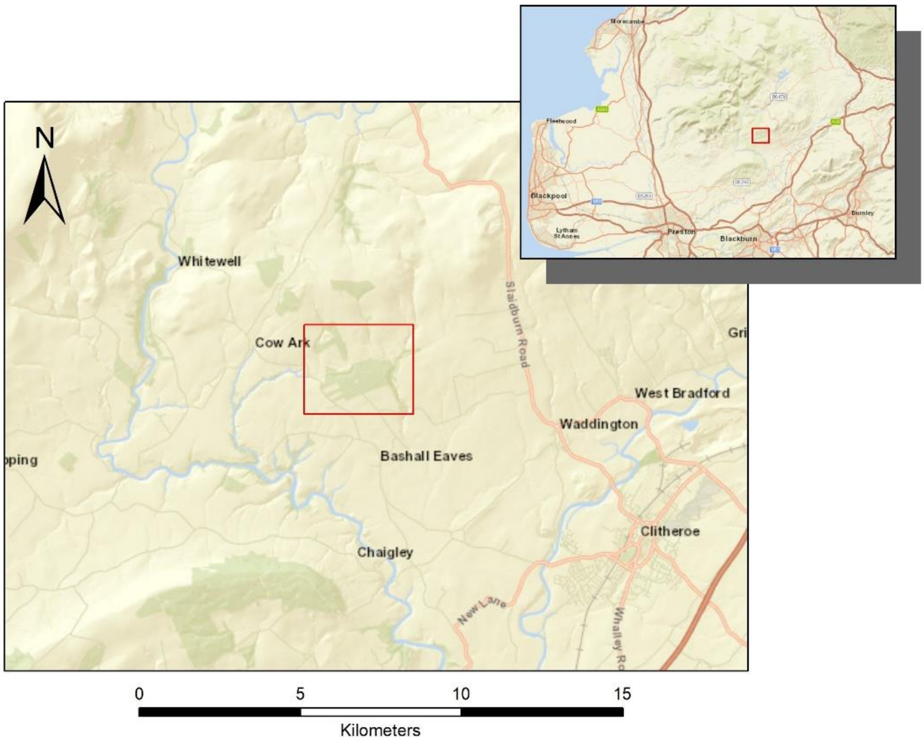

Figure 3.1.1. Map (and inset map) showing the location of Browsholme Hall within Forest of Bowland and northwest England.

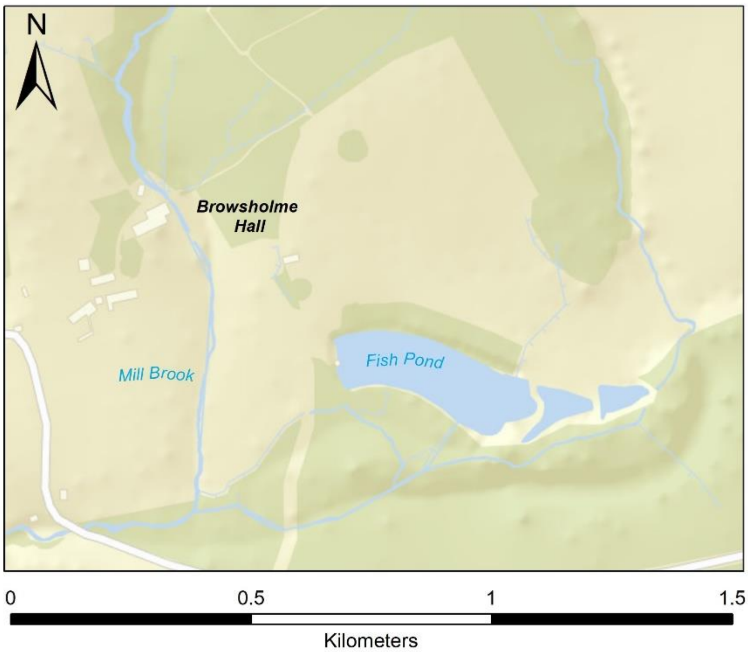

Figure 3.1.2. Map of the Browsholme Estate.

Figure 3.1.3. Left: aerial photograph of Browsholme Hall and its estate (all right reserved © Browsholme Hall); right: photograph illustrating the type of environment surrounding the Browsholme Estate in Forest of Bowland.

Figure 3.1.4. Photographs illustrating the type environment present at the Browsholme Estate. Left: confluence zone at the Bull Ring. Right: unnamed pond in the foreground with the Fish Pond in the background.

3.2 Potential Hydropower Sites

Potential hydropower sites were identified by assessing whether the waterbodies within the Browsholme Estate possessed either sufficient flow or head (or both) for hydropower generation. Six potential hydropower sites were identified:

1. Mill Brook (Butler's Cottage)
   - Immediately north of Browsholme Hall, located in a mixed woodland environment.

2. Mill Brook (Lawn)
   - One of a series of cascading steps on Mill Brook that runs adjacent to the lawn and garden in front of Browsholme Hall. ***n.b***. discharge measurements were conducted a few metres upstream of the potential hydropower site on one of the preceding steps. This location was chosen to measure discharge as its channel was deemed more suitable to accurately perform discharge measurements as well as the step's proximity to the potential hydropower site.

3. Mill Brook (Bull Ring)
   - Located south of Browsholme Hall, Mill Brook flows over an artificial waterfall into the Bull Ring where it converges with two other streams. This site is adjacent to woodland and pastureland.

4. Redundant Pond
   - Located in Bashall Moor Wood, adjacent to the Bull Ring, the Redundant Pond was once a wetted area maintained by a former weir, which has since been breached. Currently, the area only has a small stream running through it. However, there are plans to retrofit the old weir and divert flow from the Fish Pond and/or the surrounding streams to rewet the area to raise water levels and create a small reservoir.

5. Rectangular Weir (Silt Trap)
   - The weir structure is located on the edge of the eastern most pond (Silt Trap). The weir is one of two outflows for the Silt Trap, the other being an overflow which drains into the unnamed middle pond.

6. Calf House Stream

    - This site is located by Calf House between two farmer’s fields. This stream runs though Bateson’s Wood to the measurement site at Calf House before flowing into the silt trap.

In addition, a scenario was proposed in which flow would be diverted to the Redundant Pond from all of the other on-site water bodies to create a reservoir for hydropower and maximise the flow available for hydropower generation at a single location.

Images of each potential hydropower site are shown in Figures 3.2.1-3.2.4, with the exception of the Calf House Stream site, which could not be shown due to image data corruption. A map showing the location of all potential hydropower sites are 6. rec Figure 3.2.5.

Figure 3.2.1. Photograph of the Mill Brook (Butler’s cottage) potential hydropower site.

Figure 3.2.2. Photographs of the Mill Brook (Lawn) potential hydropower site. The left image shows the head and potential location of a small-scale hydropower scheme. The right image shows the location where discharge was measured immediately upstream of the potential hydropower site.

Figure 3.2.3. Photographs of the Mill Brook (Bull Ring) (left) and Rectangular Weir (Silt Trap) (right) potential hydropower sites.

Figure 3.2.4. Photographs of the Redundant Pond potential hydropower site. Top: breached weir and stream leading to the Bull Ring. Bottom: Redundant Pond area and stream upstream of the breached weir.

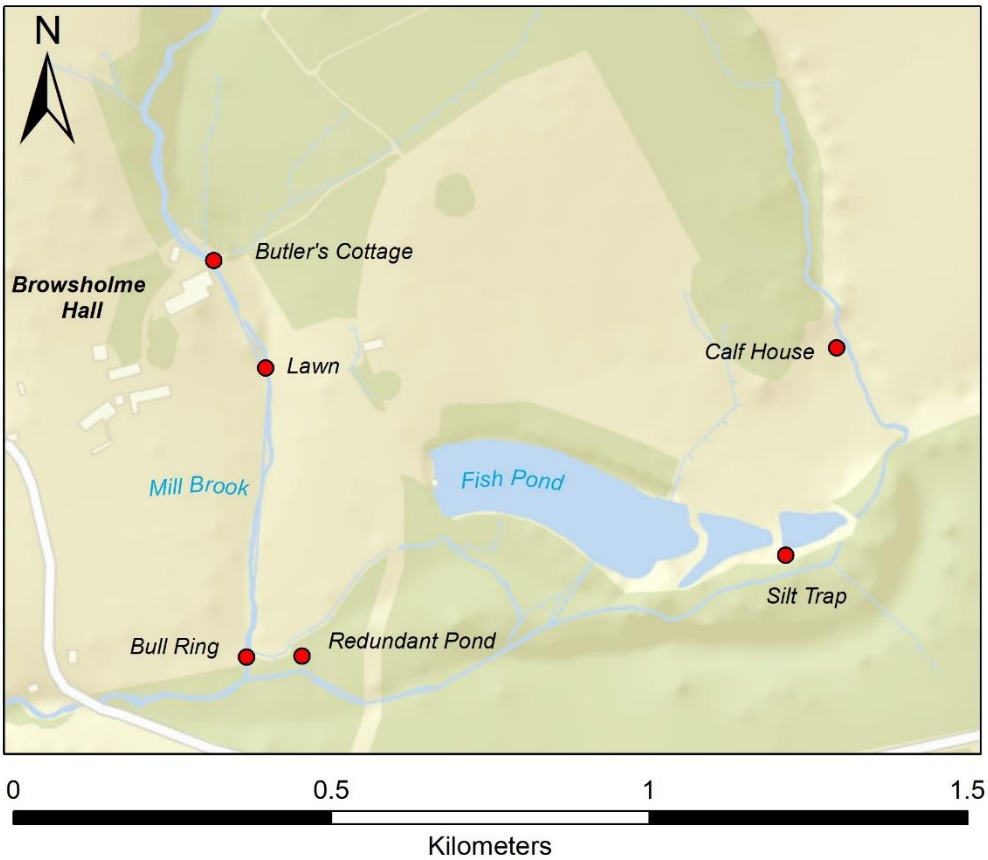

Figure 3.2.5. Map of the Browsholme Estate showing the location of the six potential hydropower sites.

3.3 Power Calculations

The primary aim of this project was to assess the feasibility of generating hydropower to a sufficient level using the natural flow of water within the Browsholme estate. The minimum "sufficient" level of power generation was defined through consultation with the owners, who admitted that it unlikely that the estate's total energy demand could be met with hydropower alone, as the estate's total energy consumption is quite high. Consequently, a 1000W (1kW – hereinafter, all power values are quoted in kilowatts) and an ideal power output of at least 3kW were defined as two desirable generation thresholds. 1kW generation would be able provide power to one or two buildings on the property, whilst 3kW generation could provide power to a few buildings and would equal between 20-25% of the estate's total energy demand, which was deemed a significant contribution to energy supply. Therefore, the main task of this project was to calculate the amount of hydropower that could be generated at the sites identified in 3.2, and to compare these amounts with these 1kW and 3kW thresholds. Potential hydropower generation was calculated using the following equation:

$$P = \rho Q g H e \quad (1)$$

where P is power (Watts); ρ is the density of water (taken here as 1000 kgm^{-3}); Q is the volumetric discharge rate of water (m^{3}s^{-1}); g is gravitational acceleration (taken here as 9.81 ms^{-2}); H is the hydraulic head generating the power (m); and e is the efficiency. An efficiency of e = 0.75 was used, which is a typical efficiency rate for small hydropower systems (Renewables First, 2015b).

This left the discharge (Q) and hydraulic head (H) to be quantified to allow calculation of the potential power resource. Both required extensive measurements and calculations, as described in the following sections. Furthermore, due to the limited time period of the project ran (one year in total, which in practice only allowed a few months of data collection), the primary data collected it did not capture the full variability of the hydro-meteorological phenomena driving the water flow from which power was proposed to be taken. Knowledge of this variability is essential for determining the proportion of time during which the 1kW and 3kW thresholds would be exceeded in the long term, and thus the viability of any proposed hydropower system.

The most appropriate longer-term proxy records for stream discharge available were rainfall records from nearby Environment Agency meteorological stations. Therefore, a vital, additional part of the analyses involved determining the longer-term variability from entering those rainfall records and topographic measurements of the estate into a model which would output long term time series of discharge in the estate's streams. This is explained in detail in the section (3.6) following those on the discharge (3.4) and head loss (3.5) measurements and calculations.

3.4 Discharge Measurements

The different characteristics of the six sites implied that different methods for measuring discharge at them were appropriate. In all, three different methods were used; these are described in turn in the following sections.

3.4.1 Velocity-Area Gauging using Manning's Equation

The channel of the Mill Brook (Lawn) and Mill Brook (Bull Ring) sites was sufficiently uniform and deep to allow gauging stations to be set up, enabling the velocity-area method to be used to calculate discharge. To calculate the cross-sectional area of flow (*A* [m^2]), measurements of the flow width (*W* [m]) and depth (*D* [m]) were required. Flow width was straightforward to measure at these sites as the wetted channel was approximately rectangular meaning width was effectively constant at all flow rates. However, given that depth naturally varied over time, a method which recorded depth over an extensive period was required. To achieve this, a one metre stage-board was installed at each station. Time-lapse cameras were also installed and focused on the stage-boards to permit continuous monitoring of the water level, which ran from the 22nd January – 1st May, 2019 (shown in Figure 3.4.1). The time-lapse cameras were originally set to take a photo of the water level every 15 minutes. However, due to data processing time constraints, the camera settings were subsequently altered to take a photo every hour. A sensitivity analysis showed this change made negligible difference to the outcome of the subsequent calculations. A total of 3881 and 3877 water level measurements were obtained for the Lawn and Bull Ring sites respectively during the recording period. Each flow depth measurement was functioned with its corresponding channel width to calculate the cross-sectional area of the flow (*A* = *WD*).

The channel characteristics at these two sites were also deemed appropriate – i.e. to have sufficiently uniform flow and bed conditions – to use Manning's equation to estimate the cross-sectional mean flow velocity. Manning's equation was used in the form:

$$V = \frac{1}{n} R_h^{2/3} S^{1/2} \tag{2}$$

where *V* is cross-sectional mean flow velocity (ms^{-1}), *n* is Manning's roughness coefficient ($s/m^{1/3}$); R_h is the hydraulic radius (m) – the ratio (*A*/*P*) between channel cross-sectional area (*A*) and wetted perimeter (*P*), defined as the total length of channel bottom and sides in direct contact with the water body (2 x water depth x width of channel bottom); *S* is channel bed slope (dimensionless). Manning's roughness coefficient (n) is determined by the physical characteristics of the channel bed, such as roughness and sinuosity, and quantified via standardised look-up tables (Chow, 1959). Here, a value of *n* = 0.035 was selected, which is the value for a cobbled bed, as this reflected the nature of the channel bed of most of Mill

Brook. However, it should be noted that where the gauging stations were actually situated, the channel is formed of a short section of masonry, and this may have changed the value of Manning's coefficient slightly. For each pair of velocity and area values (corresponding to a single measure of flow depth from the remote camera-stageboard data), discharge (Q [m^3s^{-1}]) was calculated as $Q = VA$.

Figure 3.4.1. Photographs of the stage-boards and time-lapse cameras set up at the Mill Brook (Lawn) and Mill Brook (Bull Ring) potential hydropower sites to measure flow depth.

3.4.2 Weir Gauging

Discharge over rectangular weirs, such as the one at the silt trap site, is usually calculated using the following equation (Ackers *et al*., 1978):

$$Q = (2/3)^{3/2} C_p b\sqrt{2g} H^{3/2} \tag{3}$$

where Q is discharge (m^3s^{-1}); C_p is the coefficient of discharge, which depends on weir geometry; g is gravitational acceleration ($9.81ms^{-2}$); b is the width of the weir (m); and H is the total head relative to the top of the weir (m). However, the coefficient C_p is a function of two ratios h/L and $h/(h+P)$. For the equation to be applicable, the two ratios must meet both of the following conditions:

$$0.08 < h/L < 0.33 \quad \text{and} \quad 0.18 < h/(h+P) < 0.36 \tag{4}$$

where L is the length of the weir in the direction of flow (m); P is the depth of the water from the top of the weir to the bottom of the channel upstream of the weir structure (m); and h is the depth of the water from the top of the weir crest to the surface of the water upstream of the weir structure (m).

At the silt trap, a combination of weir geometry and low flow rates indicated that the two ratios fell below the required range for most of the time. It was only during periods of high flow that both ratio values fell into the required range to allow for accurate discharge calculations. Furthermore, during periods of peak flow, the ratio values exceeded the range, and hence would provide inaccurate estimations. Therefore, as the ratio values required for the coefficient to work were not achieved most of the time, it would have been inaccurate to use the rectangular weir equation to estimate discharge due to uncertainties in accuracy. Instead, the velocity-area method, as described in 3.4.1, was used at the readily measurable section of the flow where it passed over the rectangular weir. Cross-sectional area was calculated using the same remote camera and stage-board method (shown in Figure 3.4.2) as previously described for the two Mill Brook sites. However, Manning's equation could not be used to calculated flow velocity as the presence of the weir meant that flow was non-uniform, and flow uniformity required for the Manning's equation to work. Therefore, an alternative method for measuring flow velocity was devised at this site. This comprised of measuring the length of time (t [seconds]) taken for a surface float (ping pong ball) to traverse the channel length of the rectangular weir (L_{weir} [m]) at various water stage levels, and subsequently, calculating flow velocity as $V = L_{weir}/t$. Time was measured by filming each float as it traversed the weir, and subsequently using Adobe Premier Pro to freeze the film and determine the timestamps at the start and finish of each traverse. Each measurement at a given stage level was repeated five times to capture variability and quantify the precision of the measurements (in the form of standard deviations of the five repeats).

Figure 3.4.2. Photograph of the stage-board and time-lapse camera set up at the Rectangular Weir (Silt Trap) potential hydropower site to measure flow depth.

Because this method was more intensive in terms of fieldwork requiring a researcher to be present, discharge was only calculated at four stage levels (whereas at the Mill Brook sites, Manning's equation could be used and discharge calculated for every stage measurement obtained via the remote camera and stage-board data). To infer discharge values corresponding to each hourly stage measurement, a power law relationship of the form $Q = ch^{m}$ was assumed between stage and discharge (as is generally found in open channel flow

[Gore & Banning, 2017]) the coefficients of which (m and c) were determined by identifying the best fit linear regression of $\log_{10}Q$ onto $\log_{10}h$:

$$log_{10}Q = m \cdot log_{10}h + c \tag{5}$$

3.4.3 Dilution Gauging

The three remaining potential hydropower sites (Butler's Cottage, Redundant Pond and Calf House Stream) did not possess uniform flow/bed characteristics or a weir, and subsequently, neither of the two methods described above were appropriate. As a result, discharge at these sites was measured using the gulp dilution gauging method. This also allowed a triangulation of the other two methods, to ensure that they were all giving discharge values that were at least of the same order of magnitude. Dilution gauging measurements were taken once a week from the 4th February, 2019 to the 1st May, 2019. At each site, 0.75 kg of sodium chloride (table salt) was dissolved into 12 litres of stream water in a bucket. An electroconductivity (EC) meter (EM) was placed in the stream at a location defined as the sampling station. The EC meter was set to measure conductivity at two-second intervals. Following this, the bucket of dissolved salt was injected into the stream at an injection station, which was located approximately 30 metres upstream from the sampling station. Stream EC was measured prior to the dissolved salt reaching the EM – to give a background reading. As the dissolved salt passed the EM, its presence was registered as an increase in measured conductivity, which was converted into salt concentration via a pre-calibrated relationship. Measurements continued until conductivity levels returned to at least 90% of the background conductivity, indicating the passage of the salt tracer past the sampling station. From this data, discharge (Q) was calculated using

$$Q = \frac{V_o C_1}{\int_{t1}^{t2} (C_2 - C_0) \partial t} \tag{6}$$

where V_o is the volume of water in the bucket into which the salt was dissolved (L); C_1 is the input salt concentration (mg/L); C_0 is the background salt concentration in the stream (mg/L); C_2 is the salt concentration at downstream sampling site at time t (mg/L); t_1 is the start time of measurements; and t_2 is the end time of measurements. The integral of C_2-C_0 values represents the area under the salt tracer time series, which was calculated using the trapezium rule. Additionally, dilution gauging was used to measure discharge in Mill Brook directly downstream of the Bull Ring. This was to ascertain the total discharge flowing out of the property, as all water bodies on-site converge and flow into Mill Brook at the Bull Ring.

3.5 Head Loss Measurements

Quantifying the hydraulic head lost in the conversion of the potential energy of water as it passes through a hydropower installation is essentially a case of measuring the loss of vertical height undergone by the water. The hydraulic head available at each of the potential hydropower sites were measured using a Real-Time Kinematic Global Positioning System (RTK GPS), Total Station and Dumpy Level (see the section below on topographic measurements for more details). Head measurements were conducted on the 7th and 21st March, 2019. The Butler's Cottage, Lawn, and Silt Trap sites' measurements were recorded using RTK GPS, whereas the Calf House Stream was measured using a combination of RTK GPS and Dumpy Level, as the potential point of abstraction was under canopy cover, which caused significant RTK GPS signal interference. The Bull Ring and Redundant Pond were surveyed using the Total Station, as RTK GPS signal was insufficient at these sites. The head at the Redundant Pond was measured from a metre above the channel (the proposed height of the abstraction intake) to the water's surface at the Bull Ring. An abstraction intake height of 1 metre above channel bottom was selected, despite the breached weir being 3 metres tall. This is because the Environment Agency sets a height limit of 1.5 metres for constructing or retrofitting weirs on upland watercourses (Environment Agency, 2016c)

Where the distance travelled by the water through a pipe between the potential intake and outflow of the proposed hydropower installations was significant, this available hydraulic head would be reduced due to friction between the flowing water and pipe. This frictional head loss through a pipe was calculated using the Darcy-Weisbach equation:

$$h_f = \frac{4 f_D l}{h_d} \cdot \frac{V^2}{2g} \tag{7}$$

where h_f is head loss (m); f_D is the Darcy friction factor; l is the length of the pipe (m); h_d is the pipe's hydraulic diameter (m); V is the velocity of water through pipe (ms^{-1}); g is gravitational acceleration (ms^{-2}). In order to establish the Darcy friction factor, the Reynolds number, a parameter of the flow through the pipe had to be determined. This was calculated as:

$$Re = \frac{Vd_h}{v} \tag{8}$$

where V is the velocity of the water through the pipe (ms^{-1}); h_d is the hydraulic diameter (m); and v is the kinematic viscosity of water (m^2s^{-1}). The Darcy friction factor could then be calculated using the Colebrook-White equation, which is highly accurate when the water flowing through pipes is turbulent (Ratnayaka *et al.*, 2009).

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7h_d} + \frac{2.51}{Re\sqrt{f}}\right) \tag{9}$$

where f is the Darcy friction factor; and ε is the absolute roughness, which is a property of the pipe material. In this instance, steel was selected, which has an absolute roughness value of 0.03 (Stewart, 2016).

3.6 Modelling of Long-Term Variability of Stream Discharge

To quantify and characterise the long-term variability in the stream discharge, rainfall data was used as this was the closest proxy available. As there is no automated rain gauge at Browsholme Hall itself, data from the four closest Environment Agency weather stations were collated and interpolated. Two of these were situated in the Forest of Bowland, one at Footholme (53° 58′ 29″N, 2° 31′ 49″ W), and the other at Stocks Reservoir (53° 59′ 13″N, 2° 25′ 54″ W), approximately 9km northwest and 10km northeast of Browsholme Hall respectively. The remaining two stations were located at Kebb Farm, Great Harwood (53° 47′ 17″ N, 002° 25′ 07″ W) and Mearley Hall (53° 51′ 47″ N, 002° 21′ 13″ W), Lancashire, located approximately 13km southwest and 9km west of Browsholme Hall respectively. The locations of all rainfall monitoring stations used for interpolation can be seen in Figure 3.6.1. The interpolation method used was inverse distance weighting (IDW), which calculated the value to be interpolated, z_P, as

$$z_p = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i}\right)} \tag{10}$$

where z_i is the i^{th} known value, d_i is the distance of the location at which z_i was taken from the location at which data are being interpolated; and n is the total number of data values used in the interpolation (n = 4 here for each datum in the interpolated rainfall time series). Although three of the stations have data back to the 1990s, the fourth, Mearly Hall only began recording rainfall in January 2007. Therefore, the interpolated daily rainfall time series runs from 21st January 2007 to 18th June 2019.

Efforts were made to check the interpolated rainfall time series by placing three Kalyx-RG tipping bucket rain gauges and data loggers at varied locations on-site (a semi-wooded area, between two of the ponds, and on the lawn in front of the Hall) to measure rainfall between 12th December, 2018 and 30th April, 2019. The gauges were programmed to log continuously, recording rainfall (in mm) every 15 minutes. On the 4th February, 2019, additional manual rain gauges were installed approximately 5 m from each of the tipping bucket gauges to ascertain the latter's accuracy. The manual gauges were able to record up to 70mm of precipitation and were emptied approximately once a week during site visits. However, the Kalyx-RG rain gauges did not accurately record precipitation – apparently due to electronic malfunctions – and the weekly manual gauge measurements gave only coarse comparisons over a short time period. The latter gave some reassurance that the interpolated data were accurate, but no further verification of them was achieved beyond this.

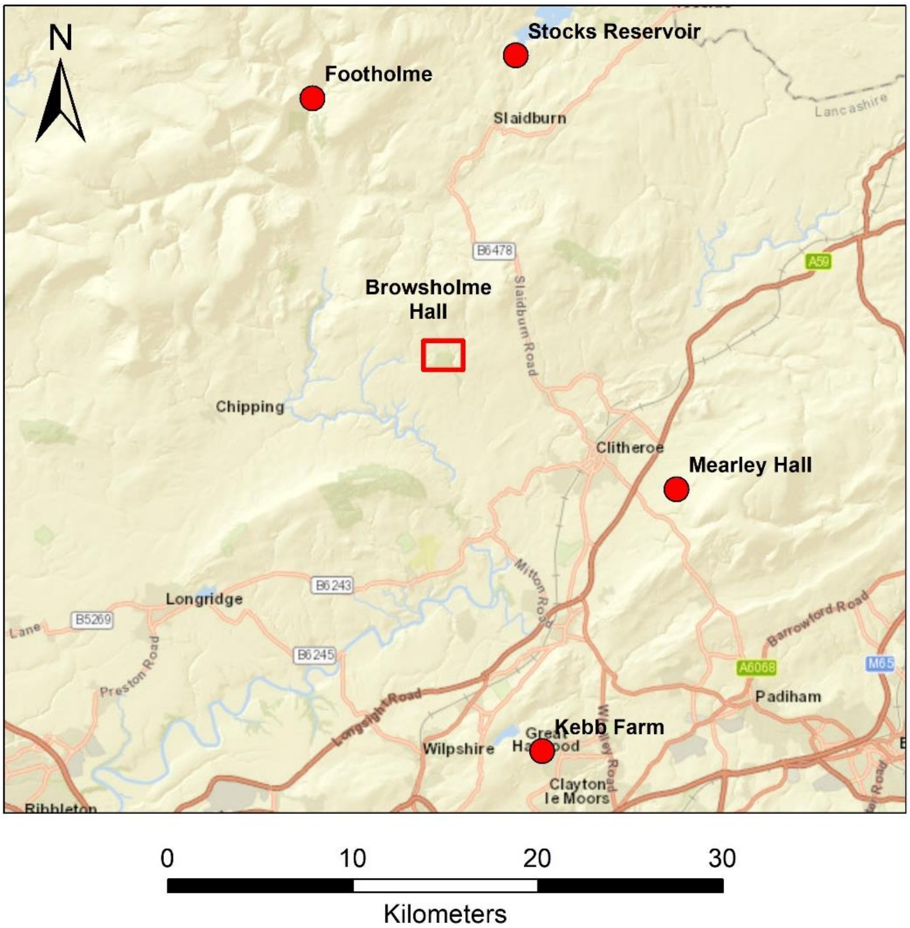

Figure 3.6.1. The location of the Environment Agency monitoring stations in relation to Browsholme Hall.

3.7 Reservoir Scenario Testing

3.7.1 Scenario Set-Up

To test the scenario in which flow would be diverted to the Redundant Pond from all of the other on-site water bodies to create a reservoir for hydropower, and thus maximise the available hydropower generation at a single location, total discharge for the estate was derived from the daily interpolated rainfall. Total rainfall was converted to discharge by calculating the Knox County, Tennessee (2008) rational method runoff coefficients using the land-use, slope and soil types at Browsholme Hall. This estimates that 50% of rainfall becomes runoff. To convert the interpolated daily rainfall (mday^{-1}) to total volume of rainfall (m^{3}day^{-1}), daily rainfall was multiplied by the area of the local catchment (1 km^2), which was calculated from topographic maps of the local area. Following this, the total volume of rainfall was divided by total number seconds in a day (86400), in order to be expressed as m^3/s^{-1}. The total volume of rainfall was then halved (using the Knox County coefficient) to give the runoff, which was equated with the total available discharge.

Feasibility of this scenario was assessed in two ways. Firstly, an assessment was made as to whether the proposed reservoir could provide continuous power generation. This was determined using a water balance equation (3.7.1), which was used to calculate the flow required to sustain continuous power generation and thus the required difference between inputs to and outputs from the reservoir. Secondly, the feasibility of variable hydropower generation was assessed. To do this, discharge modelling was used to evaluate whether sufficient time periods of significant power generation could be achieved amongst periods of insignificant generation.

3.7.2 Water Balance Equation

In order to determine whether a reservoir could be used for continuous hydropower generation at the redundant pond, its inputs and outputs were compared using the water-balance equation:

$$P + Q_{inflow} \geq Q_{hydro} + G_{water} + ET \quad (11)$$

where P is precipitation falling directly onto the reservoir; Q_{inflow} is the discharge of reservoir inflow(s), including adjacent runoff flowing directly into reservoir; Q_{hydro} is the discharge of the hydropower scheme; G_{water} is the groundwater recharge of the reservoir; and ET = evapotranspiration rate on-site (all in units of m^3s^{-1}). To convert P and ET from $mmday^{-1}$ to m^3s^{-1}, the values were divied by the total number of seconds in day (86400), then multiplied by the area of the redundant pond ($1600m^2$). The left side and right side of this equation represent the inputs and the outputs of the reservoir respectively. To successfully maintain a reservoir for hydropower, the inputs must be greater than or equal to the outputs.

The discharge of the hydropower scheme required to generate a given amount of power P was calculated by rearranging equation (1). Groundwater recharge (G_{water}) was calculated as

$$G_{water} = P_c - ET - R_{basin} \quad (12)$$

where P_c is the precipitation falling over the local catchment; R_{basin} is the runoff from the basin (all terms in units of m^3s^{-1}). R_{basin} was quantified as the mean average discharge from the estate, derived from the interpolated daily rainfall data from January 2007 to June 2019. The evapotranspiration rate (ET) was taken from the Centre for Ecology and Hydrology's Climate, Hydrology and Ecology research Support System (CHESS) online database and tool (CEH, 2019). CHESS estimates various environmental measures at 1 km^2 resolution. The tool's "*Potential Evapotranspiration with Interception correction (mm per day)*" function was used to retrieve daily evapotranspiration rate estimates. To convert P_c and ET from $mmday^{-1}$ to m^3s^{-1}, the values were divided by the total number of seconds in a day (86400), then multiplied by the area of the catchment ($1km^2$). As the above groundwater recharge calculation gives the volume of groundwater recharge across the whole catchment, in order to calculate the groundwater recharge at the redundant pond (equation 11), the figure must be multiplied by the percentage of area that the redundant pond covers across the catchment (0.16%).

3.8 Ecological Surveys

Finally, in order to assess the potential ecological impacts of any proposed hydropower scheme, ecological surveys were undertaken for legally protected species that are known to either inhabit the area or have been reported on the estate in the past. The species surveyed are listed below, accompanied by details of the methodology used.

3.8.1 Badgers

Badger (*Meles meles*) surveys were conducted in February and March, and consisted of two types: sett surveys and latrine surveys. Two sett surveys were conducted in February, as the best time to survey is during winter, between the period of vegetation die-back and spring flush, when setts are most visible (Harris *et al*., 1989). Two latrine surveys were conducted in March, as latrines are most frequented during the early spring, when signs of territorial marking (which coincides with the mating season) are more likely to be in evidence (Harris *et al*., 1989; Woods, 1995). The areas adjacent to the waterways of the potential hydropower development were surveyed during sett and latrine surveys, and are illustrated in Figure 3.8.1. As these waterways were visited frequently outside of the survey period from October 2018 to July 2019, any incidental signs of badger activity were also recorded. The descriptions of badger activity are shown in Appendix A.

3.8.2 Otters and Water Voles

Otter (*Lutra lutra*) and water vole (*Arvicola amphibious*) surveys were conducted concurrently during two formal surveys on 27th March and 10th April during daytime hours. The survey followed the route marked on Figure 3.8.1 around the water bodies potentially affected by the proposed hydropower development. The surveys sought to identify indirect signs of otter or water vole activity such as footprints and faeces as well as physical sightings of both mammals. Early spring surveys were chosen due to increased mammal activity and shorter bankside vegetation, enabling easier identification of indirect signs of activity, such as footprints and faeces (Lancashire Wildlife Trust, 2019). However, it should be noted that informal observations were also made during each site visit (approximately weekly on average) from October 2018 to July 2019 for incidental evidence of both otters and water voles. The signs of activity for otters and water voles used to determine the presence of both mammals during the survey are found in Appendix B.

3.8.3 Birds

Two bird surveys were conducted during the early morning hours of the 10th and 23rd April 2019. This involved walking a slow pace along Browsholme Hall's waterways (route highlighted in Figure 3.8.1) with a pair of binoculars, a camera, a notepad and a British bird identification guide, whilst paying close attention to any bird songs/calls and sightings. Photos and video recordings were taken of unknown birds (and/or their songs/calls) to enable identification at a later date using further resources as an identification aid. Unique taxa identifications were recorded but the total number of sightings/calls of each taxon were not. As for otters and water voles, informal recordings were also made of incidental sightings of any uncommon, unusual or important bird species during the regular site visits from October 2018 to July 2019. Survey results were compared against the National Biodiversity Network's (NBN) record of bird sightings to establish whether any protected, endangered or rare bird species had been identified.

3.8.4 Great Crested Newts

A Great Crested Newt (*Triturus cristatus*) survey was not undertaken as a licence is required to survey them, which had not been obtained by the author. However, there are no recorded instances of this species on-site, despite there being appropriate habitat.

3.8.5 Fish

Two species of fish had previously been recorded on-site: brown trout (*Salmo trutta*) and European bullhead (*Cottus gobio*), with the latter being a protected species in the UK (NBN, 2019)

Fish surveys are typically conducted in the UK via the electrofishing method, where fish are temporarily stunned by submerging electrodes along a reach of river or stream. Stunned fish are collected, identified, weighed, measured, and often undergo minor de-scaling for DNA analysis before being released (Environment Agency, 2016b). However, electrofishing equipment was not made available for this project and, subsequently, a fish survey could not be completed. Additionally, European bullhead are usually surveyed from mid-late August to October to minimise the impact on juvenile development and to avoid catches comprising predominantly of juvenile fish (Cowx & Harvey, 2003). If equipment had been available, due to time constraints, it would have been exceptionally difficult to complete a survey at this time of year, as the project was in its final stages.

3.8.6 Bats

Two bat surveys were conducted on 16th July, 2019 and 14th August, 2019. The area around the hall and the ponds was surveyed on the first date and the area surrounding the other water bodies, such as Mill Brook, on the second date. Bats were identified using a heterodyne, visual sightings and roost emergence times.

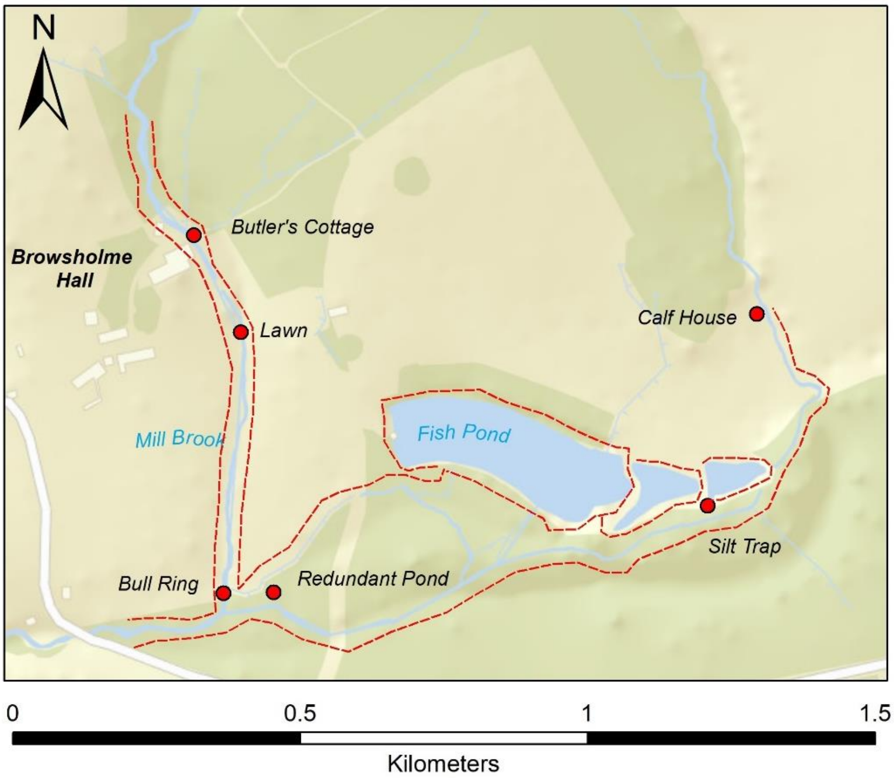

Figure 3.8.1. Map of the Browsholme Estate showing the route of the badger, bird, otter and water vole surveys (dotted red line).

4. Results

4.1. Gauging Station Measurements

At all three potential hydropower sites fitted with gauging stations, sufficient power generation was only possible for small fractions of the 3-4 month measurement period; for the majority of the time, potential power generation was well below 1kW. Discharges large enough to generate 1kW or more were confined to peak flow events. Of the three gauging stations, the Bull Ring experienced the highest discharges and potential power generation. Results from each gauging station are shown below. Greatest potential for power generation across all sites was experience during March, when high levels of rainfall led to relatively high discharges.

4.1.1. Mill Brook (Bull Ring)

Head at the Bull Ring gauging station was 1.47m. The hydrograph for this station is shown in Figure 4.1.1. Mean discharge was 0.020 m^3s^{-1}, median discharge was 0.005 m^3s^{-1}, and maximum discharge was 1.11 m^3s^{-1}.

Potential power generation can be seen in Figure 4.1.2. Mean, median and maximum power generation were 0.28 kW, 0.055 kW and 11.96 kW respectively. Potential power generation equalled or exceeded 1kW approximately 5.5% of the time, roughly 5.5 days over the measurement period, and equalled or exceeded 3 kW for 0.8% of the time (Figure 4.1.3), which equates to less than a day over the measurement period. The stage-discharge relationship is shown in the rating curve in Figure 4.1.4.

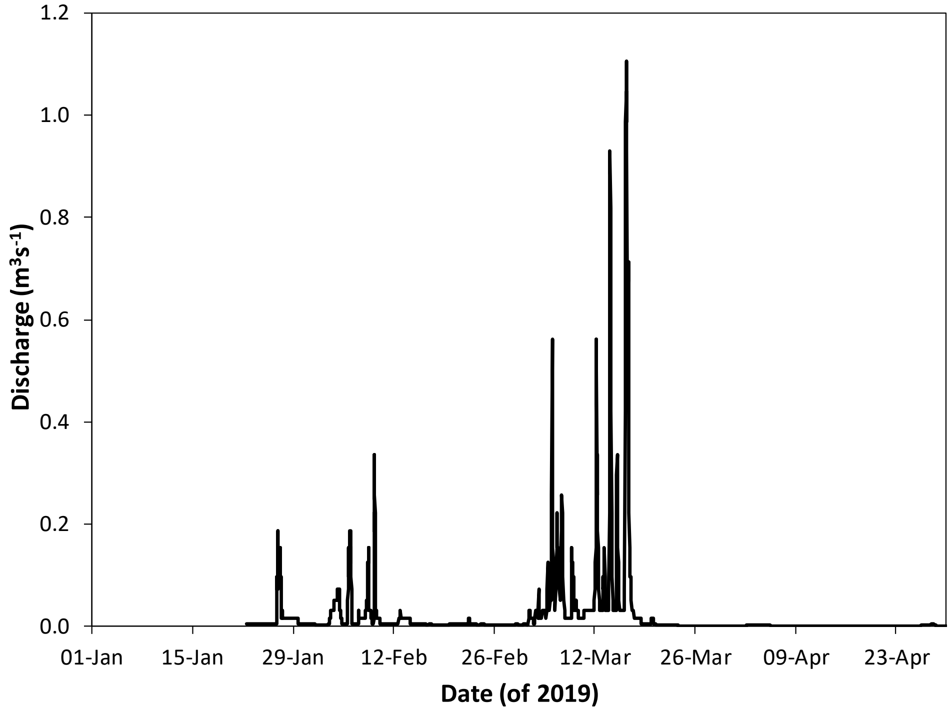

Figure 4.1.1. Hydrograph showing discharge estimated from stageboard-camera measurements at the Bull Ring gauging station on Mill Brook from 22nd January to 1st May 2019.

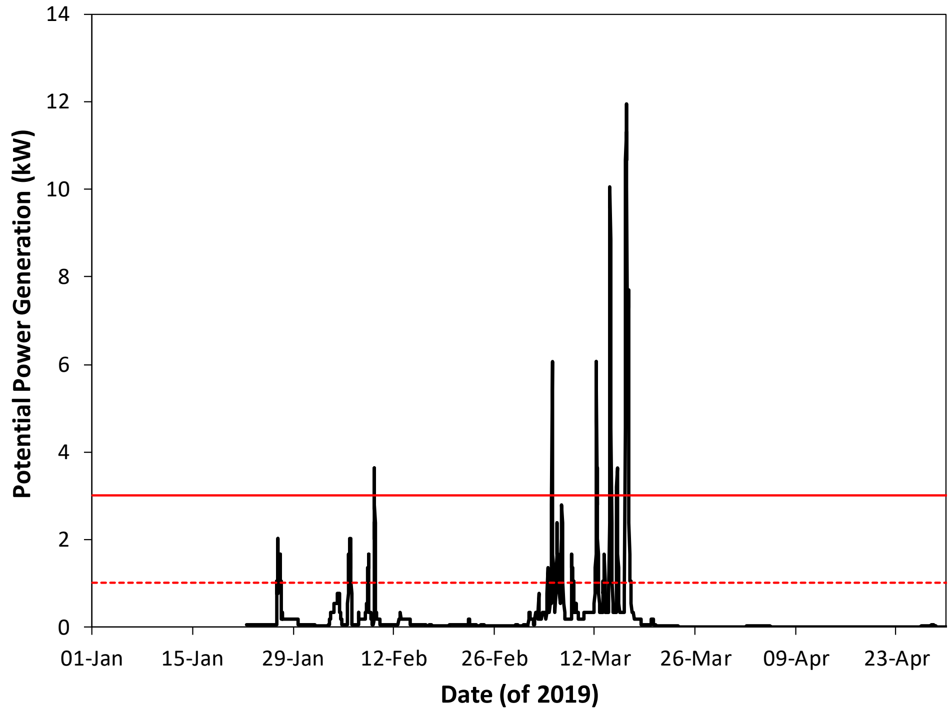

Figure 4.1.2. Potential power generation at the Bull Ring gauging station on Mill Brook – calculated from the discharge data in Figure 4.1.1 – from 22nd January to 1st May 2019, with the1 kW (dotted red line) and 3 kW (solid red line) levels indicated.

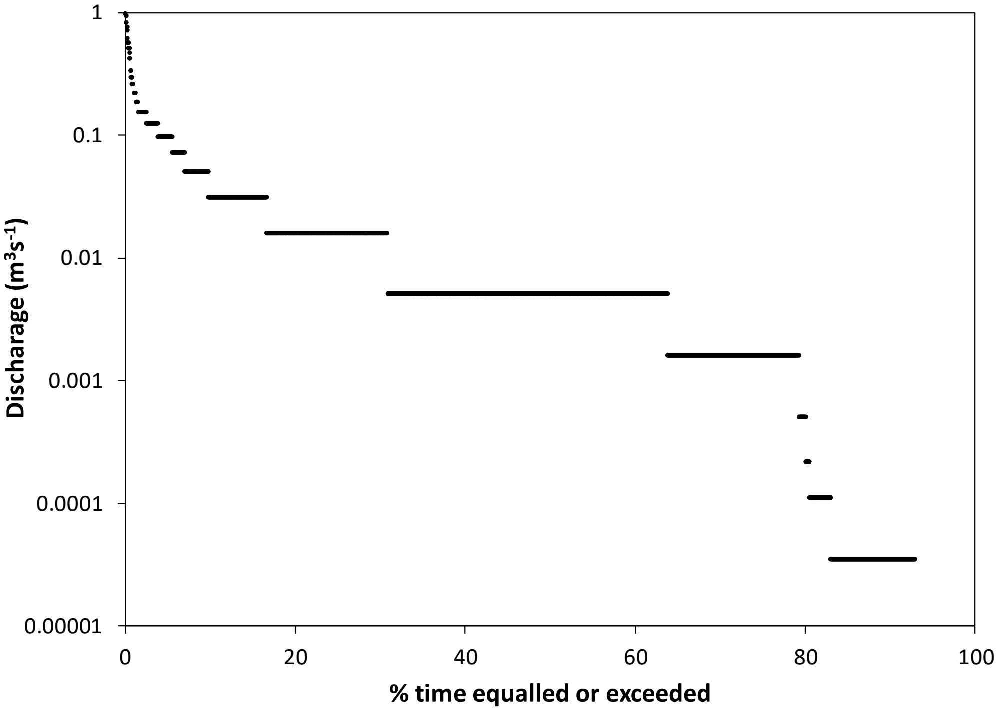

Figure 4.1.3. Semi-logarithmic plot of the flow-duration curve for the Bull Ring gauging station on Mill Brook from 22nd January 2019 to 1st May 2019.

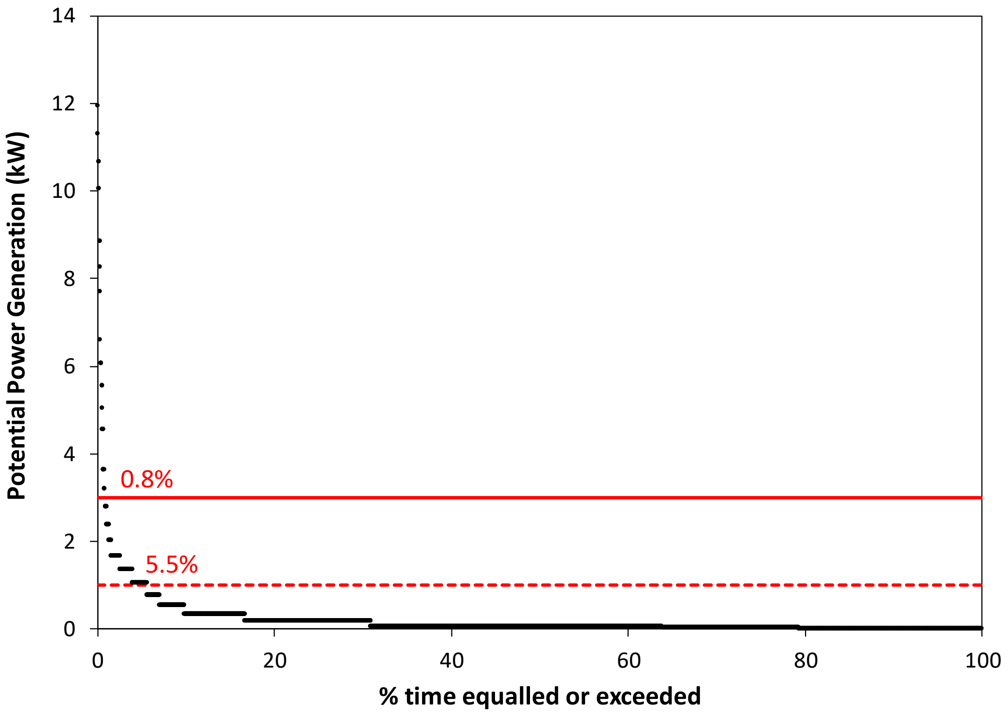

Figure 4.1.4. Power-duration curve for the Bull Ring gauging station on Mill Brook for 22nd January to 1st May 2019, with the 1 kW (dotted red line) and 3 kW (solid red line) levels – and the percentage of time for which they were equalled or exceeded (5.5% and 0.8%, respectively) indicated.

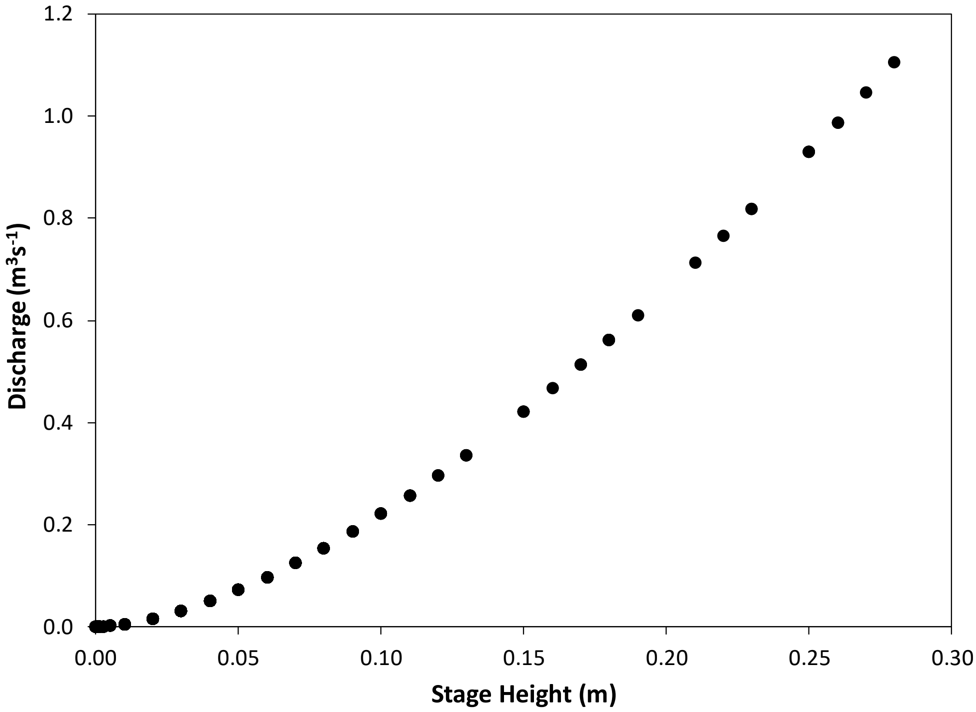

Figure 4.1.5. Stage-discharge rating curve for the Bull Ring station on Mill Brook from 22nd January to 1st May 2019.

4.1.2. Mill Brook (Lawn)

Head at the lawn gauging station on Mill Brook was 1.70m. The hydrograph for this station can be seen in Figure 4.1.6. Mean, median and maximum discharges over the measurement period were 0.12 m^3s^{-1}, 0.0035 m^3s^{-1} and 0.71 m^3s^{-1}, respectively. The flow duration curve is shown in Figure 4.1.7.

Potential power generation is shown in Figure 4.1.8. Mean, median and maximum power generation were 0.28 kW, 0.055 kW and 8.85 kW respectively. Potential power generation equalled or exceeded 1 kW approximately 3.5% of the time – roughly 3.5 days over the measurement period, and exceeded 3 kW approximately 0.5% of the time, or roughly half a day over this time period (Figure 4.1.9). The stage-discharge relationship can be seen in the rating curve in Figure 4.1.10.

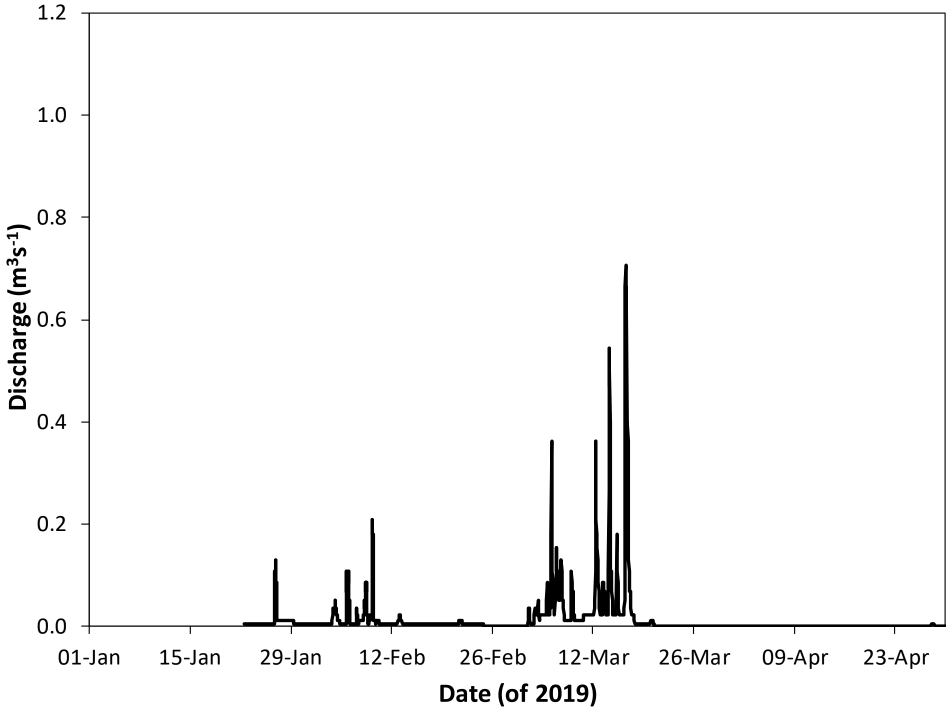

Figure 4.1.6. Hydrograph showing discharge estimated from stageboard-camera measurements at the Lawn gauging station on Mill Brook from 22nd January to 1st May 2019.

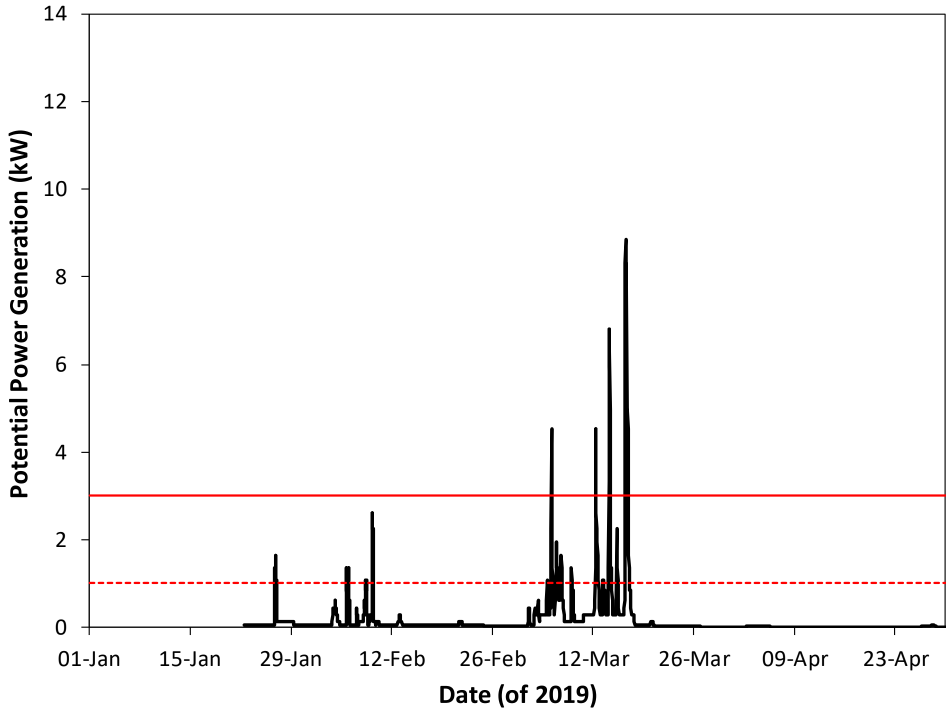

Figure 4.1.7. Potential power generation at the Lawn gauging station on Mill Brook – calculated from the discharge data in Figure 4.1.6 – from 22nd January to 1st May 2019, with the 1 kW (dotted red line) and 3 kW (solid red line) levels indicated.

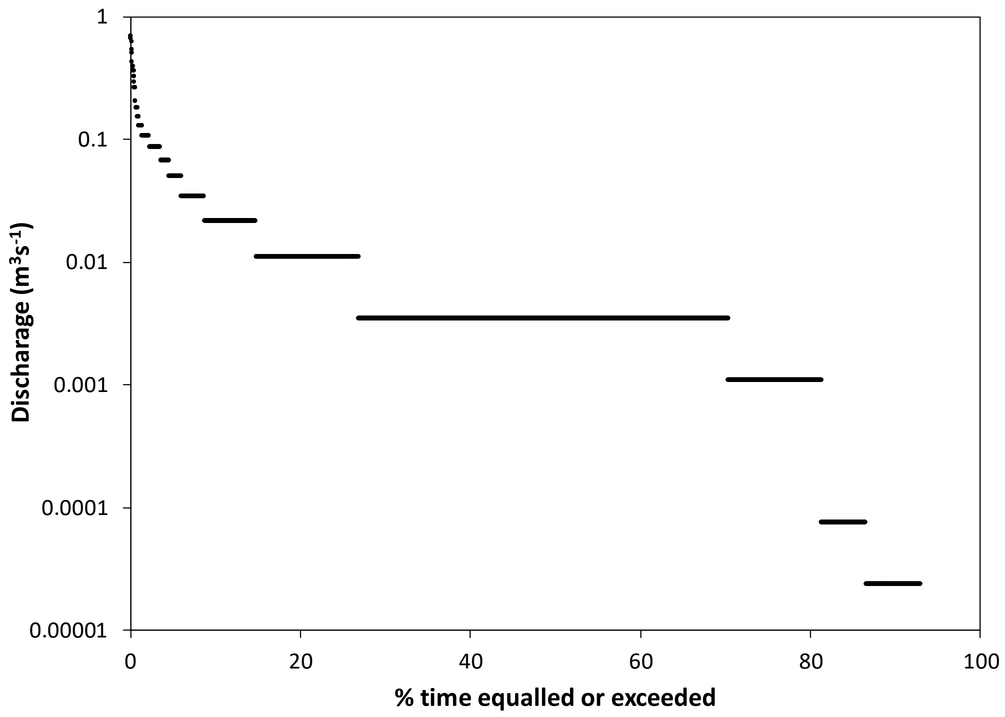

Figure 4.1.8. Semi-logarithmic plot of the flow-duration curve for the Lawn gauging station on Mill Brook from 22nd January 2019 to 1st May 2019.

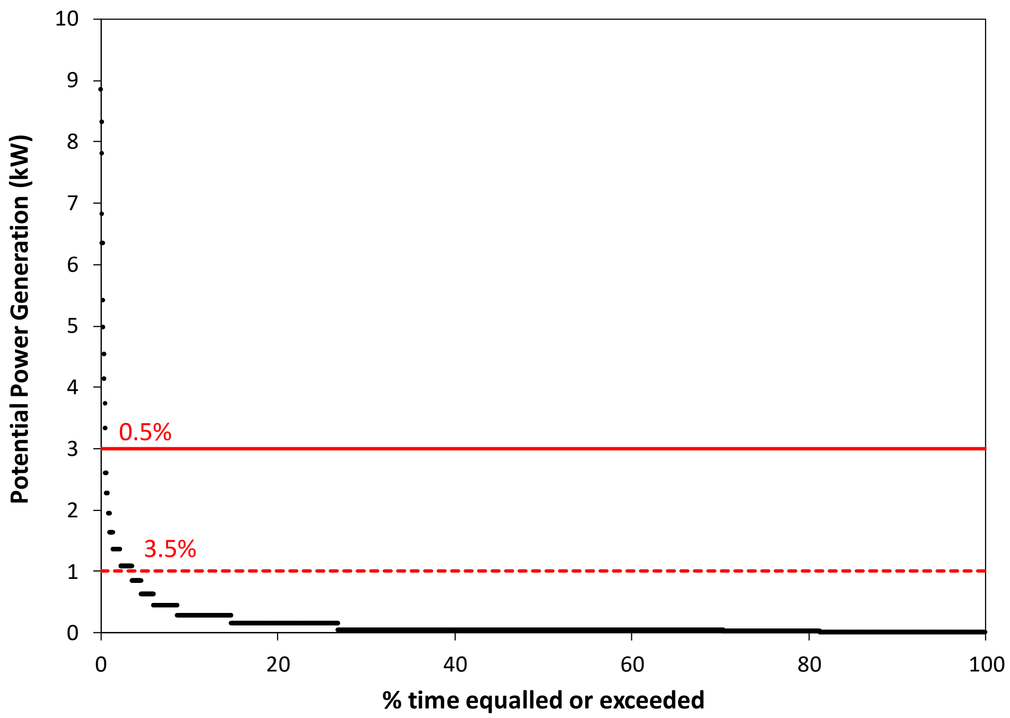

Figure 4.1.9. Power-duration curve for the Lawn gauging station on Mill Brook for 22nd January to 1st May 2019, with the 1 kW (dotted red line) and 3 kW (solid red line) levels – and the percentage of time for which they were equalled or exceeded (3.5% and 0.5%, respectively) indicated.

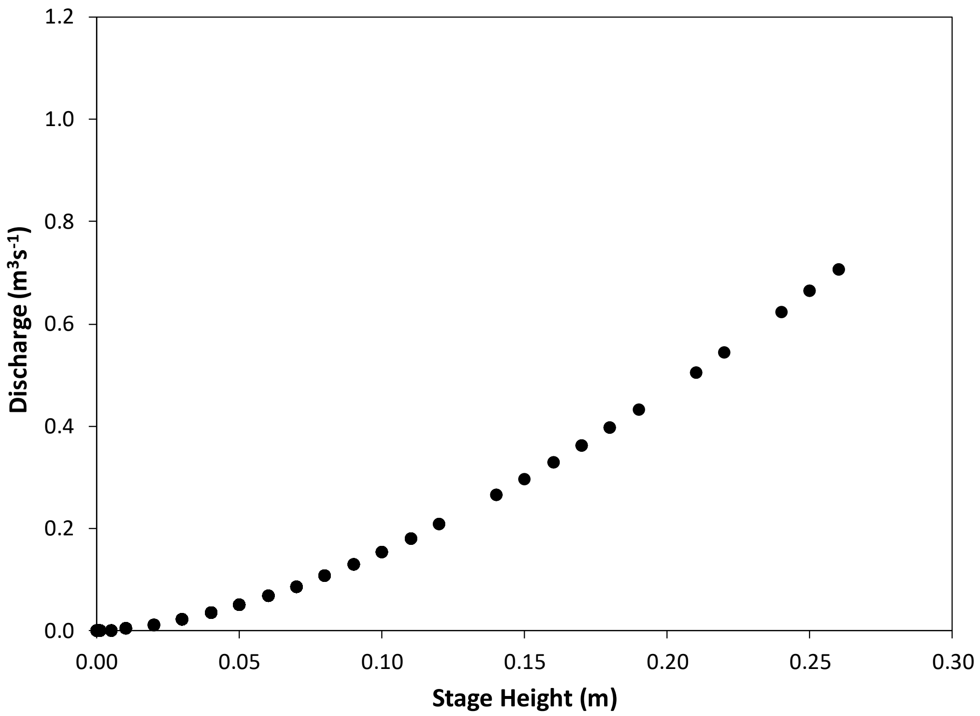

Figure 4.1.10. Stage-discharge rating curve for the Lawn station on Mill Brook from 22nd January to 1st May 2019.

4.1.3. Rectangular Weir (Silt Trap)

Head at the Silt Trap gauging station was 0.49m. The hydrograph displaying the discharge of the outflow of the Silt Trap is shown in Figure 4.1.11. Mean, median and maximum discharges were 0.011 m^3s^{-1}, 0.007 m^3s^{-1} and 0.48 m^3s^{-1}, respectively. Note that the median discharge at the silt trap was higher than the median discharges at both of the gauging stations on Mill Brook.

Potential power generation is shown in Figure 4.1.12. Mean, median and maximum power generation were 0.039 kW, 0.025 kW and 1.71 kW, respectively. Approximately 0.2% of the time potential power generation equalled or exceeded 1 kW (Figure 4.1.14), which equates to roughly 5 hours over the 100-day time period. Potential power generation did not reach 3 kW at any point. The stage-discharge relationship is shown in Figure 4.1.15.

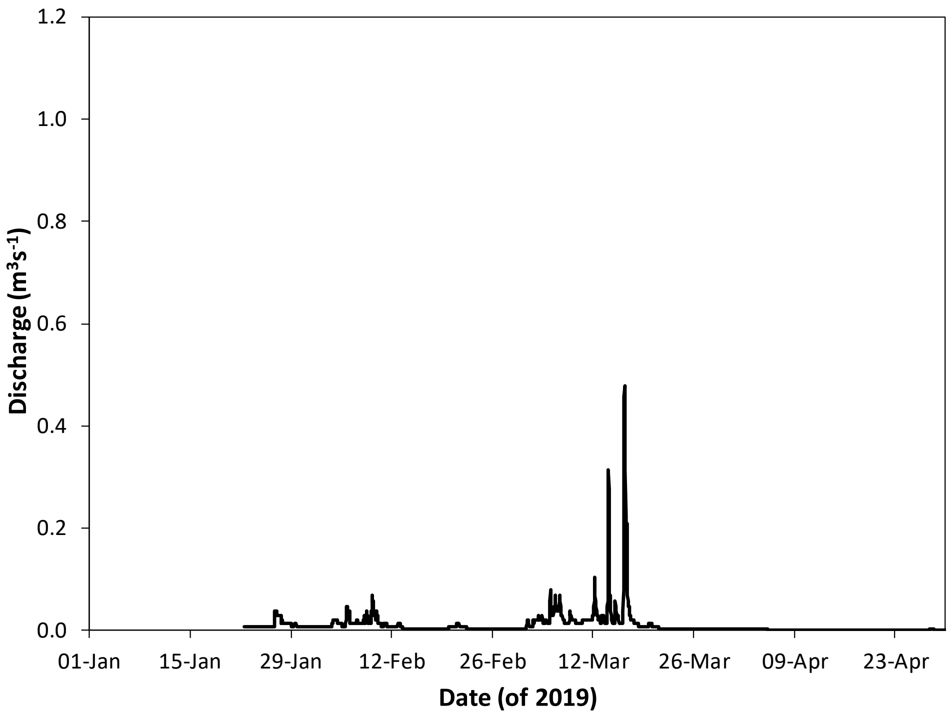

Figure 4.1.11. Hydrograph showing discharge estimated from stageboard-camera measurements at the Silt Trap gauging station from 22nd January to 1st May 2019.

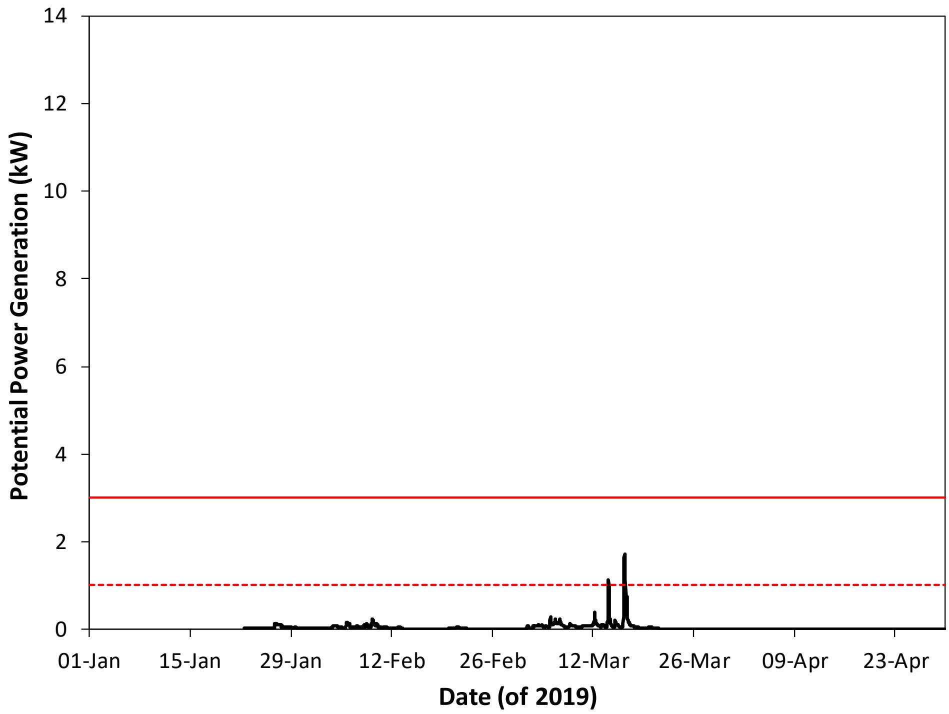

Figure 4.1.12. Potential power generation at the Silt Trap station – calculated from the discharge data in Figure 4.1.11 – from 22nd January to 1st May 2019, with the1 kW (dotted red line) and 3 kW (solid red line) levels indicated.

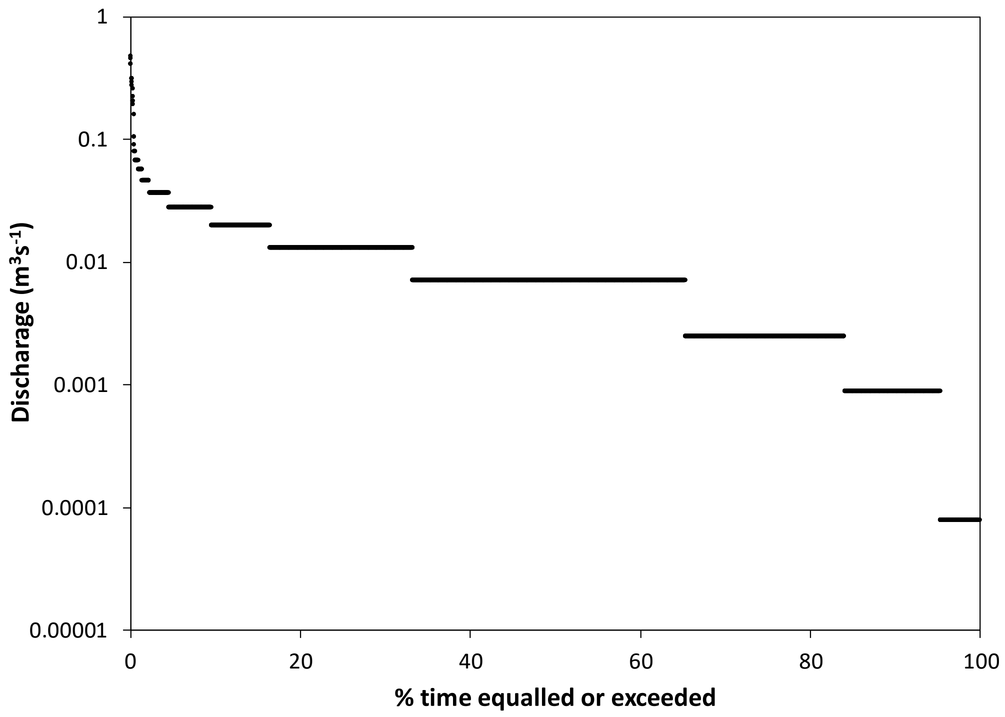

Figure 4.1.13. Semi-logarithmic plot of the flow-duration curve for the Silt Trap gauging station from 22nd January 2019 to 1st May 2019.

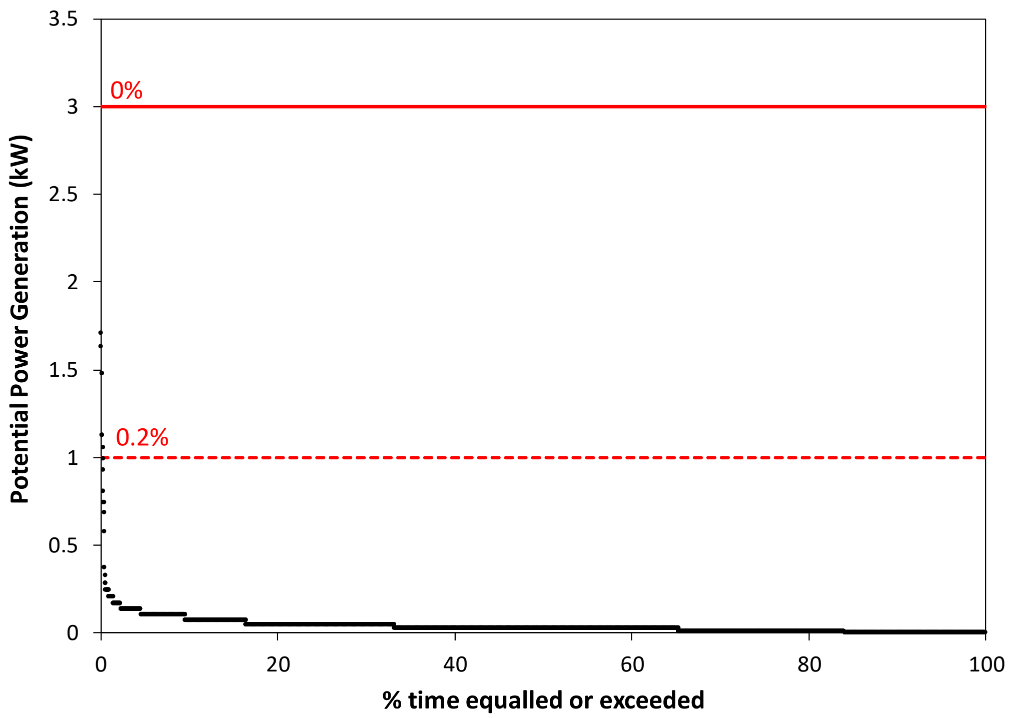

Figure 4.1.14. Power-duration curve for the Silt Trap gauging station for 22nd January to 1st May 2019, with the 1 kW (dotted red line) and 3 kW (solid red line) levels – and the percentage of time for which they were equalled or exceeded (0.2% and 0%, respectively) indicated.

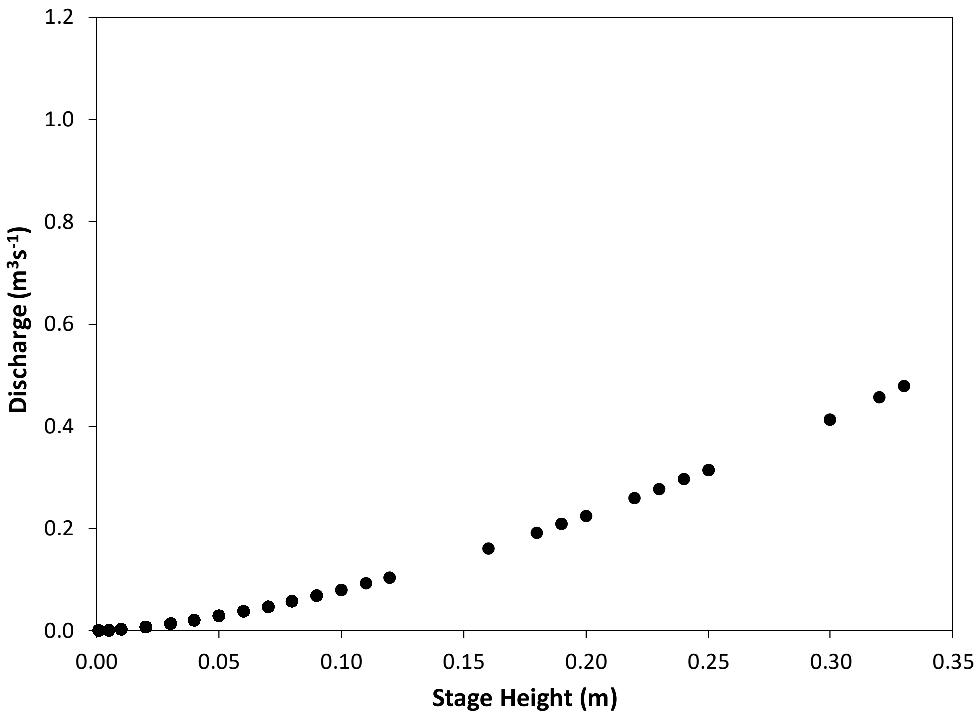

Figure 4.1.15. Stage-discharge rating curve for the Silt Trap station from 22nd January to 1st May 2019.

4.2 Dilution Gauged Sites

The discharges estimated by dilution gauging at the potential hydropower sites at Butler's Cottage, Redundant Pond and Calf House, as well as the location in Mill Brook downstream of all the potential sites, are shown in Table 4.2.1. Head at the Butler's Cottage, Redundant Pond and Calf House sites was 0.76m, 2.00m and 4.79m respectively.

Out of the three potential hydropower sites measured via dilution gauging, Butler's Cottage experienced the highest discharges, peaking at 0.066 m^3s^{-1}. Discharge across all sites was relatively low, with particularly low flows occurring from 28th March to 1st May. Average discharge leaving the site via Mill Brook was 0.039 m^3s^{-1}.

Due to instrument malfunction and low flow conditions which prevented accurate dilution gauging, the mean and median discharges of all three potential hydropower sites are likely to be lower than estimated, particularly at the Redundant Pond, where on six occasions, stream flow velocity was too low to accurately record discharge. This is particularly evident as the mean discharge of the Redundant Pond is higher than that of Calf House, despite Calf House predominantly having larger discharge estimates than the Redundant pond when both sites recorded discharges on the same date. Moreover, mean discharge is the same at the Redundant Pond and Butler's Cottage, despite the latter often recording discharges magnitudes higher than at the Redundant Pond. These data inconsistencies emphasise how the instrument malfunction and low conditions cause the mean discharges to be somewhat unreliable.

Discharge (m^3s^{-1})				
	Downstream from Bull Ring	Mill Brook (Butler's Cottage)	Redundant Pond	Calf House
04/02/2019	0.0550	0.0230	0.00698	0.00918
12/02/2019	0.0277	0.0114	*	0.00688
21/02/2019	0.0349	0.0131	0.00418	0.00727
25/02/2019	*	0.00265	**	0.00130
04/03/2019	0.0709	0.0188	0.00896	0.0112
07/03/2019	0.177	0.0655	0.0355	0.0329
11/03/2019	0.0568	0.0241	*	0.0130
19/03/2019	0.0273	*	0.00230	0.00482
28/03/2019	0.00589	0.00226	**	0.000704
03/04/2019	0.0103	0.00449	**	0.00151
10/04/2019	0.00349	*	**	**
23/04/2019	0.00150	**	**	**
01/05/2019	0.00242	0.000890	**	**
Mean	0.0394	0.0166	0.0116	0.00887
Median	0.0275	0.0192	0.00698	0.00708

*Table 4.2.1. Dilution gauging discharge estimates (3 s.f.) at potential hydropower sites Butler's Cottage, Redundant Pond and Calf House, as well as estimated discharge on Mill Brook, downstream from the Bull Ring, where all on-site water bodies converge. * indicates that data was unsuccessfully recorded due to data logger malfunction. ** indicates that flow velocity was too low to accurately record dilution gauging discharge estimates. Dilution gauging discharge estimates were recorded during weekly (or bi-weekly) visits from 4th February to 1st May 2019.*

As discharge naturally varies over time, and dilution gauging was only carried out once every 1-2 weeks during site visits, a degree of uncertainty is introduced to the average discharge values at each site. It is possible that higher flow events were missed due to the infrequency of the dilution gauging measurements. Furthermore, the average discharge leaving the site in Mill Brook was $0.039m^3s^{-1}$, which is less than the average discharge recorded at the Bull Ring and Lawn gauging stations. Considering that all on-site water bodies converge downstream of the Bull Ring, this section of Mill Brook would be expected to experience the highest discharges. This suggests there may be inaccuracies in either or both of these discharge measurement methodologies, although it may also be a consequence of the dilution gauging only being done on relatively infrequent occasions, and the mean value derived from the dilution gauging therefore not being representative of the fuller variability captured by the gauging method. The relatively low discharges are in line with the interpolated average monthly rainfall at Browsholme Hall, which indicates that February to May are some of the drier months in the year, with April being the driest. This is mirrored in the discharge data, which shows that April experienced the lowest discharges.

Potential power generation estimates at Butler's Cottage, Redundant Pond and Calf House were all relatively low (Table 4.2.2). The maximum potential power generation measurement across all three sites was 1.16 kW, at Calf House. Calf House also had the highest mean potential power generation, followed by Redundant Pond and lastly Butler's Cottage. However, the Redundant Pond has many instances of discharges that were too small to measure, indicated by ** in Table 4.2.2, which is likely to mean that potential power generation would be low during these periods. Therefore, the Redundant Pond's mean potential power generation would be lower than the value given in Table 4.2.2.

As for the calculated discharges from which they have been calculated, the estimates of mean power generation may not be accurate at these sites as discharge measurements were only taken once every 1-2 weeks, potentially failing to capture a great deal of the variability of each site hydrograph. However, based on these power generation estimates, the threshold of 1 kW was only exceeded on one occasion out of 35 times when measurements were either taken or where the discharge was too low to take measurements (** in Table 4.2.2). In this single case, potential power generation was calculated as 1.16 kW, thus on no occasions was 3 kW achieved. In the case of the Redundant Pond, it cannot provide significant power generation with the stream that currently flows through it. The amount of diverted water required in order to create a reservoir to provide consistent, significant power generation is explored in the following sections.

	Power (kW)		
	Mill Brook (Butler's Cottage)	Redundant Pond	Calf House
04/02/2019	0.129	0.103	0.323
12/02/2019	0.0640	*	0.242
21/02/2019	0.0736	0.0615	0.256
25/02/2019	0.0148	**	0.0456
04/03/2019	0.105	0.132	0.393
07/03/2019	0.367	0.522	1.16
11/03/2019	0.135	*	0.456
19/03/2019	*	0.0338	0.170
28/03/2019	0.0127	**	0.0248
03/04/2019	0.0252	**	0.0531
10/04/2019	*	**	**
23/04/2019	**	**	**
01/05/2019	0.00497	**	**
Mean	0.0931	0.170	0.312
Median	0.0688	0.103	0.249

*Table 4.2.2. Potential hydropower generation estimates (3 s.f.) at the Mill Brook (Butler's Cottage), Redundant Pond and Calf House sites, based on the estimated discharges derived by dilution gauging. The Calf House power estimates do not take into account of head loss due to friction through a pipe, therefore, actual power estimates may be lower. * indicates that power estimates could not be calculated due to missing discharge data is missing stemming from data logger malfunction. ** indicates that power estimates could not be calculated due to missing discharge data caused by low flow velocity preventing accurate dilution gauging.*

4.3. Redundant Pond – Proposed Reservoir

4.3.1. Hydropower Installation Design and Available Head

A configuration for the hydropower installation in the proposed reservoir at the Redundant Pond was designed, in which the available head of water for power generation was 2m. Head losses due to friction were calculated for this design, in which the water would have to pass through a pipe of length 3.0m. A pipe diameter of 0.6m was selected. The kinematic viscosity of water at a typical water temperature for the site of 10°C is 1.307×10^{-6} m^2s^{-1} (IAPWS, 2008). Using the calculations detailed in Section 3.5, these values gave a flow speed through the pipe of 0.72 ms^{-1}, and thus a Reynolds Number of 331,013. Riveted steel was chosen as the pipe material, which has an absolute roughness of 0.03 (Stewart, 2016). Therefore, the Darcy friction factor was 0.057, giving a head loss of 0.0095m. As the head loss was so small compared to the 2m of available head, it was considered negligible and not included in the subsequent power calculation for the Redundant Pond.

4.3.2. Water Balance calculations

Equations 11 and 12 in section 3.7.2 were used to quantify the water balance in the proposed reservoir and calculate the potential available power that could be generated. The dataset used to derive the time series of the variables in the water balance equation was the interpolated daily rainfall data for January 2007 to June 2019 (see section 3.6). This is shown in Figure 4.3.1. The average daily precipitation over this period was 4.16 mm, giving an average annual precipitation of 1518.4 mm. Median daily precipitation was 1.08 mm, and individual daily precipitation ranged from 0 to 92.9 mm.

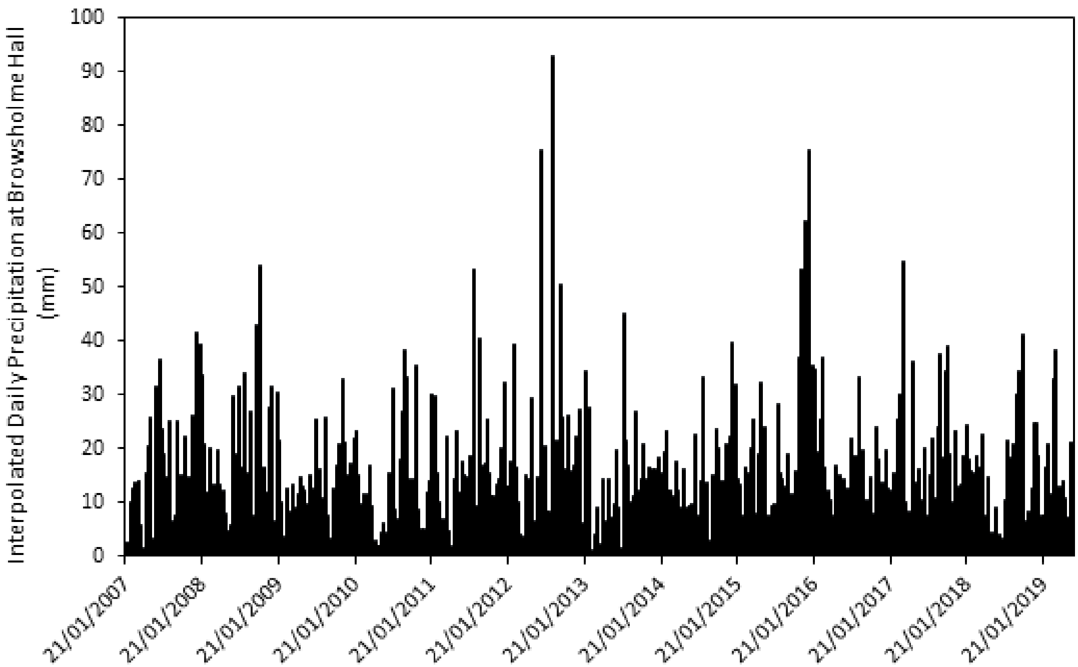

Figure 4.3.1. Interpolated daily precipitation at Browsholme Hall from 21st January 2007 – 18th June 2019. Data is derived from EA rain gauges at Footholme, Stocks Reservoir, Kebb Farm and Mearley Hall.

The average monthly precipitation for each month of the year is shown in Figure 4.3.2. The driest month on average was April (66.7 mm), while the wettest month was December (208.3 mm).

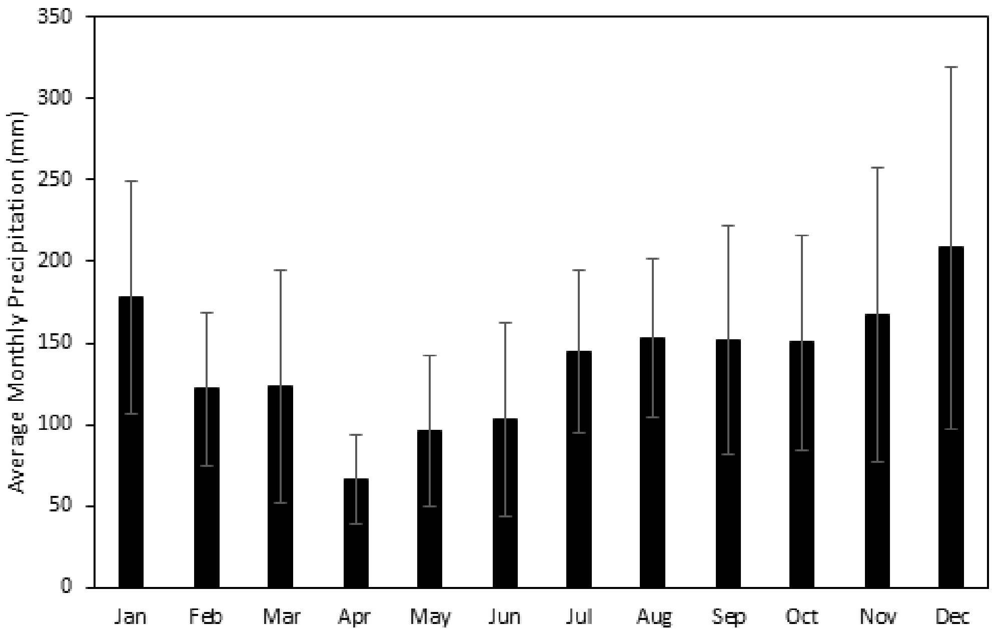

Figure 4.3.2. Interpolated average monthly precipitation at Browsholme Hall, January 2007 – June 2019. Error bars denote standard deviation.

December also had the highest variability of precipitation. Based on these interpolated precipitation values, January to April 2019, the period during which the on-site discharge measurements were carried out, was cumulatively slightly (8%) wetter than average for the time of year, experiencing 487.68 mm of precipitation compared to the January-April average for 2007 to 2018 of 448.63 mm. However, March 2019 was significantly (163%) wetter than the March 2007-2018 average (266.17 mm compared to 101.12 mm), whereas January, February and April were drier than average, experiencing 55%, 22.54% and 23.60% of the corresponding average precipitation respectively.

4.3.2.1 Continuous Generation

The required Q_{inflow} for 1kW and 3kW power generation was calculated using equation (11) (see section 3.7.2):

$$P + Q_{inflow} \geq Q_{hydro} + G_{water} + ET$$

For 1kW generation, the parameter values were: P = 7.70 x $10^{-5}m^3s^{-1}$ (interpolated average daily precipitation; see section 3.6); Q_{hydro} = $0.068m^3s^{-1}$ (determined by rearranging equation 1; see section 3.3); G_{water} = 1.18 x $10^{-5}m^3s^{-1}$ (see equation 12, section 3.7.2); ET = 2.67 x $10^{-5}m^3s^{-1}$ (see section 3.7.2). This gives a required Q_{inflow} of ≥ $0.06804m^3s^{-1}$.

For 3kW generation, the parameter values were: P = 7.70 x $10^{-5}m^3s^{-1}$; Q_{hydro} = $0.204m^3s^{-1}$; G_{water} = 1.18 x $10^{-5}m^3s^{-1}$; ET = 2.67 x $10^{-5}m^3s^{-1}$. This gives a required Q_{inflow} of ≥ $0.20403m^3s^{-1}$

As P, G_{water} and ET were magnitudes smaller than Q_{inflow} and Q_{hydro}, they were deemed negligible Therefore, maintaining a reservoir at the redundant pond required $Q_{inflow} \geq Q_{hydro}$. Given this, hydropower feasibility at the proposed reservoir was assessed using the estimated total discharge at Browsholme Hall. Consequently, to maintain a reservoir for continuous 1 kW or 3 kW power generation, Q_{inflow} had to be greater than or equal to $0.068m^3s^{-1}$ or $0.204m^3s^{-1}$ respectively. Average discharge (Q_{inflow}) was 0.024 m^3s^{-1} leaving a deficit of $0.044m^3s^{-1}$ [for 1 kW] and $0.1799m^3s^{-1}$ [for 3 kW] of flow to maintain reservoir levels. Hence, flow was too low for continuous power generation.

4.3.2.2 Variable Generation

A hydrograph showing potential daily discharge from the reservoir is shown in Figure 4.3.3. Mean, median and maximum estimated discharges were 0.024 m^3s^{-1}, 0.0062 m^3s^{-1} and 0.537 m^3s^{-1}. The flow duration curve is shown in Figure 4.3.4.

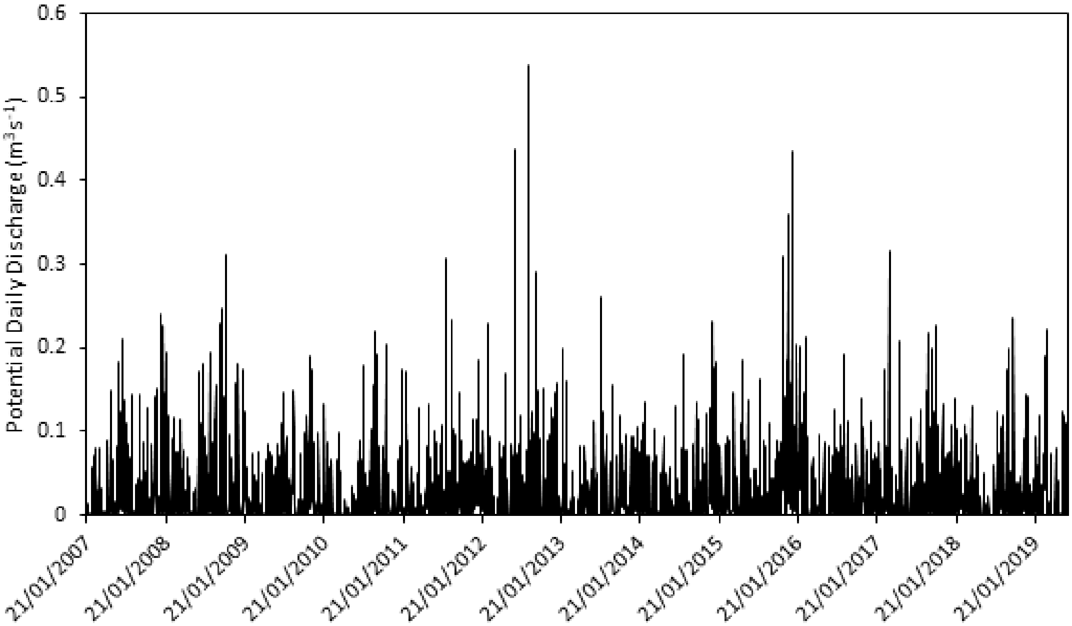

Figure 4.3.3. Hydrograph of estimated total discharge at Browsholme Hall from the 21st January 2007 – 18th June 2019, based on interpolated daily rainfall figures.

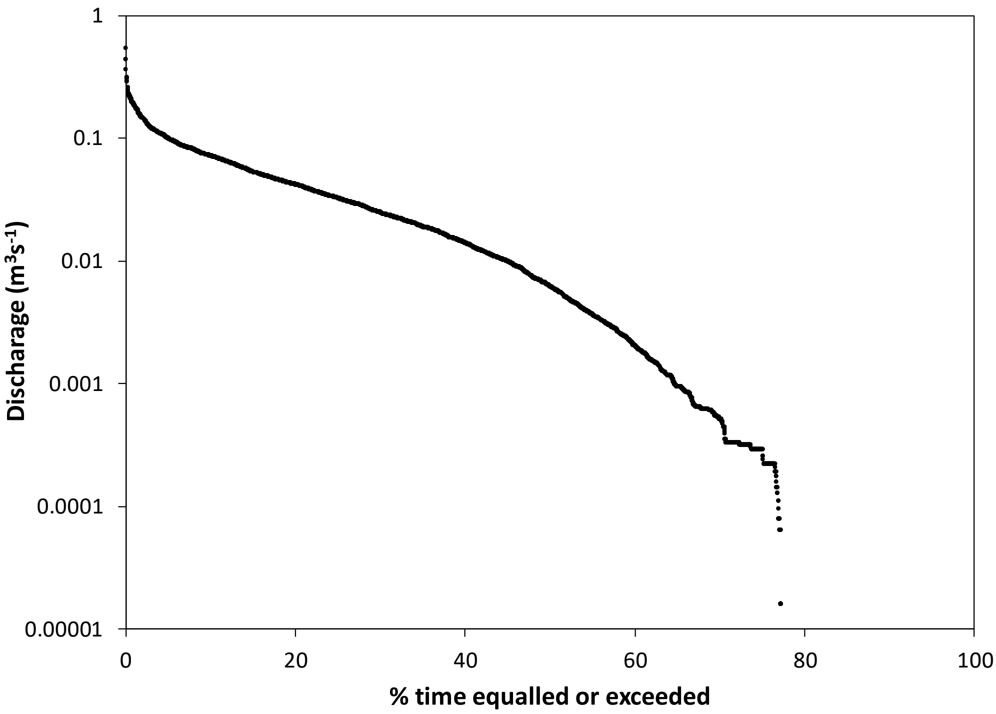

Figure 4.3.4. Flow duration curve of the estimated total discharge at Browsholme Hall from the 21st January 2007 – 18th June 2019, based on interpolated daily rainfall figures.

Daily power estimates from January 2007 to June 2019 are shown in Figure 4.3.5. Mean and median potential power generation were 0.35 kW and 0.092 kW respectively, while maximum potential power generation was 7.91 kW. From the 21st January 2007 to 18th June 2019, there were 501 days when potential power generation equalled or exceeded 1 kW, which equates to 40.35 days per year (11.05% of time) (Table 4.3.1). Over this time period, 3 kW potential power generation was equalled or exceeded on only 32 days, an average of 2.58 days per year or 0.71% of the time (Figure 4.3.6). The median potential power generation rate for each month from January 2007 to June 2019 is shown in Figure 4.3.7. The highest average monthly generation rate was 0.24 kW, the lowest was 0.025 kW. On average, the month of the year with the greatest potential for power generation is December, while April has the least potential for power generation (Figure 4.3.8).

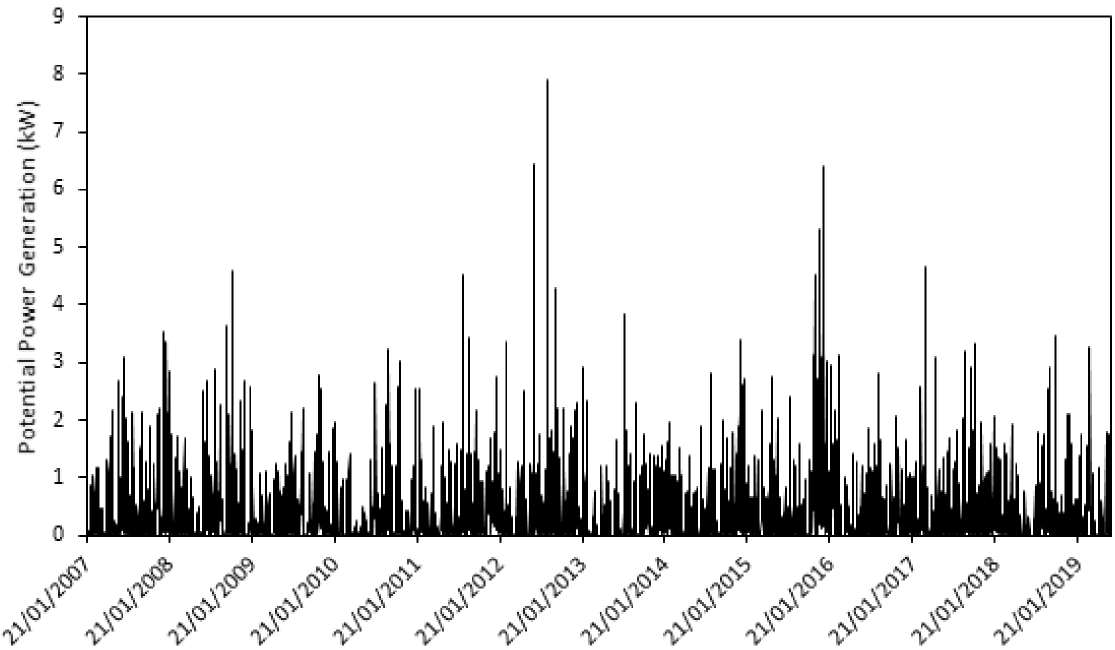

Figure 4.3.5. Potential power generation at Browsholme Hall from 21st January 2007 – 18th June 2019 if all on-site water bodies were diverted into the proposed reservoir at the Redundant Pond. Based on interpolated rainfall derived discharge estimates.

	≥1kW	≥2kW	≥3kW	≥4kW	≥5kW
No. of days generation equalled or exceeded:	501	109	32	10	4
Days per year generation equalled or exceeded:	40.35	8.78	2.58	0.81	0.32
% of time generation equalled or exceeded:	11.05	2.41	0.71	0.22	0.09

Table 4.3.1. Hypothetical power generation exceedance statistics at Browsholme Hall from 21st January 2007 – 18th June 2019 if all on-site water bodies were diverted into the proposed reservoir at the Redundant Pond. Power calculations are based on a 2 metre head.

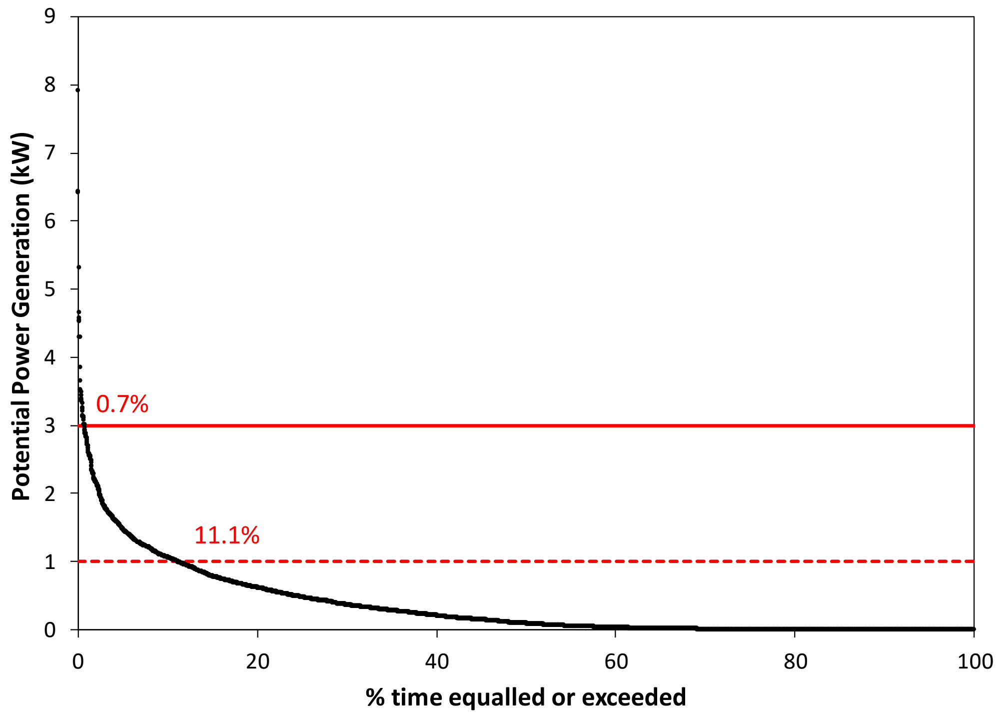

Figure 4.3.6. Diagram showing the percentage of time potential power generation equalled or exceeded a certain value if all on-site water bodies were diverted to the proposed reservoir at the Redundant Pond.

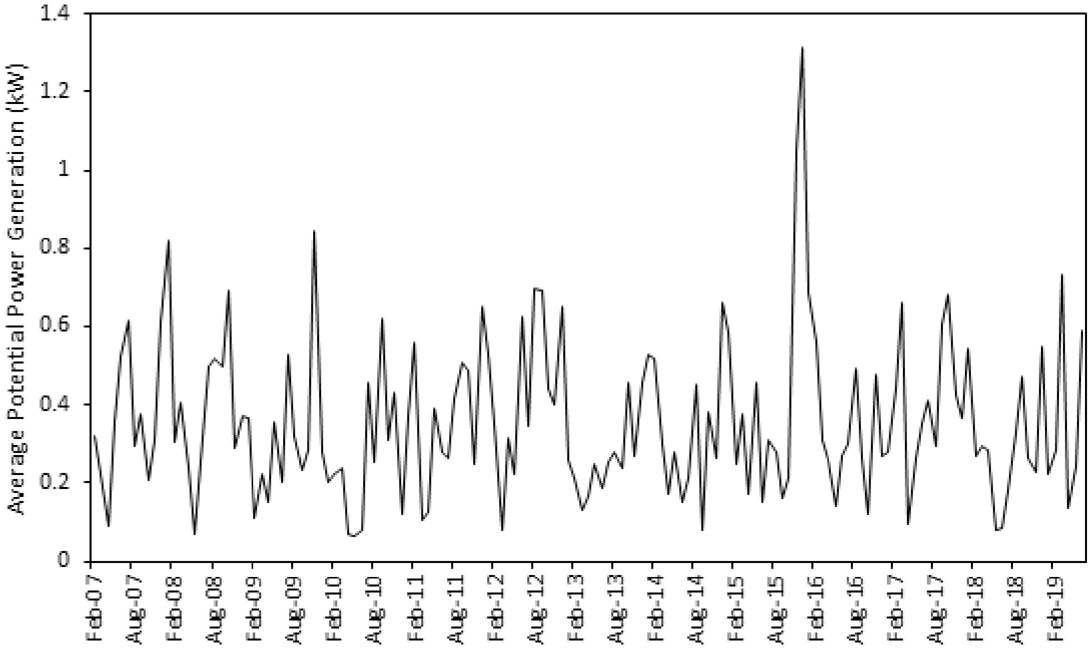

Figure 4.3.7. Average potential power generation rate of each month from January 2007 to June 2019 if all on-site water bodies were diverted to the proposed reservoir at the Redundant Pond.

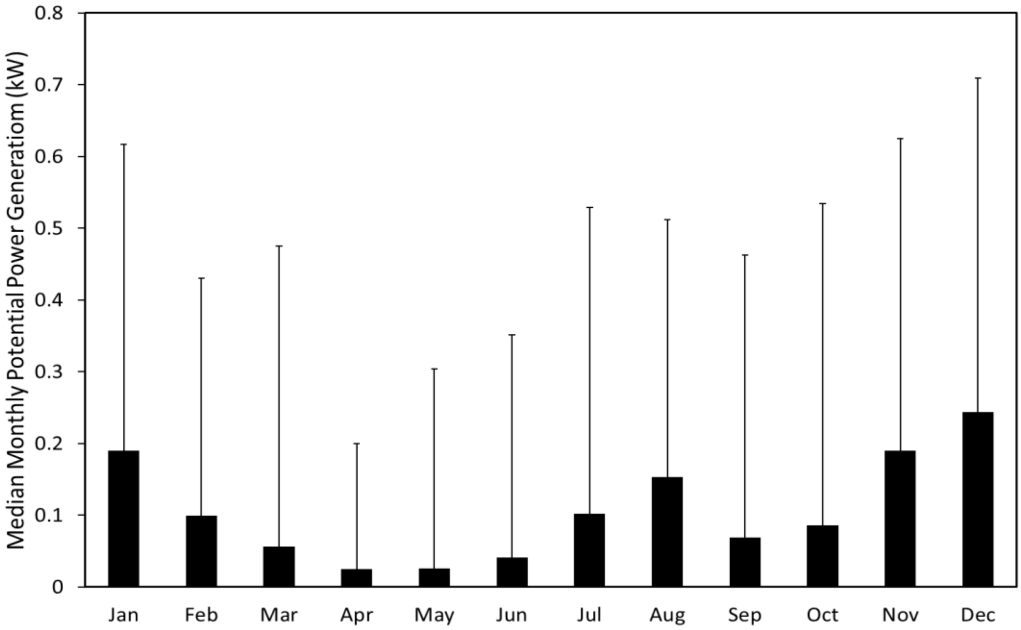

Figure 4.3.8. Hypothetical average monthly power generation at Browsholme Hall from January 2007 – June 2019 if all on-site water bodies were diverted into the proposed reservoir at the Redundant Pond.

These calculations imply that even if all on-site water bodies were diverted to the Redundant Pond to create a reservoir, the potential for significant variable power generation is limited. Even if it were possible to increase the available head height of the water significantly, the likelihood of flows sufficient to generate the required levels of hydropower are low (Table 4.3.2). To provide an understanding of the magnitudes of head and discharge that would be required to enable sufficient power to be generated by the proposed reservoir to make it a viable proposition, Figure 4.3.9 gives an indication of the levels of discharge and head required to generate different levels of power output. For example, with a 3 m head, 0.045 m^3s^{-1} of discharge is required to generate 1 kW of power. Flow only equalled or exceeded this value 18.46% of the time from January 2007 to June 2019 (Figure 4.3.4), a little over 2 months per year on average. Therefore, it is unlikely to be able to produce power at the required levels on a regular basis.

Discharge (m^3s^{-1})	0.05	0.1	0.2	0.3	0.4	0.5
No. days discharge equalled or exceeded:	737	229	33	8	3	1
Days/year discharge equalled or exceeded:	59.36	18.44	2.66	0.64	0.24	0.08
% of time discharge equalled or exceeded:	16.26	5.05	0.73	0.18	0.07	0.02
Estimated power generation (kW)	0.74	1.47	2.94	4.42	5.89	7.35

Table 4.3.2. Flow duration statistics of the estimated total discharge at Browsholme Hall from the 21st January 2007 – 18th June 2019, based on interpolated daily rainfall figures.

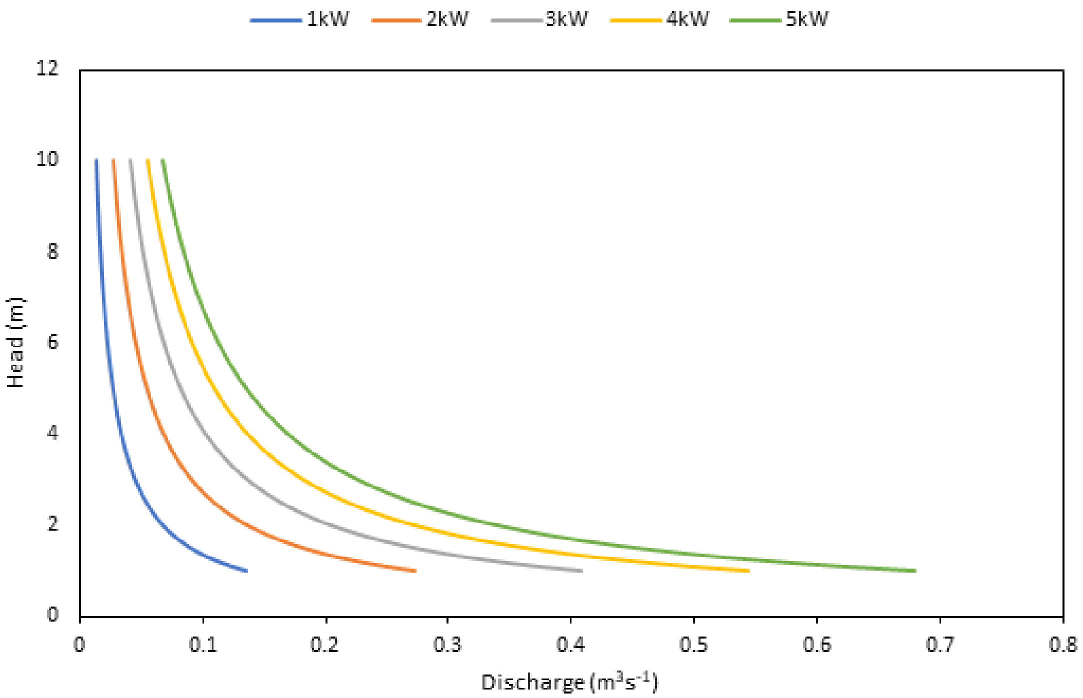

Figure 4.3.9. The level of hydropower generated from the proposed reservoir at the redundant pond for a range of combinations of discharge and head.

4.4 Ecological Surveys

4.4.1 Badgers

No badger sightings, setts or latrines were made during formal surveys or through incidental sightings during site visits.

4.4.2 Otters and Water Voles

No sightings or signs of otter or water vole activity were made during formal surveys or through incidental sightings during site visits. Although there was appropriate habitat present for water voles; during periods of low rainfall from February to April, 2019, numerous slow-flowing waterbodies preferred by water voles (PTES, 2019) contained little to no water (deuced by weekly site visits). Although possible, it is unlikely that any water voles are present at Browsholme Hall due to the ephemerality of the streams on-site.

The owners previously stated that otters had been spotted in the silt trap. The streams leading up to the silt trap contained little water during extended periods of low rainfall. Therefore, it casts a degree of doubt whether otters are likely to be resident at Browsholme Hall, as water levels are too low to provide the required navigable waterway habitat for otters.

4.4.3 Birds

4.4.3.1 Incidental Sightings

A single Barn Owl (*Tyto alba)* was spotted on four occasions from October 2018 – March 2019 flying around the ponds and the adjacent fields. Two to three pairs of Oyster Catchers (*Haematopus ostralegus*) were residing by the ponds from Late February to early April. A single resident Grey Heron (*Ardea cinerea*) was spotted regularly throughout the year by the ponds and the adjacent fields. The ponds were home to a flock of Canada Geese (*Branta canadensis*) and a flock of Greylag Geese (*Anser anser*). Grey Wagtails (*Motacilla cinerea*) were spotted on a few occasions from March 2019 onwards by Mill Brook by the Butler's Cottage and by the gardens in front of the Hall.

4.4.3.2 Bird Surveys

A list of birds spotted during the two surveys on 10th and 23rd April 2019 are seen in Table 4.4.1 overleaf. 26 bird species were identified. The number of species occurrences were not recorded.

Common Name	Scientific Name
Blackbird	*Turdus merula*
Blue Tit	*Cyanistes caeruleus*
Canada Goose	*Branta canadensis*
Carrion Crow	*Corvus corone*
Chaffinch	*Fringilla coelebs*
Chiff Chaff	*Phylloscopus collybita*
Coal Tit	*Periparus ater*
Common Gull	*Larus canus*
Goldcrest	*Regulus regulus*
Goldfinch	*Carduelis carduelis*
Great Tit	*Parus major*
Greater Spotted Woodpecker	*Dendrocopos major*
Grey Wagtail	*Motacilla cinerea*
Greylag Goose	*Anser anser*
Mallard	*Anas platyrhynchos*
Pheasant	*Phasianus colchicus*
Pied Wagtail	*Motacilla alba*
Robin	*Erithacus rubecula*
Sky Lark	*Alauda arvensis*
Song Thrush	*Turdus philomelos*
Tree Pipit	*Anthus trivialis*
Treecreeper	*Certhia familiaris*
Willow Tit	*Poecile montanus*
Willow Warbler	*Phylloscopus trochilus*
Woodpigeon	*Columba palumbus*
Wren	*Troglodytes troglodytes*

Table 4.4.1. Bird list of birds identified during the two bird surveys at Browsholme Hall on the 10th and 23rd April 2019.

4.4.4 Bats

The bat survey carried out on the 16th July 2019 found several species of bat present around the Hall and Lake. Shortly after sunset, a solitary noctule bat (*Nyctalus noctule*) was spotted flying across the south western corner of the hall towards an adjacent patch of woodland.

Common pipistrelles (*Pipistrellus pipistrellus*) and soprano pipistrelles (*Pipistrellus pygmaeus*) were spotted at several locations, around the woodland adjacent to the road leading to the back of the hall; the area surrounding the Butler's cottage, the hall gardens, around the lake and by the barn.

Two natter's bats (*Myotis nattereri*) were spotted at the back of the hall approximately 40 minutes after sunset. A daubenton bat (*Myotis daubentonii*) call was detected on the heterodyne around the lake approximately 50 minutes after sunset. However, no visual sightings could be made due to the darkness.

The bat survey conducted on the 14th August 2019 identified numerous common and soprano pipistrelles in the areas surrounding the streams on-site.

5. Discussion

5.1 Hydropower feasibility

The results presented imply that hydropower generation would not be feasible at Browsholme Hall due to the intermittency of potential power generation to sufficient levels. Across all potential hydropower sites, the highest percentages of time potential power generation equalled or exceeded 1kW and 3kW was at the Redundant Pond, with 11% and 0.71% respectively. However, these generation figures are based on the hypothetical premise that all on-site water bodies were diverted to the Redundant Pond in order to create a reservoir. In reality, it is unlikely that the Environment Agency would permit such drastic alterations to water courses, particularly one that diverts all on-site water to a new reservoir. Diverting all water bodies would likely to remove numerous existing habitats, thus significantly degrading the environment. In order to divert a significant proportion of flow on-site, rigorous environmental surveys would need to be produced and presented to the Environment Agency to provide evidence that altering water courses would not have a detrimental environmental effect. Moreover, if any water bodies were diverted to the Redundant Pond, the number of water bodies/volume of water diverted would likely be much lower than in the devised hypothetical scenario, resulting in lower discharge and subsequent power generation.

Moreover, the potential power generation calculations assumed that all available water flowing through a water body would be abstracted for hydropower generation. However, the Environment Agency sets a maximum abstraction threshold of 1.3 times the mean discharge for all run-of-river hydropower schemes in England and Wales (Environment Agency, 2016c), which would be likely to be the design of the proposed scheme. These abstraction limits would drastically limit the potential hydropower generation on-site. For example, the maximum power generation for the reservoir creation scenario would fall from 7.98kW to 0.46kW, well below the minimum power generation threshold of 1kW. Furthermore, the mean potential power generation would also be lowered by this abstraction limit, and as mean potential power generation was already low at all sites, hydropower generation would become even less viable. It is possible to apply to the Environment Agency for higher abstraction levels but supporting evidence in the form of environmental reports would be required, demonstrating that greater abstraction would not affect the performance of the WFD objectives; would not cause unacceptable impacts to protected species or sites; and would not cause significant impacts to the rights of other water users (Environment Agency, 2016c). Overall, the maximum abstraction threshold set by the Environment Agency indicates that significantly higher flows are required in order to sufficiently generate hydropower.

A comparison of discharge and potential power generation reveals that significant power generation at Browsholme Hall would be predominantly confined to peak flow events, which are infrequent. Moreover, utilising peak flow events for power generation is problematic as a hydraulic jump may be formed during high flows, which may reduce head significantly. If flows are such that water levels rise above the level of the turbine, it can reduce power generation and may even cause the turbine to become inoperable (Pelz & Froehlich, 2016). As the head at all the proposed gauging stations is moderately small, considerable thought would need to be given at the design stage to ensure that the level at which the turbine would be situated would be unlikely to affect its performance due to high water levels during peak flows. To achieve this (assuming hydropower was feasible), further on-site investigations prior to construction would be advisable to measure the variability of water levels, particularly during peak flows.

Furthermore, significant discharges were only achieved during periods of heavy rainfall, whilst periods of low discharge were associated with low or no rainfall. This would suggest that streamflow at Browsholme Hall is rainfall-dominated, implying that stream flow is likely to be consistently low during the drier periods of the year, as surface waters will not be recharged by aquifers to the same extent as groundwater-dominated rivers (Sear *et al*., 1999). Rainfall-dominated streams are not unfeasible for hydropower *per se*, but if they are coupled with naturally low flow rates, being rainfall-dominated may not be helpful.

5.1.1 Data Uncertainties

There is a high degree of similarity in flow estimation between the dilution gauging method and Manning's equation-derived discharges at low to medium flow rates. However, during high flow events, the Manning's equation-derived discharge method tends to provide higher estimates of flow rate than the dilution gauging. For example, at 12pm, on 7th March, 2019, the measured water level at the Bull Ring gauging station was at 0.1 m. At that time, dilution gauging estimated that discharge was 0.066 m^3s^{-1} in Mill Brook at Butler's Cottage. Using Manning's equation, the discharge in Mill Brook at the Bull Ring at the same time was calculated as 0.221 m^3s^{-1}, which is almost 3.5 times higher than the measurement taken at Butler's Cottage, less than a kilometre upstream. Furthermore, the dilution gauging measurement taken downstream of the Bull Ring, where multiple streams converge, had a discharge measurement of 0.177 m^3s^{-1}. Thus, the calculated discharge at the Bull Ring not only exceeds the value upstream (at Butler's Cottage), but also the value downstream, where discharge is expected to be higher due to the convergence of multiple streams. This is highly unlikely. However, it could be argued that estimated discharges that are being compared at different locations use differing techniques, and therefore, comparing the similarities between the estimates is not a suitable way to assess the accuracy of discharge measurement made. It is possible that these different locations experience varying levels of groundwater discharge and recharge, as well as runoff, which could cause discharge at the two points in the same stream to differ. For example, the land cover surrounding the Butler's Cottage contains more woodland that the Bull Ring, which is predominantly composed of open grassland. The latter would likely experience higher rates of runoff than the former, where the woodland would intercept a higher proportion of rainfall. These land cover type differences could explain why discharge may be different at these two points, and hence, why compares two separate sites may not be a fair indicator of discharge accuracy.

Nevertheless, although stream bed characteristics such as slope, morphology and material, as well as land type cover, may change slightly between Butler's Cottage and the Bull Ring, it is unlikely that there would be a significant difference in discharge on such a small stream, especially given their close proximity to one another. The change in land type cover is unlikely to explain the approximate 3-fold increase in flow less than a kilometre downstream, particularly as bed characteristics stay the same for the most part between measurement sites. Therefore, we can assume that during high flows, the Manning's equation may be overestimating stream velocity and subsequent discharge. A reason for this could be that the Manning's equation assumes that stream flow is uniform. This may be the case during low flows, where a high level of similarity between dilution gauging and Manning's equation estimations are observed. However, during high flows, stream flow becomes strongly non-uniform, rendering the Manning's equation ineffective for measuring discharge during these periods. This would explain why during peak flow events, discharge is calculated by this method to be much higher than at low or medium flows.

However, Tazioli (2011) states that dilution gauging is also subject to inaccuracies in discharge measurement during high flows. Injected tracers may be partially absorbed by suspended sediments during high flows, leading to overestimations of discharge. Moreover, the study also states that other measurements of discharge are subject to inaccuracies, such as current metering, which may produce unreliable estimates during minimal flow or flood events

(Tazioli, 2011). This highlights that each method of measuring discharge has its own advantages and disadvantages, which makes inter-comparison particularly difficult. Furthermore, as no research has been conducted comparing dilution gauging to Manning's equation-derived discharge estimates, it is difficult to ascertain the accuracy of the discharges recorded by both methods during this study.

Nevertheless, even if we assume that the estimates derived from the Manning's equation are accurate, the discharge would not be great enough to provide sufficient power to act as a consistent power source. The mean potential power generation at the Bull Ring gauging station on Mill Brook was 0.28kW, well below the required 1kW output; and the potential power output only exceeded 1kW approximately 5.5% of the time. It is only during peak flow events that a hydropower installation at this station could hypothetically provide a suitable level of power, but they typically tend to last only a day or two at most.

As on-site discharge measurements began at the end of January, it might be argued that the recorded discharges did not provide an accurate representation of annual discharges, as February, March and April all fall within the top five average driest months of the year at Browsholme Hall. Moreover, January, February and April, were all drier than average. Therefore, recorded discharges from January – April 2019 might be lower than usual and only capture discharge during the driest time of the year, leading to inaccurately low power estimates. Moreover, as the UK has been statistically wetter than the 1961-1990 average, experienced seven of the ten wettest years from 1998 to 2017 (Kendon *et al*., 2018), and is predicted to experience more precipitation during the winter in the future (Met Office, 2019), it can likely be argued that the discharges recorded from January – April 2019 are not representative of usual conditions. Therefore, if additional feasibility assessments are to be undertaken in the future, it would be advised to take new measurements over these months and extend the length of data collection to a year at least, to investigate whether any differences occur in a later year, as well as to identify if any trends appear in the data.

5.1.2 Potential Solutions to Increase Hydropower Feasibility

It could be argued that with appropriate battery technology, hydropower feasibility at Browsholme Hall could be achieved. However, hydropower schemes accompanied with battery technology are a rarity, currently belonging in a bespoke marketplace. Advances in battery technology are developing but their utility is still very limited. For example, Cobalt Project Management Ltd presented their co-located hydropower batteries at the BHA annual conference in 2018. Their batteries have a discharge time of up to two hours, which is very short (Blaber, 2018). If a battery of these design specifications were installed at Browsholme Hall, it would not be able to provide energy security as the intermittent nature of power generation greatly exceeds two hours. Nevertheless, renewable battery research and development is underway, particularly for solar power. For example, the Faraday Institution has announced it will reward up to £55 million to five UK-based consortia to conduct innovative research into new battery chemistries, systems and manufacturing methods (The Faraday Institution, 2019). If significant improvements in battery technology are achieved for another renewable technology, it is not unwise to assume that improved battery technologies will become available for hydropower in the future. Therefore, it may be assumed that small-scale hydropower feasibility could increase at Browsholme Hall in the future.

Alternatively, power generation could be maximised by installing multiple small-scale hydropower schemes on the premises. However, even if these were installed at Browsholme Hall, the percentage of time that power generation would be significant would still be low. For example, if a hydropower scheme was installed at each of the three gauging stations, Bull Ring, Lawn and Silt Trap, 1kW and 3kW power generation would only be equalled or exceeded 9.27% and 1.37% of the time respectively, which is still relatively low. Furthermore, installing multiple small-scale hydropower schemes is likely to be costly given the low power generation capacity of each scheme. Additionally, installing multiple small-scale hydropower schemes would likely increase the environmental impact, as indicated by recent research highlighting cumulative impact of numerous small-scale hydropower schemes on the environment (Kibler & Tullos, 2013; Mayor *et al*., 2017).

Another way to increase hydropower feasibility at Browsholme Hall is to explore engineering solutions to increase head and subsequently hydropower output. However, substantial engineering would likely be required to produce significant power generation increases. As average discharge across Browsholme Hall's water bodies is relatively low, head would need to be increased by several metres to produce consistent and significant power generation (as illustrated in Figure 4.3.9), which may not be possible. For example, at the redundant pond, it would prove difficult to significantly increase head. Firstly, the height of the proposed abstraction intake could not be raised by more than 50 centimetres, as the Environment Agency imposes a height restriction of 1.5 metres on all newly constructed or retrofitted weirs on upland watercourses. Lowering the height of the turbine to increase head would also be met with significant issues. In order to significantly increase head, a penstock would need to be constructed that stretches between 800 metres and 1 kilometre downstream. This would require extensive construction and would likely be very costly. Moreover, even with a 10-metre head, if the average cumulative on-site flow ($0.024m^3s^{-1}$) was diverted through the penstock, only 1.77kW could be produced. This is without taking the Environment Agency's maximum abstraction limit into account, which would significantly reduce the potential power output. Consequently, the construction of such an extensive penstock in order to increase head is unlikely to be cost effective given the low potential power output. Additionally, the land downstream of the Bull Ring is not under the ownership of the Parker Family, and subsequently, would require permission from all landowners for any form of construction to take place, which may prove difficult to obtain and may greatly complicate the planning process.

The Fish Pond could potentially be utilised to increase feasibility. If a penstock were constructed from the Fish Pond to the Bull Ring, the available head would be approximately 9 metres. Assuming that all on-site flow was diverted to the Fish Pond, 1kW generation would become more feasible. To produce 1kW generation with 9 metres of head, a discharge of $0.015m^3s^{-1}$ would be required through the hydropower scheme. As average cumulative on-site discharge was $0.024m^3s^{-1}$ (interpolation derived), the potential inflow would be greater than that of the outflow, allowing for successful maintenance of the reservoir. This would increase the percentage of time that 1kW generation could be equalled or exceeded, from approximately 11% to 39%. Moreover, the Fish Pond's ability to store water could be used to release flow at specific times to generate power. This could be achieved in the Fish Pond's existing state by determining how much water can be extracted whilst still sustainably maintaining the reservoir. For example, if it was deemed that the reservoir could not empty below 75% of its total capacity, continuous 1kW generation could in theory be sustained for approximately 11.5 days if allowed to empty from 100% to 75%. This shows that that percentage of time that 1kW generation could be equalled or exceeded may actually be greater than 39%. However, this could only be done sustainably if there is evidence that strongly suggests that the reservoir will be replenished soon thereafter.

Alternatively, the Fish Pond's capacity could be expanded in order to store excess flow during high flow events. The $50000m^2$ Fish Pond currently has an average depth of 1.2 metres, giving it an approximate volume of $60000m^3$. The top 1% of flow events at Browsholme Hall cumulatively equalled or exceeded approximately $16100m^3$ per day (interpolation derived). Without expanding the Fish Pond's capacity it may be difficult to capture all of the flow during these high flow events. But if it was expanded, captured water could then potentially allow for higher generation thresholds to be achieved, as well as increasing the percentage of time significant hydropower generation can be maintained.

However, all of the calculations above do not account for the Environment Agency's abstraction limits for run-of-river hydropower schemes. With said abstraction limits applied, the maximum abstraction (1.3 x mean discharge) permitted would be $0.031m^3s^{-1}$. Although this does not decrease the percentage of time 1kW could be equalled or exceeded, it does significantly limit the maximum power output achievable through the scheme. Maximum power output would be capped at 2.05kW with these abstraction limits, meaning the desirable 3kW power output could not be achieved. Even without the Environment Agency's abstraction limits applied, high power outputs could not be sustained for long periods as it would risk draining the reservoir quicker than it can be replenished. For example, to continuously produce 3kW over a period of one day, approximately $3900m^3$ of abstracted water would be required, which represents around 6.5% of the Fish Pond's current capacity.

Additionally, this scenario relies upon the assumption that all water bodies are diverted to the Fish Pond. As previously mentioned, is it unlikely that the Environment Agency would permit such significant changes to existing waterbodies given the extensive environmental disruption it would cause. In all likelihood, the actual amount of flow that could be diverted to the Fish pond would be much lower, leading to lower potential power output. Realistically, approximately two thirds of flow from all water bodies would need to be diverted to the fish pond in order to meet the 1kW generation threshold, which may be difficult to achieve given the restrictions applied by the Environment Agency.

Overall, engineering works to increase feasibility at Browsholme Hall may potentially be too extensive to be cost effective. This is particularly pertinent if a hydropower scheme were constructed at the Fish Pond. Extensive construction would be required to divert water bodies, expand the storage capacity of the Fish Pond and to run a 250-metre penstock to the Bull Ring. It may be more cost effective to invest in an alternative renewable energy source at Browsholme Hall (as discussed later in 6. Recommendations), especially as 1kW cannot be generated most of the time. If significant engineering projects were pursued to increase hydropower feasibility, detailed cost-benefit analyses would be required to determine whether a potential hydropower scheme at Browsholme Hall would be economically worthwhile.

5.2 Ecological Surveys

Although hydropower has been deemed unfeasible at Browsholme Hall, the following sections will discuss the results of the ecological surveys and the implications that protected species may face by installing a hydropower scheme on-site. Despite the outcome of the feasibility assessment, the proprietors of Browsholme Hall may decide to pursue hydropower as a source of energy, and therefore, it was deemed appropriate to discuss how a hydropower scheme may affect protected species on-site.

5.2.1 Otters

Otters are known to have a large range, with some covering distances of 20km or more of river habitat (The Mammal Society, 2016). Otters previously spotted at Browsholme Hall are likely to have been exhibiting exploratory foraging behaviour. This behaviour is dependent on prey availability and abundance. In riverine environments where food availability is low, otters tend to hunt for prey "on-the-move" as they continuously travel through waterways. Conversely, in riverine areas where prey availability is high, otters situate themselves in these areas for longer stretches of time, exploiting the abundance of food sources (Kruuk, 1995). Observed prey species abundance and diversity is low at Browsholme Hall, with only brown trout and Bullhead identified in the past, suggesting that otter prey availability is likely low (NBN, 2019). Lower prey abundance and availability may explain why otters have been spotted in the past for only short periods, as they are exhibiting exploratory foraging behaviour as they travel through waterways with low prey availability.

However, it can be argued that the lack of otter sightings could be down to the timing of the survey. Otters are primarily active an hour prior to dusk until an hour before dawn, with a peak in activity occurring at dusk and the, immediately following, period of night (Mason & Macdonald, 1986). As the surveys took place during daytime hours, one could argue that the chances of sighting otters would be significantly reduced, therefore, diminishing the reliability of the surveys. However, as the surveys also sought to identify signs of otters, such as footprints and spraint, the absence of such signs is indicative that Browsholme Hall does not fall under any otter's range, particularly due to the lack of spraint, which is frequently used by otters as a form of territorial marking (Mason & Macdonald, 1986). Consequently, the previous statement regarding the reliability of the survey during daytime hours can be refuted.

If a hydropower development was constructed at Browsholme Hall, it is unlikely to cause notable disruption to any migratory otters. As otters are semi-aquatic, a small barrier on a waterbody can be navigated by exiting the water and walking around/over it, unlike fish, which require a fish pass. Additionally, the flooding of land for the creation of a reservoir may provide beneficial wetland habitats which otters can utilise. Otters often prey on organisms other than fish, such as amphibians, invertebrates and birds (Lanszki *et al*., 2015). The creation of a reservoir at Browsholme Hall would likely provide additional habitat for common frogs and toads, which are already present in a number of the ponds and streams on-site and form a significant portion of otters' diets (Slater, 2002; The Mammal Society, 2016). Hence, common frog and toad population increases could provide a potential food source for visiting otters, which is significant, as otters' traditional food, such as salmon and eels, have been declining in rivers and streams (Kruuk, 2014), leading to an increased reliance on amphibians as a food source. It is well documented that otters switch from their preferred prey: fish, to alternative food sources when fish availability is low (Pagacz & Witczuk, 2010). For example, otters in north-eastern Scotland migrated to marshland 3.5 kilometres away to prey on hibernating amphibians when fish stocks drastically decreased during the winter (Weber, 1990). Similarly, otters in central Finland switched to feeding primarily on amphibians, after the resident lake froze, preventing otters from accessing the fish below (Sulkava, 1996). Conversely, Pagacz & Witczuk's (2010) study found that amphibians can be an equally important component of otters' diets, even when fish are abundant. Amphibians and fish comprised 43% and 42% of prey occurrences, as well as 54% and 44% of prey biomass respectively, at the study area in the Bieszczady Mountains, south-east Poland. Moreover, studies have shown that otters feeding habitat is significantly dependant on seasonality, where spring months typically see amphibians form a higher percentage of the otter diet (Britton *et al*., 2006; Lanszki *et al*., 2015). Therefore, as previously stated, the creation of a reservoir for a proposed hydropower development at Browsholme Hall could prove beneficial to any migratory otters. Creation of additional wetland habitats may attract animals such as amphibians, birds and crustaceans, increasing otter prey availability and abundance.

5.2.2 Birds

If a hydropower development were constructed at Browsholme Hall, it is unlikely that this development would cause significant concern for birds on-site. Most of the disruption is likely to be confined to the construction phase, where construction equipment may cause behavioural disturbances or damage to habitats. If a development is likely to cause significant disruption to key bird habitats, mitigation strategies, such as habitat creation and installation of nest boxes, should be considered. One species that may be affected by any future developments is the grey wagtail, which nests by waterways in small hollows and crevices filled with moss and twigs. Grey wagtails prey on ants and midges beside rivers, as well as snails and tadpoles in shallow waters (The Wildlife Trusts, 2019). Alterations to flow regime may potentially, cause significant changes to the grey wagtail's habitat and prey, in which case mitigation strategies should be employed. This can include, commencing construction outside of the breeding season, removal and creation of habitat before the nesting season and installation of nest boxes (Natural England, 2015).

Similarly to otters, the creation of a small reservoir is likely to encourage wetland bird species to nest at Browsholme Hall, increasing the biodiversity of the property. Creation of wetland habitats is vitally important as wetlands have declined by 64% globally since 1900, with inland wetland disappearing at a faster rate than coastal ones (Ramsar, 2015). The RSPB (2011) estimates that 90% of Britain's wetlands have disappeared since Roman times, emphasising the importance of wetland creation across Britain. Wetlands are some of the most productive ecosystems on the planet, providing habitats for birds, fish, invertebrates and mammals. They are highly important for juvenile animals, acting as a nursey grounds for said species (WWF, 2018). Although wetland creation is not the primary objective of building a hydropower scheme at Browsholme Hall, it is a welcome and indirect effect which would be beneficial to the local environment.

5.2.3 Bats

A proposed hydropower development is unlikely to cause harm to bats on-site. If construction were to commence, further surveys would need to be conducted to identify where the bats were roosting prior to construction. If roosts were identified in trees or structures likely to be affected by the proposed hydropower scheme, appropriate mitigation would need to be carried out, such as constructing around existing roosts, creation of artificial roosts (for example, bat boxes) and minimising artificial lighting to avoid behavioural disturbances. Moreover, post-development population monitoring is recommended to assess whether the mitigation had been successful, and if it had not, what further measures could be implemented to ensure mitigation was successful (Bat Conservation Trust, 2019).

A previous bat survey conducted at Browsholme Hall by the East Lancashire Bat Group in May and July, 2016, found that a number of roosts were present in the Hall and Butler's Cottage. This suggests that many of the bats on-site were roosting in buildings and subsequently unlikely to be affected by any proposed hydropower developments. However, it has not been established whether bats were roosting in the woodland present on-site. Therefore, additional surveys would still be required if a hydropower scheme was to be developed at Browsholme Hall.

5.2.4 Fish

As a fish survey could not be carried out in this project, it would be highly advisable to conduct one if a hydropower development is planned in the future. Findings of a fish survey will enable an appropriate fish pass design which permits the passage of all resident and migratory fish in the river system.

5.2.5 Great Crested Newts

If a hydropower development is planned in the future, it would also be advisable to conduct a great crested newt survey. Despite no official record of great crested newts at Browsholme Hall (NBN, 2019), there is potential for newt presence given the abundance of appropriate habitat, as well as presence of common frog tadpoles, which adult newts prey on (Frog Life, 2019). However, the high abundance of common frogs at Browsholme Hall (visual observation) may indicate that great crested newts are not present, as this would normalise population numbers. Furthermore, great crested newts generally do not inhabit the same waterbodies as fish (Frog Life, 2019), and as there are official recordings of brown trout and Bullhead fish on-site, this may rule out the presence of newts. Nevertheless, it would be best practice to conduct a great crested newt survey.

5.2.6 Data Uncertainties

The results of the bird survey were presented as a simple list, which limits the scientific value of the survey (BirdLife, 2019). The number of sightings of each unique taxon was not performed due to the limited experience of the surveyor, as well as a lack of training prior to the survey. Therefore, it was deemed more appropriate for the surveyor to simply note down what species they witnessed, rather than risk miscounting the number of observations made. The lack of bird surveying experience also raises questions about the reliability and accuracy of the bird taxa recorded. It is likely that bird taxa were either misidentified and/or missed, as two thirds of identification during a bird survey is done through song/calls alone (I. Hartley, personal communication, 2019). The post-survey taxa identification using identification resources and photos/videos taken during the survey does increase the reliability of the survey to a degree, particularly when identifying taxa using song/calls, which can be difficult to undertake correctly on the spot. However, this post-survey identification is still prone to error.

Nevertheless, the comparison of the bird list to the NBNs recorded bird sightings does reveal that all the species identified during the bird surveys have previously been identified on-site. Moreover, NBN records show that the instances of vulnerable species are rare. Species that could be affected by a small hydropower development are even rarer, such as Dippers, which have only been spotted once on-site (NBN, 2019). It could be argued that even with a lacking, extensive, professional bird survey, the risk of harm to birds by constructing a small hydropower development is negligible. If a future development is planned, it would be advisable to conduct additional surveys to formally assess the bird population on-site.

5.3 Limitations of the Study

5.3.1 Hydrometric Measurements

A problem with the discharges estimated from interpolated rainfall values is that they do not account for lag time. In this model, rainfall at Browsholme Hall is assumed to automatically become runoff. A lack of lag time should not affect discharge values themselves but does raise questions about the accuracy of the temporal variability of discharge in this model. For example, on the 7th March, 2019, discharge was estimated as 0.177m^3s^{-1} in Mill Brook downstream of the Bull Ring, whereas the interpolated rainfall-derived discharge was 0.0291m^3s^{-1}. However, using the discharge value from the previous day (6th March, 2019), to account for a lack of lag time, gives a discharge value of 0.107m^3s^{-1}, which is notably closer to the dilution gauging estimate, albeit still significantly different. Therefore, in order to achieve greater accuracy modelling rainfall-runoff processes, further research may benefit from greater temporal resolution, as is shown in Huang *et al*., (2019) which indicates that increasing temporal resolution is one of the critical factors in improving rainfall-runoff model performance. Moreover, increases in temporal resolution should be prioritised over spatial resolution increases, as the study found that the latter caused insubstantial or marginal performance increases across all study catchments (Huang *et al*., 2019).

Additionally, discharges derived from the interpolated rainfall figures are based purely on rainfall at Browsholme Hall and do not account for baseflow. This model assumes that when there is no rainfall, there is no discharge, which is not necessarily true. This may cause inaccuracies in discharge estimation, for example, the average on-site interpolation-derived discharge was $0.024m^3s^{-1}$, whereas the dilution gauging method determined average discharge to be $0.039m^3s^{-1}$, a 62.5% increase. Moreover, this is likely to skew the average potential power generation at Browsholme Hall, as discharge will be zero whenever there is no rainfall, reducing the reliability of the feasibility assessment. However, given that discharge must be magnitudes higher to ensure constant or variable hydropower viable, the current underestimation of discharge is unlikely to affect the conclusion of the feasibility assessment. Furthermore, if the discharges derived from interpolated rainfall were in line with the dilution gauged discharges, feasibility would not significantly improve. Therefore, the discharges and potential power estimates derived from interpolated rainfall could be treated as conservative or minimum values. Nevertheless, to model discharge more effectively, a model that encompasses more variables in its calculation of runoff should be chosen or created, such as the ReFH 2 model, which contains numerous parameters, including baseflow recharge, maximum soil moisture capacity and unit hydrograph time to peak (CEH, 2007).

This thesis also did not investigate the Fish Pond's potential feasibility for hydropower generation thoroughly. The hydropower feasibility assessment at Browsholme Hall would benefit from the same kind of analysis done at the redundant pond at the Fish Pond. Flow measurements taken at the inflows of the Fish Pond would allow for an accurate assessment of how much hydropower could potentially be generated whilst maintaining the reservoir. Currently, the discussion surrounding the Fish Pond's potential utility primarily focuses on feasibility if all on-site water bodies were diverted to the Fish Pond, rather than the Fish Pond's potential for hydropower generation in its current state. However, in section 5.1.2 – Potential Solutions to Increase Hydropower Feasibility, the discussion does state that even if all flow were diverted to the Fish Pond, potential hydropower generation would still be low and limited, in part due to the Environment Agency's restrictions. Even though the Fish Pond has potential for hydropower generation, a thorough feasibility assessment may only confirm that its potential is inadequate considering the relatively high energy demand at Browsholme Hall.

5.3.2 Environmental Impact Assessment

Overall, the potential impact of a hydropower scheme to protected species at Browsholme Hall appears to be low. However, this may, in part, be due to the lack of protected species present at the Hall, and therefore, cannot necessarily be generalised to other similar sized hydropower schemes. Furthermore, the ecological surveys conducted only surveyed protected species and did not survey commonly occurring species, which are likely to be affected by a hydropower scheme. For example, aquatic invertebrates, are likely to be affected by changes in flow regime as they are the most sensitive to environmental changes in freshwater ecosystems as well as the most diverse group of freshwater organisms (Bilotta *et al*., 2017). A review of the environmental impact of small-scale hydropower found that the effect on aquatic invertebrates was just as significant as the effect on fish (Rivinoja *et al*., 2010). Moreover, no assessment was conducted investigating the potential changes to riparian zone vegetation diversity and community assemblages. Changes in riparian zone vegetation are usually seen both upstream and downstream of dams or weirs, which can cause changes to diversity and functionality of riparian ecosystems (Nilsson & Berggren, 2000). Negative impacts on riparian vegetation are numerous; Demars & Britton (2011) state that riparian zone bryophytes and lichens can be negatively affected by desiccation due to water abstraction at hydropower schemes; a model produced to predict vegetation development on newly formed reservoir shorelines (using chronosequences of numerous reservoirs) indicated shoreline vegetation diversity decreased over time compared to shoreline diversity prior to reservoir creation (Nilsson *et al*., 1997).

Moreover, abiotic impacts, such as geomorphological and water quality changes, were not considered when assessing the potential environmental impact of the hydropower scheme, limiting the validity of assessment. Furthermore, abiotic environmental impacts often have ecological consequences. For example, channel narrowing downstream of dams and weirs following hydropower scheme construction frequently leads to non-native species colonisation of newly formed floodplains (Sankey *et al*., 2015). Additionally, hydropower-induced reductions in water quality, such as thermal pollution and supersaturation, can cause significant aquatic ecological harm (American Rivers, 2005; NSW Department of Primary Industries, 2006).

The lack of investigation into the potential abiotic impacts as well as the impact on commonly occurring species introduces a degree of uncertainty of the potential environmental effect of the hypothesised hydropower scheme at Browsholme Hall, indicating that the environmental impact may be greater than previously assumed.

5.3.3 Lifecycle Carbon Emissions Assessment

A lifecycle carbon emissions assessment of the proposed hydropower scheme at Browsholme Hall was not carried out, and subsequently, the potential carbon savings resulting from hydropower scheme installation could not be quantified. This was, in part, due to the conclusion that hydropower was unfeasible on-site but devising a lifecycle carbon emissions assessment would have been useful for a cost-benefit analysis. If the carbon savings were relatively small compared to the cost of the development, it could be argued that the cost outweighed the benefits of the project. This stated, it may have been difficult to accurately quantify the lifecycle carbon emissions of a small-scale hydropower scheme installed at Browsholme Hall without further investigation. Kadiyala *et al.,* (2016) estimate that the average small-scale impoundment hydropower scheme has a lifecycle carbon release of 21.05 $gCO_2eqkW^{-1}h^{-1}$. However, due to the variation in generation capacity that constitutes small-scale hydropower, the lifecycle carbon emissions of the proposed scheme at Browsholme may differ significantly. As the most likely way to produce hydropower at Browsholme Hall is by creating a reservoir, the amount of flooded vegetation must be considered, as flooded vegetation has been attributed to methane emissions in hydropower reservoirs (Deemer *et al*., 2016). As these findings have only recently been discovered, flooded vegetation is generally not considered in lifecycle carbon emissions calculations (Varun *et al*., 2012), which introduces a degree of uncertainty for potential carbon savings. Carbon emissions can be reduced by using mitigation strategies, such as vegetation removal prior to reservoir creation. However, each mitigation strategy is still subject to carbon releases of varying degrees, making lifecycle carbon emission assessment more difficult to quantify.

5.4 Wider Implications of Research

Overall, the findings of this study indicate that without significant head, areas which experience high levels of precipitation are not necessarily viable for consistent hydropower generation unless they are situated by a substantial river or a lake/reservoir, which either possesses significant discharge or volume. Small streams and ponds, such as those investigated at Browsholme Hall, are not large enough to sustain significant and consistent hydropower generation. However, this conclusion may only be applicable to developed nations which have high energy demands, and subsequently, may be a reason why small-scale hydropower is more viable within the developing world as the required energy generation threshold is much lower.

The results of the hydropower feasibility at Browsholme Hall also provide the ability to generalise findings to other areas with similar hydrological and topographic features. For example, the area in the immediate vicinity of Browsholme Hall can likely be deemed unfeasible for hydropower as it does not drastically differ hydrologically and topographically compared to Browsholme Hall. The results of this study are particularly beneficial to other stately homes as they are likely to have similar energy demands, allowing for speedier hydropower feasibility assessment to determine the most appropriate renewable energy source for their property. Furthermore, areas with similar topography and hydrology as Browsholme Hall can be identified, not only in the UK, but also globally, and systematically categorised as unfeasible for hydropower generation, eliminating the need for individual feasibility assessment. Moreover, this can be developed further to categorise favourable hydrological and topographic characteristics, which would aid in the identification of areas that are likely to be viable for hydropower, helping to narrow down the number of potential hydropower sites.

The development of a tool which would permit individuals to self-evaluate whether their area is feasible for hydropower generation would greatly streamline the renewable energy implementation process, helping to reduce GHG emissions and produce clean energy faster. This would be particularly helpful for communities in rural and remote locations who are considering installing privately owned energy generation infrastructure to power their homes, aiding them to choose the most appropriate technology whilst saving time and money.

The findings of this study also raise vitally important questions regarding how to provide listed buildings with renewable energy. As hydropower may be unfavourable for much of the UK, particularly in England, where the topography is not especially mountainous, other renewables such as solar and wind should be prioritised to provide clean energy. However, there are currently strict planning permission regulations surrounding renewable energy infrastructure installation on and around listed buildings. These regulations effectively prohibit listed buildings from being powered by renewable energies, which is counterintuitive for the UKs renewable energy and carbon neutral targets. Whilst it could be argued that listed buildings are able to be wholly powered by renewable energy from the national grid, however, given that the majority of the UKs energy is produced from fossil fuels (IEA, 2019), providing listed buildings with energy derived 100% from renewable sources may not be possible. Moreover, strict planning permission denies listed buildings the ability to privately own energy generation infrastructure, decreasing their energy security. This is particularly important for rural developments, where power is often prioritised for urban centres during shortages, potentially leaving rural establishments without power.

The strict planning permission regulations governing renewable energy infrastructure installation surrounding listed buildings should be relaxed or altered to improve energy security and renewable energy implementation in the UK. Furthermore, the problem of installing renewable energy infrastructure in the vicinity of listed buildings without causing significant changes to the appearance and the cultural heritage may aid in the development or optimisation of renewable technologies which operate in less than desirable conditions.

Finally, the results of the feasibility assessment at Browsholme Hall indicates that the transition to renewable energies in the UK should not be overly reliant on hydropower, but rather place emphasis on adopting alternative renewables such as solar and wind power, which show greater utility in the UK. Understanding the UKs hydropower feasibility will allow for a smoother transition to a clean energy society whilst optimising the future selection efficiency of hydropower sites.

6. Recommendations

6.1 Hydropower

The work reported in this thesis has concluded that hydropower installation would not be a viable or sustainable option for renewable energy generation at Browsholme Hall. However, although it is not recommended, if the owners were to decide to pursue hydropower, it would be advisable to consult with an engineering consultancy to discuss how engineering modifications, such as increasing hydraulic head, could be made to increase the viability of hydropower on-site. Furthermore, it would be recommended to conduct further hydrological measurements over a longer time frame to record discharge and precipitation variability over the course of a full year or longer, as well as, additional hydrological measurements at the Fish Pond to assess hydropower feasibility. For precipitation, this could be achieved by installing a number of automatic rain gauges with data loggers in different locations on-site. If the rainfall interpolation model is maintained in the future, precipitation figures obtained at Browsholme Hall can be compared against the interpolation-derived figures to assess the accuracy of the model. Various methods can be employed to measure discharge variability, but due the channel bed characteristics of the water bodies at Browsholme Hall, it would be recommended to measure discharge using dilution gauging. Continuous discharge measurements using dilution gauging could be achieved by injecting a constant rate of salt tracer into waterways using siphons, battery-powered pumps or Mariotte bottles (Moore, 2004).

Additionally, consultation with the Environment Agency should be considered to discuss the possibility of diverting water bodies on-site to maximise hydropower utility. Finally, comprehensive environmental impact assessment should be taken into consideration to ascertain the full scope of potential environmental impacts faced by installing a small-scale hydropower scheme on-site. Despite hydropower being found not to be viable, two other potential sources of renewable energy may have hitherto untapped potential at this site, namely solar power and wind power.

6.2 Solar Power

Given that hydropower feasibility at Browsholme Hall is low, it is recommended that the feasibility of on-site solar power is explored. There are several unlisted buildings surrounding the hall owned by the Parker family, on which solar PV panels could be installed. As the potential for hydropower generation at Browsholme Hall is intermittent, it is likely that solar panels would provide greater and more consistent power generation. Strictly speaking, solar panels cannot be installed on any buildings within the grounds of a listed building (Ministry of Housing, Communities & Local Government, 2015). However, as previously discussed in the introduction, planning permission restrictions are somewhat ambiguous and thus, highly subjective. As the Browsholme Hall estate covers a large area of land, it may be possible to install solar panels on buildings within the estate but distant from the hall.

Alternatively, ground-mounted and floating solar panels could be installed in a field, or on the Fish Pond respectively. However, little environmental impact research exists for either type of solar panel. Of the studies that do exist, research indicates that ground-mounted solar panels are likely to affect the ground-level microclimate and therefore soil processes (Armstrong *et al*., 2014; Armstrong *et al*., 2016). Even less environmental impact research exists for floating solar panels, but it has been hypothesised that they may block light from penetrating into the water column, which could degrade water quality, leading to deleterious ecological effects (Jones & Armstrong, 2018). Moreover, as the Fish Pond at Browsholme Hall is home to many bird species, installing floating solar panels may impact their habitat and thus bird species diversity. As planning permission applications often require environmental impact assessments to be carried out, the uncertainty surrounding ground-mounted and floating solar panels' environmental impact may lead to rejection of planning permission, wasting time, money and resources. Consequently, it may be wiser to install solar panels on the roofs of unlisted buildings to minimise environmental impact. As UK sunshine hours have progressively increased over the last half century, and temperatures are expected to rise across the UK during the 21st century (which will likely be in conjunction with increased solar irradiance) (Met Office, 2019), the utility of solar power is likely to increase, adding to the potential value of solar power installation at Browsholme Hall.

6.3 Wind Power

Another option could be to refer to the local planning authority once more to discuss whether it is possible to site a wind turbine anywhere on the estate. Specific discussions regarding the size, dimensions and power output of a proposed wind turbine could be made to attempt to secure planning permission and determine the cost effectiveness of the project. If it is deemed plausible to install a wind turbine on-site, further environmental impact assessments are likely to be required as part of the planning permission process.

Wind power would be an appropriate choice for Browsholme Hall, as the conditions for wind power utilisation are favourable in the northwest. Moreover, Met Office (2019) climate projections predict that near surface winter wind speeds are likely to increase over the latter half of the 21st century in the UK, which would increase the utility of wind power. Additionally, the projected increases in near surface wind speeds are expected to be accompanied by an increase in frequency of winter storms. In theory, an increase in storminess could also lead to a growth in wind power utilisation. However, it is uncertain whether increased storm frequency could damage wind turbines. Overall, installing a wind turbine at Browsholme Hall would be a reliable way to produce clean, renewable energy.

7. Conclusion

Despite precipitation being relatively high at Browsholme Hall, small-scale hydropower was deemed unfeasible due to the intermittency of significant potential power generation. This was due to the low discharge and head across the site. The results suggest that without substantial head, water bodies must contain significant flow or storage to be feasible for small-scale hydropower generation. This is an important finding as it indicates that areas with similar topography and hydrological regime may also be unfeasible for small-scale hydropower generation; the implications of which, are particularly helpful in assessing small-scale hydropower feasibility in the UK, especially in northwest England. Moreover, this feasibility assessment, and those similar ones, aid in establishing the physical characteristics required for considerable small-scale hydropower generation, which could ultimately lead to the development of a system whereby feasibility is assessed quickly and remotely, without the need for extensive physical measurements to be made.

Furthermore, the results of this study imply that solar and wind power may be more appropriate to generate renewable energy at Browsholme Hall. Subsequently, it is recommended that solar power and wind power feasibility assessments be conducted on-site to determine which renewable is most suitable. The results of these assessments could then be used to inform other similar houses and businesses in the local area, or throughout the northwest, which renewable is the most appropriate to install. Moreover, as climate is predicted to change, it would be wise to consider climate projections in feasibility assessments to determine whether certain renewables are likely to become more feasible over time. Alternatively, a longer-term, small-scale hydropower feasibility assessment could be conducted, which may help to identify how to make hydropower more viable at Browsholme Hall. The findings of such a study would be applicable, enabling existing schemes to maximise generation as well as facilitating further small-scale hydropower schemes to be built in the future, particularly in the less than desirable locations. Furthermore, a longer-term feasibility assessment may yield more accurate and precise data, as feasibility was assessed in a relatively short time frame in this thesis.

Although feasibility was not achieved at Browsholme Hall, the findings reveal a number of insights regarding renewables. Firstly, the results of this study suggest that small-scale hydropower may be more suitable in the developing world, where energy demand tends to be lower. This would also explain why small-scale hydropower schemes are largely installed in developing nations, particularly in remote areas where energy demand is low. Conversely, if small-scale hydropower feasibility is low in the UK, in order to transition to a society powered by renewable energies, emphasis should be placed on alternative renewables such as wind and solar power, rather than relying on hydropower. Developing an understanding of the feasibility of each renewable technology in a variety of regions, environments and conditions, will enable more effective implementation of renewables on a wider scale globally, helping to mitigate climate change. Moreover, quantifying the impact each renewable will have on climate change mitigation will enable policy makers to accurately calculate the magnitude of investment required for each renewable.

Additionally, the findings highlight the issue of providing listed buildings with renewable energy. If small-scale hydropower is less viable than previously assumed, it may be difficult to provide listed buildings with renewable energy, as strict planning regulations often prevent the installation of other renewables, such as wind and solar, on the premises of listed buildings. This indicates that policy changes are needed to permit greater implementation of renewables on the premises of listed buildings to reduce carbon emissions and mitigate climate change. This is imperative, as the IPCC states that rapid changes are required in all aspects of society to curtail climate change. Prohibiting any aspect of society from implementing low carbon practices could lead to the failure of the targets set out in SR15.

There are, however, considerable concerns regarding the environmental impact of small-scale hydropower. Early research indicates that the impact on ecological communities may be greater than previously assumed, which may impede implementation. Nevertheless, at such a critical moment in the fight against climate change, a compromise between continued GHG emissions and ecological health may be required in order for society to meet the targets set out by the IPCC in SR15. In any case, extensive implementation of these technologies comes with significant risks as the impacts of small-scale hydropower are not fully understood, and subsequently, could potentially contribute towards climate change, which has recently been shown with methane emissions resulting from flooded vegetation decay in large-scale hydropower reservoirs.

To conclude, small-scale hydropower is a highly useful renewable technology, providing many benefits, such as cheap, efficient electricity, energy security and less extensive construction. Although feasibility may not be particularly high in the UK, small-scale hydropower has the potential to be critically important in the fight against climate change in the developing world, or in areas with low energy demand. Therefore, whilst uncertainty surrounding the environmental impact of small-scale hydropower remains, small-scale hydropower should not be disregarded as an effective renewable energy source, as its environmental impact has not yet been fully quantified. Nevertheless, further environmental impact research is required before small-scale hydropower schemes are installed extensively. However, to realistically achieve the targets set out by the IPCC, all options which could potentially reduce global carbon emissions must be considered, even if that means ecological health may be degraded.

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Appendices

Appendix A – Signs of Badger Activity

Setts:

- Sett entrances are typically oval shaped, measuring 250-300mm wide.
- Large spoil heaps are usually present in front of sett entrances. Spoil heaps often contain discarded bedding (vegetation) and hairs.

Confusion with fox and rabbit holes

- Badger setts are often confused for fox dens and rabbit burrows due to similarities in appearance. Fox and rabbit holes tend to be smaller in diameter and taller than they are wide. However, examination of the tunnel size and shape should be made, as fox and rabbit entrance holes are usually larger than the tunnel itself.
- Other signs to decipher Badger setts and fox/rabbit holes includes the presence of hair and discarded bedding material in spoil heaps. Rabbits tend to have rabbit droppings in their spoil heaps, and occasionally tufts of rabbit fur from grooming or fighting. Fox holes are usually sprayed with a characteristic odour, and their spoil heaps often contain fox scat and/or remnants of prey. Badgers rarely bring back prey to the sett and therefore, it is unlikely to see food remains leading up to a sett entrance.
- Furthermore, excavated soil leading to spoil heaps tends to be more extensive at badger setts, due to badgers dragging bedding material backwards into setts, creating distinctive deep ditches prior to entrances.
- Lastly, presence of latrines, footprints and claw marks on trees adjacent to entrances can be used to discern between badger and fox/rabbit holes.
- However, identification of fox/rabbit activity does not rule out the possibility of a badger sett. Rabbits and foxes are known to live within the same sett as badgers on occasion, occupying different sections of the same sett. Moreover, foxes and rabbits can also occupy a temporarily disused badger sett.

Latrines:

- Badger droppings are deposited into special dung pits called latrines. Latrines are small, oblong holes measuring in 100mm in depth. Latrines are used by badgers repeatedly and are left uncovered. Latrines can be found either close to a badger sett or along the boundaries of a territory.

- Badger droppings may have a soft, runny texture or may be a dry sausage shape, normally pointed at one end but never twisted. Size varies, but typical droppings are around 20mm thick and up to 100mm in length. Occasionally, latrines can contain a yellow-brown jelly like substance, which is thought to be a secretion from badger's anal glands.

Other signs:

- Footprints – badger prints are easily recognisable, resembling small bear prints. Prints show five toes with long claws and toes pads visible, positioned close together almost in a row. Sometimes the front paw prints are missing the impression of the ball of the foot. Front paw prints tend to be between 40-60mm wide and 50mm in length. If the heel pad is present in the print, the impression length can be up to 60mm. Hind paw prints are smaller than front prints, measuring 45mm wide (without heel pad) and 35-40mm long. When heel pad is present, print length is approximately 65mm in length.
    - The distance between prints while striding is 400-600mm and 700-900mm when trotting.
- Badger Runs – badgers often use the same paths to visited frequented places in their territory such as setts and latrines. Paths become well defined with frequent use and are easily recognisable.
- Scratching Posts – scratch marks can be found on trees located close the setts, which may stem from stretching or scent marking behaviour.

The information above regarding badger identification signs are derived from the following sources: Bang & Dahlstrøm's (2001) "*Animal Tracks and Signs*", Harris *et al*., (1989) "*Surveying Badgers*", Olsen's (2013) "*Tracks and signs of the animals and birds of Britain and Europe*", Scottish Badgers' (2019) webpage "*Badger Surveying*", TB Hub's (2015) "*Identifying Badger Activity*" and Woods (1995) "*The Badger*".

Appendix B – Signs of Otter and Water Vole Activity

Otters:

- Footprints; large round prints measuring 50-70mm wide and 60-90mm long. Five-toed prints, although, frequently only four toes appear in prints. Print impressions are typically found in clay, mud, sand and snow along river and stream banks.
  - The best identifiable prints are usually found in clay, as the material allows for a deep impression to be made.
- Otter faeces (spraint); spraint is tarry, black and slimy in appearance and texture when fresh, with a distinctive, enduring oily smell. As spraint dries, it becomes light grey in colour and crumbly in texture. Spraint is generally composed of fish bones and scales; crustacean shells, feathers and fur. Spraint is typically found in small quantities, deposited on raised sections of the riverbank on logs or rocks.
  - Spraint is commonly used as scent marker to other otter group members or as a form of territorial marking.

Water voles:

- Burrows – oval-shaped, typically located by the water's edge and bank above, approximately 50-80mm wide. Many burrows have a distinctive grazed "lawn" entrance.
  - Can be confused with other small mammal, rodent and crayfish refuges.
- Feeding Stations; numerous chewed stalks (plants still rooted), piles of removed plant stems with a distinctive 45° cut at one or both ends. Occasionally, incisor marks can be identified on the stems.
  - Water voles are herbivores and consume approximately 80% of their body weight a day. Hence, signs of feeding are a key identifying feature during survey.
- Piles of droppings (latrines). Droppings are a cylindrical, cigar-like shape, with blunt ends. The droppings vary in colour from green to brown or even black to purple and are odourless.
  - During the breeding season, females use latrines as territory markers.
- Footprints; prints usually measure from 15-25mm from heel to toe.
  - Can easily be mistaken for the prints of Brown Rats.

The information above regarding the signs of otter activity is adapted from Bang & Dahlstrøm's (2001) "*Animal Tracks and Signs*" and The Mammal Society's (2019) webpage "*Otter*"; whereas, the signs of water vole activity are derived from The Wildlife Trusts' (2016) "*Water for Wildlife: A guide to water vole ecology and field signs*".