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The feasibility of a conceptual model, EXP-Hydro, to simulate streamflow as a potential for hydropower generation of seven catchments in Wales for the years of 2040-2080, benchmarked against Kling-Gupta Efficiency

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The feasibility of a conceptual model, EXP-Hydro, to simulate streamflow as a potential for hydropower generation of seven catchments in Wales for the years of 2040-2080, benchmarked against Kling-Gupta Efficiency.

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Abstract:

Hydrological modelling is a modelling tool widely used for the investigation of understanding the implications of climate change on flow regimes. The model allows for understanding of how hydropower generation can be assessed as part of the future of renewable energy. Outcomes of investigations of hydropower potential allow arguments to be made for further investment into micro and small-scale hydropower schemes.

This study utilised a combined methodology comprising a conceptual hydrological model, EXP-Hydro, with ArcMap for spatial analysis. The study assessed the ability of EXP-Hydro to simulate streamflow in seven catchments in Wales for the years 2040-2080. UKCP18 data was utilised with the scenario of choice being RCP8.5.

The aim of this investigation was to assess the model performance of EXP-Hydro using a known criterion in the field of hydrological modelling, Kling-Gupta Efficiency (KGE), to validate the model. The results of this investigation were below expectations. The KGE values ranged from 0.31 to 0.48 for all seven catchments. This raises the question of how the method could be improved and /or how data handling errors could have been prevented, both of which are discussed.

A secondary aim of the research involved calculating the hydropower potential of the seven catchments. 74 new locations for hydropower were discovered, ranging from 5 kW to 1 MW.

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Thank you all. This is the true kindness of people.

Contents

1 - Introduction

1.1 - The Issue

Anthropogenically induced climate change has been one of the key reasons for the development of renewable energy (Fasol, 2002; Hamududu & Killingtveit, 2012; Safarik, 2019). Due to rising awareness of climate change, a global shift pushing global governance towards reducing the percentage of fossil fuel usage in the energy mix has occurred. This has led to the development of international climate policies, examples of which include, the Kyoto Protocol (1997), Paris Agreement (2015) and COP26 in Glasgow. To meet globally agreed targets for reducing emissions constant development of renewable energy to phase out fossil fuels has taken place (Fasol, 2002; Hamududu & Killingtveit, 2012; Safarik, 2019).

The Welsh Assembly set targets for 70% of the electricity demand to be supplied from renewable sources by 2030, as part of the Welsh Secretary's plan for the Energy, Planning and Rural Affairs (Welsh Assembly, 2017). This includes a goal of 1GW for developing renewable energy from locally owned projects, which will contribute to the electricity mix of Wales (Welsh Assembly, 2017).

1.2 - Introducing Hydropower

Hydropower has been present throughout civilisation, with evidence of systems being developed by Roman and Greek communities (Paish, 2002; Safarik, 2019). Early forms of hydropower were designed to assist irrigation and agricultural practices (Paish, 2002; Safarik, 2019). Hydropower provided the basis of the boom in the textile industry across Europe in the 18th century. In achieving this, many new channel networks developed for use by textile mills (Paish, 2002; Safarik, 2019). These led to the early development of turbines in 18th century France, yet it took until 1882 for the first hydroelectricity to be harnessed (Paish, 2002; Safarik, 2019).

Hydroelectricity has become the largest contributor of renewable energy globally for years (Hamududu & Killingtveit, 2012; Hamududu & Killingtveit, 2016; Pfister, Scherer and Buxmann, 2020), contributing 71% within Europe and 17% globally. Hydropower comes in different forms, each with individual purposes, applications, and capacities.

Firstly, there are large-scale hydropower schemes, which are dammed or impoundment schemes. Prominent examples of impoundment schemes include the Hoover Dam and Three Gorges Dam (Paish, 2002; Hamududu & Killingtveit, 2016; Zhang, 2014).

Fig. 1 – View of Three Gorges Dam outlet point from above. Taken from Zhang (2014).

Secondly, there are pumped-storage systems, which rely on the generation of electricity by water being passed between the upper and lower reservoirs. These schemes are largely utilised for periods of high demand or surges in electricity usage. An example of this in the UK is Dinorwig Power station (fig. 2, operation of the pumped-storage system).

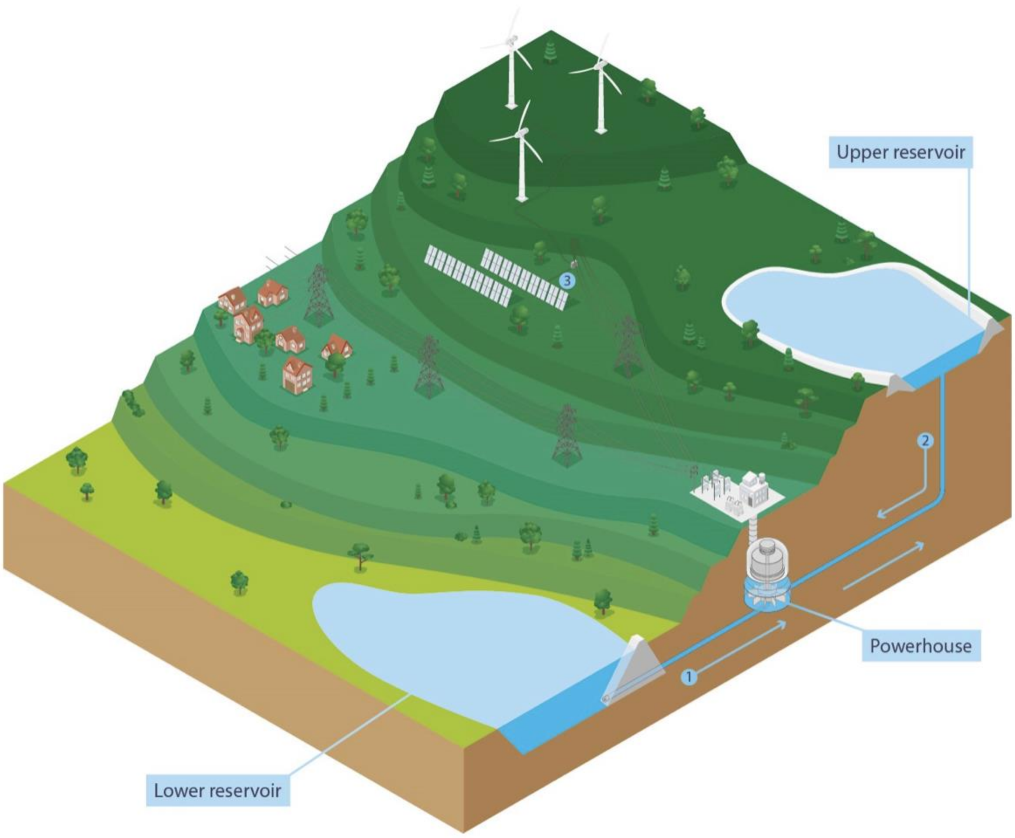

Fig. 2 – Visual representation of a closed pumped-storage scheme. The diagram shows both reservoirs and the turbine room in the centre (IHA, 2021).

Finally, there are run-of-river or non-impoundment or diversion schemes. These schemes are extremely varied, coming in many different forms. A key distinction within this category is between low and high-head schemes; the difference being the elevation change from the inlet and outlet of the penstock or diversion (for diagrammatical representation see fig. 3) (Sammartano et al., 2019). Run-of-river schemes vary based on their turbine: for example, the vortex turbine is a low-head hydroelectric turbine, utilised on pre-existing infrastructure, such as a weir or a loch (fig. 4) (Loots et al., 2015). These run-of-river schemes are the focus for this investigation as they are capable of producing electricity at lower outputs. The schemes commonly permit a further breakdown of outputs, with distinctions being made between small-scale 100 kW to 1 MW and micro-only constituting 5 kW to 100 kW (Paish, 2002; Sammartano et al., 2019).

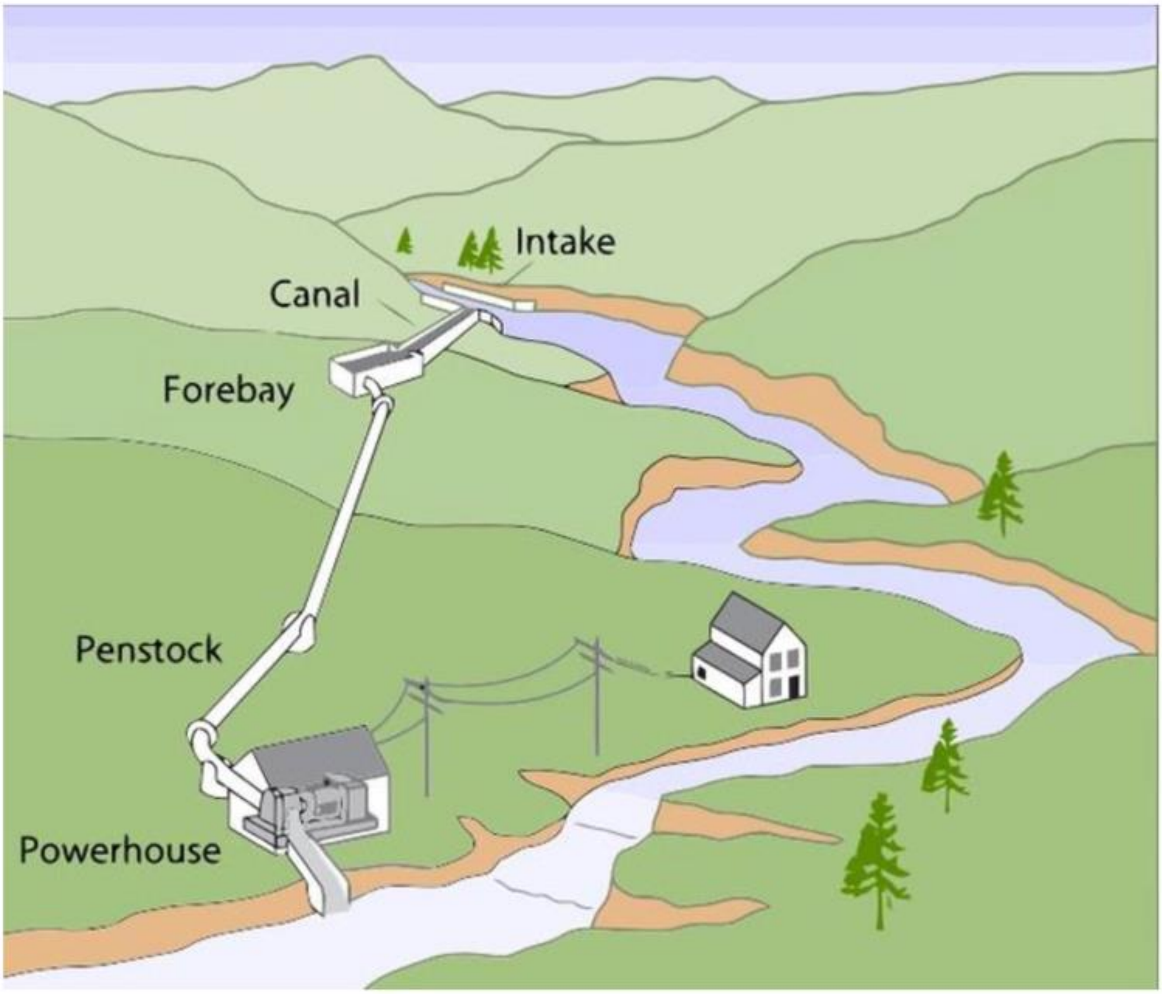

Fig. 3 – A typical run-of-river hydro scheme utilising a penstock (Algburi et al., 2018).

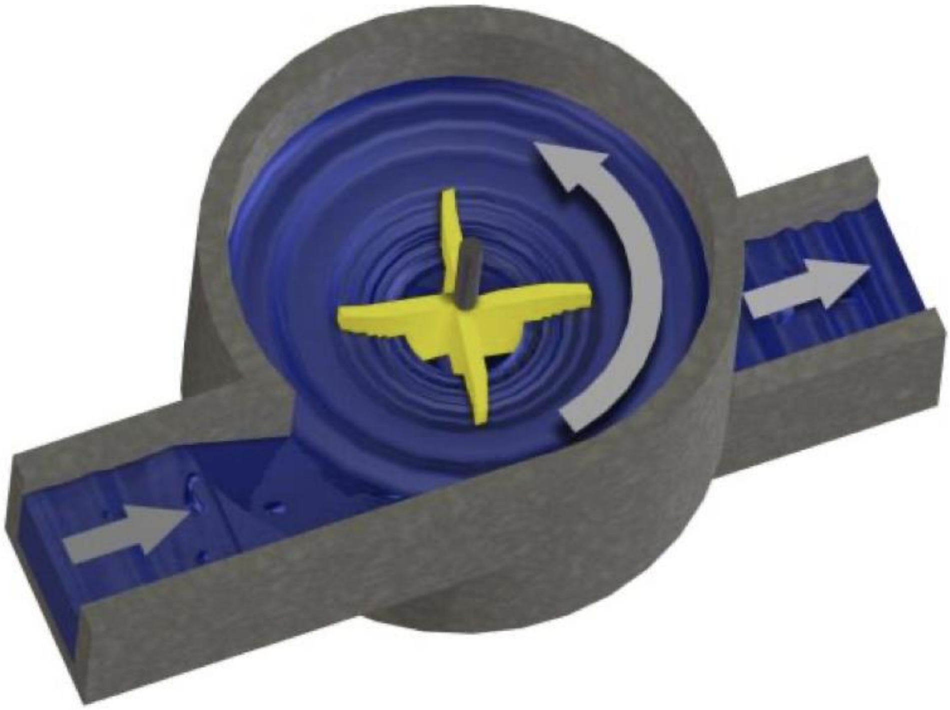

Fig. 4 – Virtual representation of the flow of a low-head vortex turbine. The representation is from a paper from Power et al., (2016).

1.3 - Hydrological Modelling

Hydrological modelling can be defined as "the characterisation of real hydrologic features and system by the use of small-scale physical models, mathematical analogues and computer simulations" (Allaby and Allaby, 1999). Hydrological modelling has become an imperative tool for investigation of hydrological transport questions. Due to the variability of environmental prediction requirements, no model can be regarded as the best option. The nature of environmental investigations means there are many plausible solutions, which vary depending on the complexity or the depth of investigation required. Hence, the 'best' model depends on the application and objectives of the project for specific circumstances. The modelling process is a simplification of the natural world, as models are developed to simulate flux and flow of water against time. These simplifications are presented in the form of equations aimed at estimating these processes.

Since the second half of the 20th century, mathematical models have become the accepted criterion for hydrological modelling practices, such as surface runoff, maximum flow, and drainage for catchments through various scales. These can be defined as conceptual models. The advantages of the conceptual modelling process include non-linearity, which offers an accurate representation of thresholds within the hydrological systems. There are two types within conceptual modelling: event and continuous modelling. Event modelling is a simulation of a single event, which can take a span of time from several days down to a number of hours. Continuous conceptual models are designed to function for extended periods. Continuous models have been evidenced to be extremely effective in ungauged catchments and in studies investigating long term characterisations of catchments (Patil and Stieglitz, 2014).

There are two distinctions within conceptual hydrological modelling: lumped and distributed. These arise in forms of variations of the same model. Lumped models represent aggregated values for catchments. Lumped models are simpler in their procedures for quantifying the physical processes through temporal variations. The main advantage of lumped models over distributed models is that the conceptual parameterisation is simple, and computation can be achieved efficiently. Distributed models have spatial variability as the focus for investigation. Distributed models require more in-depth data, which may include soil moisture and initial water depth. This added complexity makes distributed models more complete tools than lumped models, however depending on the purpose and available data, lumped models are often adequate.

The development of modelling has led to a subsection of hydrological modelling known as Rainfall-runoff modelling. These are a subset of hydrological models specifically designed for the purpose of modelling streamflow, runoff volume or discharge. These models come in both lumped and distributed formats, running from simple conceptual models to in-depth distributed models, requiring factors such as land-use, soil types and soil saturation. The process of rainfall-runoff modelling is the visualisation of water movement through a catchment based on the previous climatic events or observed data.

There are limitations to the rainfall-runoff modelling process. In distributed rainfall-runoff models, the intensity of data requirements and calibration for individual grid cells can be a significant issue, especially if not all data is distributed. To resolve this, there are methods of extrapolating data and weighting to achieve the same purpose, however this can be time consuming. In addition, the computational time for distributed modelling practices can vary significantly, from minutes per single run to hours per single run. This variation is directly attributed to the complexity of the data required, catchment size and computational restrictions. Lumped models are, in comparison, relatively easy to attain and setup for efficient modelling practice. However, there are some evident issues in using lumped rainfall-runoff models. Namely and most notably, this includes assumptions made from the simplification of real-world processes to differential equations. Within the process of setting up a lumped model, assumptions must be made to allow for the equations to be filled with observable aggregated datum. This leads to potential misrepresentation of spatial data when using a lumped model. Due to the assumptions and aggregated values, data form a homogeneous version of the investigation area and therefore does not truly represent the topographical or spatial variation in a watershed.

For this investigation, a conceptual lumped hydrological model, EXP-hydro (exponential bucket hydrologic model) was utilised. EXP-hydro is based on solving differential equations and is the visualisation of catchments being mathematically represented as two stores or buckets of water. The daily time-step data required was collected from the Met Office, with supplemental observed data from the National River Flow Archive (NRFA) and Centre for Ecology and Hydrology (CEH), which formed the collection of data for the calibration of EXP-hydro.

1.4 - Aims and Objectives

This project investigates the hydropower potential of seven catchments in Wales: Alwen, Clwyd, Conwy, Dee, Dyfi, Severn and Vyrnwy. The catchments cover urban and rural landscapes demonstrating potential for micro-hydropower to develop further in Wales. The aim of this project is to answer the following research questions:

1. Demonstrate the ability of EXP-hydro to simulate streamflow by using Kling-Gupta Efficiency as the benchmark validation tool.

2. How will climate change impact hydropower generation capacity in the seven catchment areas of Wales between the years of 2040-2080?

The process of answering the research questions will include the production of a portfolio of potentially viable locations for new micro-hydroelectric schemes within the seven catchments being investigated. This is intended to provide a resource to which communities within the seven catchments will be able to investigate the feasibility of these new locations.

2 - Literature Review

2.1 - Original line of enquiry and revised line of enquiry

The primary focus of the review of literature aligns with the original line of enquiry to assess potential for hydropower generation in small and micro scales in seven catchments of Wales, including the assessment of climate change on the potential of the available resource. Assessment of the feasibility was undertaken through modelling the potential of EXP-hydro, used to simulate streamflow, benchmarked with KGE. As the inquiry unfolded, strengths and limitations of the combined modelling methods used for the study, which could be used to facilitate comparisons with similar studies in this field in the future, became a significant, albeit secondary focus and are therefore included within the review. Whilst data analysis of the seven catchment areas yielded limited results, understanding climate change implications on hydropower generation remains a central pillar of the study and is reviewed here.

2.2 - Hydropower

The benefit of utilising a pumped storage scheme is well documented (Maabo, 2017). However, despite this form of hydropower being able to generate vast amounts of electricity quickly, there is no capacity for sustained electricity generation. Once all the water is released from the upper reservoir to the lower, no generation of electricity is possible until the water is returned to the upper reservoir (Douglas et al., 1984; Walker et al., 2007). Costs represent a further major barrier to utilising pumped storage, as evidenced in the Dinorwig Hydroelectric Power station scheme. The initial cost of developing the site was £425 million, with £10.6 million maintenance costs in a single year (2016) (Douglas et al., 1984; Walker et al., 2007).

Development of pumped-storage schemes requires specific site conditions due to the requirements of substantial elevation change, with space for construction of two manmade reservoirs and the capacity to build structures in between these reservoirs to house turbines (Maambo, 2017). In the UK at present, there are only four pumped storage schemes, with four more at the planning stage. The capacity of the schemes ranges from 60 MW to 600 MW. One of the four schemes is a conversion of the Loch Sloy Hydro scheme. This originally opened in 1950 as a conventional hydro scheme. The cost of converting the scheme was greater than £30 million, producing an installed power of 60 MW. Currently, Sloy hydro scheme is the smallest pumped-storage scheme in the UK, although these hydro schemes can generate vast amounts of electricity in a very short amount of time (Maambo, 2017).

This raises the question of further extant opportunities for pumped storage or large conventional hydro schemes in the UK. The specific physical requirements of large-scale hydro schemes, conventional or pumped-storage, means there is very little scope for major developments throughout the UK and it is limited to specific regions. Thus, a solution to increasing hydropower uptake in the UK may be through utilisation of small- and micro-hydro schemes. Despite the limitations of topographical nature and suitable climate on large-scale schemes, data such as the amount of rain, shows that the UK could potentially implement the utilisation of small or micro-hydro schemes (Gormally et al., 2012; Carless & Whitehead, 2013; Armstrong & Bulkeley, 2014; Gallagher et al., 2015). Currently, 207 micro-hydroelectric generation projects are running in Wales, with an installed total capacity of 163 MW (Messenger, 2019). In comparison, there are only four large-scale hydro schemes in the UK (Bracken et al., 2014; Cherry et al., 2017; Wade, 2017).

2.2.1 - Impoundment Schemes

Impoundment schemes are typically large-scale forms of hydropower that use a dam and reservoir to store water. These generate electricity through controlled releases of water through a turbine, which triggers a generator (Berga, 2016). Impoundment schemes are common in countries with rapid population growth as these help to meet energy demands (Zarlf et al., 2015; Zarlf et al., 2019). Dams are utilised as building blocks for electricity supply as nations pass through the development stages of their inception (Zarlf et al., 2015; Zarlf et al., 2019). Following COP21, which established the Paris Agreement, many governments agreed to expand their current percentages of energy generated from hydropower (Zarlf et al., 2015). Due to this expansion of hydropower, there are, according to an investigation by Zarfl et al., (2015), currently 3,700 dams planned or under construction, estimated to double the output of hydropower globally (Zarfl et al., 2015). The 3,700 new impoundment schemes are spread throughout the world. South America and Southeast Asia will experience significant increases in hydropower development. Africa has, in recent years, seen an exponential increase in electricity demand and to meet requirements, several impoundment hydropower schemes are under development. Europe will see an increase in the number of impoundment schemes. However, the rate of development is much slower in comparison to other regions of the globe. Nevertheless, there are an estimated 600 hydropower plants being built that will produce a capacity greater than 1 MW (Zarlf et al., 2015; Zarlf et al., 2019).

The dam and reservoir model offer a good example of stored energy as this generates electricity on demand and aids expansion of other renewable energy initiatives. The development of impoundment hydropower is an investment into the security of energy supply within a country, which has a large variety of electricity production methods (Berga, 2016; Zarlf et al., 2019). A further benefit not associated with electricity generation is that the reservoir created becomes a social benefit for the population: the reservoir can be used for flood protection, agricultural irrigation and recreational activities. Thus, the reservoir can solve multiple issues simultaneously (Berga, 2016; Zarlf et al., 2019).

On the other hand, academic and governmental communities that regulate hydropower recognise that there are significant social, environmental, and economic implications for each development of a single impoundment scheme. Furthermore, benefits of dams are usually experienced in urban areas, whereas the consequences are observed in rural areas located near the dam (Constantine et al., 2014; Siegmund-Schultze et al., 2018; Zarlf et al., 2019).

2.2.2 - Run-of-river

Micro-hydropower is a form of renewable energy which relies on the flow of kinetic energy and the utilisation of existing water resources for the generation of electricity (Agarwal, 2012; Armstrong & Bulkeley, 2014). Micro-hydropower is not new, but has been widely used since the beginning of the 19th century across Europe and in the United States (Pahl, 2007; Pahl, 2012). For example, the hydroelectric scheme Schoellkopf Power Station No.1 was built along the Niagara River in 1881, closely followed by the Edison hydroelectric scheme (Vulcan Street Plant), in 1883 in Wisconsin, which had an output of 12.5 kW (Woodworth, 2012). Over the last 50 years, micro-hydropower technology has developed rapidly. This has led to locations with small changes in elevation (low-head sites) becoming readily accessible, together with advancements in materials that significantly increase the lifespan of micro-hydro schemes, which now average between 25-50 years (Adamkowski et al., 2015).

Application of micro-hydropower to small communities is recognised as an economic form of energy technology for rural electrification. Compared to other renewable energy sources on the same scale, hydropower has greater efficiency (70-90%) and greater capacity factors (>50% for micro-hydropower) than solar (10%) and wind (30%) (Anaza et al., 2017). In addition, micro-hydropower has a slower rate of change, meaning the output from the scheme only demonstrates gradual changes daily, rather than a minute-to-minute change as experienced in solar and wind.

However, application of micro-hydropower is site-specific and of limited potential for further expansion, compared to wind and solar (Bakken et al., 2014; Anaza et al., 2017). Sites appropriate for micro-hydro schemes are reliant on flow rate of the river and elevation change. Infrastructure setup cost must be included in this calculation, requiring consideration of the distance from the site to the community (Abbaspur et al., 2007; Pandey et al., 2014; Hallouz et al., 2015). Therefore, when compared to numbers of potential sites for small-scale renewables, such as wind and solar, the number of possible sites for micro-hydropower is reduced. Furthermore, high initial costs for building micro-hydro schemes and the availability of water required are limiting factors in uptake of micro-hydropower globally (Hamududu & Killingtveit, 2012; Pandey et al., 2014).

2.2.3 - Small-scale hydropower

As with micro-hydropower, small-scale hydropower has a long history (Fasol, 2002; Pahl, 2007; Abbaspur et al., 2007; Bildirici and Gökmenoğlu, 2017). Globally, small-scale hydropower was utilised as civilisations developed, including irrigation techniques of ancient Egyptians to development of modern turbines by Bernard Forest de Belidor, author of the 'Architecture Hydraulique' (de Bélidor, 1819; Bildirici and Gökmenoğlu, 2017).

There are examples of small-scale hydropower used for generating electricity throughout history. For example, in 1880 a dynamo, powered through hydropower, provided electric street lighting for the town of Grand Rapids, Michigan (Office of Energy Efficiency & Renewable Energy, 2021). Similarly, in 1881, turbines provided power for street lighting in Niagara Falls (Office of Energy Efficiency & Renewable Energy, 2021).

In the past 100 years a surge has occurred in the development of this small-scale technology, now a cornerstone of energy mix. However, as demand for electricity has grown, no proportionate response to the growth of small-scale hydropower has taken place (Fasol, 2002; Pahl, 2007; Abbaspur et al., 2007).

2.3 - How does hydropower fit within the global energy mix?

Globally, hydropower is the most widely utilised renewable energy, comprising 71% of renewable energy generation and 17% of total electricity from renewable sources (Hamududu & Killingtveit, 2012; Gernaat et al., 2017; Pfister, Scherer and Buxmann, 2020). Global development of small-scale renewables has prompted improvements in micro-hydro technology. These include, for example, lifespan of turbines and materials used for penstocks (Hamududu & Killingtveit, 2012; Adamkowski et al., 2015; Cherry et al., 2017). These improvements enhance global application of micro-hydro schemes, in places such as Southeast Asia and Western Africa. Subsequently, this has resulted in decentralisation of energy supply in some schemes. These schemes enable the possibility of self-sufficient regulation of energy supply and demand (Khennas & Barnett, 2000). The technology has expanded across developed and developing regions of the world, including locations such as Nepal, Sri Lanka, Peru, Nigeria, Western Europe and Northern America (Khennas & Barnett, 2000; Agarwal, 2012; Armstrong & Bulkeley, 2014; Boehlert et al., 2016; Tang et al., 2019).

In a European context, development of micro-hydropower is long-established. The earliest recorded example of its use is at Cragside, a mansion in Northumberland owned by Lord Armstrong. In 1878 Armstrong installed an Archimedean screw to generate hydroelectricity to power the household's light bulbs (Irlam, 1989). An increase in micro-hydropower schemes followed in the UK. However, during implementation of the Electricity (Supply) Act 1926, existing hydro schemes were disconnected. This stemmed from a proposal from the Weir Committee to establish the Central Electricity Board, established to construct the 132 kV national grid. Construction of the national grid forced the replacement of small- or micro-hydro schemes with a few thermally efficient power stations, which could be built in place of the smaller hydro schemes. An initial tower was built in 1928, outside Edinburgh. This location was selected because of the Portobello power station, which, in 1930, formed the first part of the 132 kV national grid. The 132 kV national grid was largely completed in 1935 reducing (by 1938) the number of power stations required to provide electricity by 80%. The reduced number of power stations resulted in a 75% decrease in capital costs for powering the nation (Irlam, 1989). Since this closure of power plants, a significant rise in local hydro schemes (otherwise referred to as localised power stations) has occurred, in part driven by Government legislation that provides subsidies for their construction. Introduction of the Feed-In Tariff (FIT) (Wagner et al., 2015; Bejarano et al., 2019) in 2010 assisted the UK government's alignment with the EU's 2020 renewable energy and 2050 decarbonisation targets, initiating a method for developing a subsidy framework for small-scale low-carbon energy generation technologies (Gormally et al., 2012). By 2019, when FITs closed, the scheme had encouraged development of a variety of small-scale low-carbon energy sources throughout the UK.

The global potential for hydropower in all forms is 52 PW/yr across 11.8 million locations (Hoes, Meijer, Ent & Giesen., 2017). The UN has been a major contributor to understanding micro-hydro potential. As part of their Sustainable Development Goals, the UN facilitated several investigations. For example, Indonesia calculated the micro-hydropower potential for each of its islands, with Papua Island demonstrating the largest hydropower potential at 22.4 GW. Hydropower has been a significant contributor to Uganda's energy mix since 1947, with an installed capacity of 150 MW (IHA, 2021). Over the last three decades, Uganda has seen consistent increases in electricity production from hydropower, averaging 8% growth each year (IHA, 2021).

Western Africa has seen a growth of hydropower developments in micro-, small- and large-scale developments. One such example is Nigeria, which has significant renewable energy potential, especially in solar and hydroelectricity. Shaaban & Petinrin (2014) stated that sources of renewable energy in Nigeria are underutilised. The hydropower potential for large-scale is 10,000 MW, while that for small-scale is 734 MW (Shaaban & Petinrin, 2014). Nigeria has a growing population but unfortunately, a struggling energy sector. With a large rural population and only 40% of the population connected to the national grid, 90% of rural communities harnesses energy from fuelwood sources (Sambo, 2009; Shaaban & Petinrin, 2014; Fakehinde et al., 2018). This low connectivity issue is replicated in other developing nations, meaning there is a significant difference between installed capacity and the infrastructure available for exploiting generated electricity. Nigeria has an installed capacity of 6000 MW, yet is able to distribute only 1,600 MW of usable electricity, primarily due to transmission losses of up to 35% (Abumere et al., 2002; Kennedy-Darling et al., 2008; Shaaban & Petinrin, 2014).

Although global development of hydropower has increased, this growth has not been replicated within the United Kingdom (IHA, 2021). Between 2009 and 2016, the UK experienced a limited increase of 3.8% in annual hydropower electricity generation, from 5.2 TWh to 5.4 TWh. This compares unfavourably with the most widely utilised renewable resource, wind power, which experienced an increase of 308% in annual generation from 9.2 TWh to 37.5 TWh over the same period. Large-scale hydropower via pumped-storage schemes is a major generator of renewable electricity within the UK, meaning they generate electricity at times of peak demand.

The United Kingdom generated a total of 294 TWh of electricity in 2019; of this 119.3 TWh (36.9%) was generated from renewable sources, representing an increase of 8.5% on the previous year (Department of Business Energy & Industrial Strategy (BEIS), 2020). Of the 39.6% of electricity generated from renewable sources, hydropower contributed 6 TWh, or 5% of the renewable energy contribution (BEIS, 2020). This makes hydropower the smallest contributor of renewable electricity generators, despite an 8.5% increase in hydropower electricity generation capacity by the end of 2021 (BEIS, 2020). There is evidence that hydropower can increase contributions made to the UK energy mix (Gormally et al., 2012; Carless & Whitehead, 2013; Armstrong & Bulkeley, 2014; Gallagher et al., 2015).

The largest hydro scheme in the UK is the Dinorwig Power station in North Wales, completed in 1984. As already noted, this is a pumped-storage scheme, which generates electricity through releasing water from an upper reservoir, through turbines into a lower reservoir, at which point the water is pumped back to the upper reservoir at times of very low demand (*i.e*. late at night). The scheme can generate 1,728 MW in 16 seconds, through utilising six 300 MW turbines, and has a storage capacity of 9.1 GWh, which is enough energy to restart the national grid (Douglas et al., 1984; Walker et al., 2007; Guo et al., 2008; Gormally et al., 2012; Hamududu & Killingtveit, 2012; Messenger, 2019).

2.4 - Why is hydropower important for future development of renewable energy?

The rate of hydropower development is forecast to slow over the coming years of this decade (IEA, 2021). This could be critical to attaining net zero targets set by governments worldwide, while still achieving a diverse and reliable energy supply (Hamududu & Killingtveit, 2012; Palomino Cuya et al., 2013; IEA, 2021). Hydropower has and will continue to play a crucial role in aiding transition from a fossil fuel dependent society to one of a clean, green and low-carbon electricity mix. The global hydropower capacity is anticipated to increase by 17% between 2021 and 2030, with the most significant contributors being China, Turkey, Ethiopia and India (IEA, 2021). The IEA published these predictions, adding that the rate of hydropower development is expected to slow by 25% throughout the 2020s, based on the previous decade (IEA, 2021).

The act of reversing the slowdown of hydropower development would be a multifaceted benefit for the global population. The reverse would require substantial change in the action policies of governments, which need to address major obstacles of hydropower development. Key obstacles include making sure that hydro schemes are presentable as long-term investments, which could yield profitable revenues, and achieving this while adhering to strict sustainability standards (IEA, 2021).

In 2020, hydropower was the largest contributor to low-carbon electricity worldwide and had a greater output than all other forms of renewable energy (EPA, 2021; IEA, 2021). In the last two decades, there has been a 70% increase in hydropower capacity. It is currently the main provider of electricity for over 800 million people in emerging and developed nations (IEA, 2021). There is still space for continued growth in the hydropower sector, according to the current IEA report, stating that 50% of the global economically viable potential worldwide is untapped, reaching around 60% for developing and emerging economies.

Hydropower is an attractive form of renewable energy for developing nations; as stated previously, it provides energy security and is a constant producer for electricity, if required, or provide a store of potential energy that is utilisable for meeting moments of high demand (IEA, 2021). In addition, hydropower is an energy generation tool that does not require input of energy to generate electricity itself (Walker et al., 2007; Hamududu & Killingtveit, 2012). This is important in that once a dam or run-of-river scheme is created the only requirements are maintenance and switching of value for the generation of electricity.

2.5 - Economic and social impacts of micro and small-scale hydropower

The cost of installing a hydropower scheme is dependent on several factors: head, that is, the change in elevation between the intake and outlet point; flow rate; and maximum potential output, which in turn impacts the choice of turbine and thus the maximum power output (Bejarano et al., 2019). Included in the calculation are costs of site development, the extent of which depend on the possibility of retrofitting existing structures or building on a blank canvas. Even though retrofitting would lower cost, there appear to be no examples in which such costs are considerably reduced. In addition, the cost of hydropower systems is disproportionate between smaller and larger schemes, meaning the cost per kW is greater for smaller schemes than large schemes. For example, a 25 kW scheme could cost in the region of £169,000, equating to £6,800 per kW, whereas a 500 kW scheme may cost up to £1.6 million, and the cost per kW £3,200 (Ynni Anafon, 2015). This demonstrates the cost required for a community to develop a hydro scheme, especially in the light of considerations such as sustainability, environmental protection, and the rate of return on the investment. Furthermore, a community would need to consider daily upkeep and potential risk of developing hydropower compared to other potential renewable energy sources (Walker et al., 2007; Seyfang, Park & Smith, 2013; Armstrong & Bulkeley, 2014; Bejarano et al., 2019).

An important consideration is the cost of operating a small or micro-hydro scheme. The operating cost of schemes varies, with size of the scheme being a significant contributing factor. This can vary from £2,200 for a 5 kW scheme to £48,000 per annum for a 500 kW scheme (Bejarano et al., 2019). Hydro schemes are reliable for long-term usage. General maintenance required to clear the intake screen is the main ongoing requirement (Bejarano et al., 2019). Notably, Archimedean screws have larger intakes but are not affected by the impact of small debris and therefore daily operation would only be limited by larger-sized debris (Bejarano et al., 2019).

For a community, investment in a renewable energy scheme may rely on the rate of return of the scheme. The rate of return will be based on potential for income to be generated; this in turn is based on export price and offset value. Export price is the amount paid for every kWh of electricity exported by the scheme. Exporting of electricity requires a grid connection and the electricity to pass through an export meter, measuring the flow of electricity. The grid connection is a major cost for community owned hydro schemes, which has little opportunity to reduce as they are a single entity; an example is the Anafon Hydro scheme (National Grid, 2021).

2.6 - Status of hydropower in Wales

Wales introduced new renewable energy schemes in 2018. The Welsh Government authorised development of 166 MW new renewable energy generation capacity, which brought the total installed capacity for Wales to 3,964 MW from a portfolio of 68,728 projects, of which 778 MW are locally owned (Welsh Gov., 2019). Despite the scale of development, this represents an increase in installed capacity of only 4% from the previous year. The current generation rate in Wales for all forms of renewable energy is 7.4 TWh. The largest contributors are onshore (2,779 GWh) and offshore wind (2,200 GWh), followed by solar photovoltaics (925 GWh) and then biomass (756 GWh) (BEIS, 2020). The lack of hydropower schemes developed within Wales means this source constitutes an installed capacity of 182 MW from 364 projects, which generates 367 GWh of electricity per annum. The electricity generated through hydropower is equivalent to powering 104,000 Welsh homes (Welsh Gov., 2019).

There is a large disparity throughout Wales in areas which develop hydroelectricity. Out of 22 local authorities, Gwynedd is the local authority with the largest number of hydropower projects: 141 projects actively generating 59 MW in 2018 (Welsh Gov., 2019). However, the largest generator of hydroelectricity is Ceredigion, which generates 79 MW annually from 28 separate projects (Welsh Gov., 2019).

During the time that FITs applied, there was steady growth of micro- and small-scale hydropower developments, endorsing 274 projects which equates to 75% of all hydropower projects in Wales (OFGEM, 2020).

2.7 - Climate Change and implications for hydropower:

Climate change will have a significant impact on flow regimes and the capacity for generation of electricity (Dallison et al., 2021; Jung et al., 2021; Wasti et al., 2022). Climate change will have a significant impact globally and will not discriminate. Some regions will suffer consequences of mass dislocation and poverty (Dallison et al., 2021; Jung et al., 2021; Wasti et al., 2022).

It is well established that climate change will change our existence, through species loss, irreparable supply issues to food chains, increased displacement and rises in poverty (UNFCCC, 2021). Climate change will affect regions in quite different ways, creating more intense implications in some regions than others (UNFCCC, 2021).

2.8 - Global climate policies for renewable energy development:

Global policy agreements have been rolled out since the First Climate Summit, which was held in 1972 in Stockholm, Sweden. The first climate summit laid out a path for the principles for the future of the human environment and action plans for international governments to take environmental action (Dolf, 2012). There have been significant milestones since and the following is a summary of three of the most influential climate summits: the Kyoto Protocol (1997), Paris Agreement (2015) and COP26 (2021).

The Kyoto Protocol was the outcome of the Third meeting of the Conference of Parties (COP3). The aim of COP3 was to create a framework for reducing CO_2 emissions of developed and developing nations. The Kyoto Protocol created a list of countries, predominantly industrialised economies, which were grouped into Annex B. This was an agreement that Annex B countries would commit themselves to reducing their CO_2 emissions and lowering greenhouse gases (GHG) by 5.2% based on 1990 figures (Boehringer, 2003). Controversially, two major issues arose with the Kyoto Protocol, the first being lack of clarity for use of carbon credits on carbon sinks (forests and soils) and secondly the question of how much restriction existed around the tradability of emission rights from one country to another (Boehringer, 2003). Another controversial issue arising from the Kyoto Protocol was the refusal of the US to sign, in protest that detrimental costs for the US were too high to agree to such terms (Boehringer, 2003).

The Paris Agreement was the outcome of COP 21, held in Paris in 2015. This followed from the previous COP, held in Copenhagen in 2009. At the 2009 COP, the focus was to build on a plan to the Kyoto Protocol to help curb the rise in GHGs. However, the 2009 Copenhagen COP was unsuccessful, leading to the need for the Paris Agreement (Falkner, 2016). In comparison to the 2009 COP, the Paris Agreement, recognised the influence of domestic politics regarding climate change and so allowed countries to set their own individual targets. This was in direct contrast to the 2009 COP, which set fixed targets for groups of countries (Falkner, 2016). The framework of the COP21 Paris Agreement allowed countries to voluntarily agree climate targets, opening the Agreement to public accountability of meeting these targets (Falkner, 2016).

The Paris Agreement (COP21) set out to ensure cooperation between governments on their efforts to reduce climate change and hopefully decarbonise the global economy (Falkner, 2016). At the time of the Paris Agreement, the understanding of the rate of global warming was that it would be 2.7°C on pre-industrial levels, if all countries met their climate change agreements. For the Paris Agreement to have a lasting effect there was a change to the thought process of commitment and then review of those commitments (Falkner, 2016). Furthermore, the Paris Agreement set out an agreement that would have countries commit to reaching their peak of GHG production as soon as possible and to find a balance between production of GHGs and removal through sinks of GHGs in the second half of the century (Falkner, 2016).

COP26 held in Glasgow 2021 was intended to be inclusive and a step forward in climate policy. However, this expectation was not met. The Glasgow climate pact, the outcome of COP26, has multiple failures, which do not go far enough in laying out a path to reduce global emissions, as documented by several studies and reports produced immediately after the event. The overall failings of the COP26 pact are the watered-down wording and failure to mention the phasing out of fossil fuels (Filby and Richards, 2021).

There were also issues around 'lack of representation' in what was set to be the 'most inclusive COP', which is cited to have gatekeeping issues, lack of representation of indigenous populations, youth and accessibility issues for wheelchair users (Filby and Richards, 2021). There were positives from COP26, the Glasgow Climate Pact, laid out there should be a doubling down on financial commitments for the next year's COP27 in Egypt, where greater emission cuts will be needed (Filby and Richards, 2021). The positive outcomes of the COP26 are that there at least was an outcome, in comparison with 2009 Copenhagen COP15 (Filby and Richards, 2021). The Carbon Brief, a well-regarded scientific blog, stated "COP26 has achieved more than expected but less than hoped" (Filby and Richards, 2021).

2.9 – Climate change projections and effect on streamflow

Currently, there is a consensus on the implications of climate change on the hydrological cycle, which is represented clearly through observations of streamflow (Kay, 2021). The potential changes in flow regimes will have lasting effects on many facets in the reliance on water, such as ecology, electricity, and water quality (Kay, 2021). Many studies stipulate potential changes in the UK. These studies vary in age but utilise UKCP09 and UKCP18 for their data. The criterion of conclusions within these studies, demonstrates the UK will see drier summers and increasing flow regimes through winter.

The following focuses on the work of Purdhomme et al (2012), Christierson et al., (2012) and Sanderson et al., (2012), all of whom investigated the implications of climate change using the UKCP09 data, as well as Kay (2021), using UKCP18 data for predictions of streamflow based on implications of climate change. Prudhomme et al. (2012) utilised a semi-distributed model using UKCP09 as the data source to develop the 'Future Flows Climate' dataset. The outcome of this investigation was a likely decrease in flow regimes in the summer. There are variable flow changes over spring and autumn, however these showed significant decreases in the autumn overall (Prudhomme et al., 2012).

Christierson et al. (2012) investigated river flow across 70 catchments in the UK, utilising probable projections at a daily timestep. The Generalised Likelihood Uncertainty Estimation (GLUE) methodology along with Latin Hypercube sampling, a statistical method for randomly sampling parameter values from datasets, are multidimensional in their distribution: in this case the climate data from UKCP09. The investigation period was the 2020s and their results demonstrated small increase in winter flows in Northwest England and decreases in flow regimes throughout the year and significant decreases in the summers (Christierson et al., 2012).

Sanderson et al., (2012), investigated the seasonal mean runoff in the UK from the 2020s to 2080. The paper demonstrates that surface runoff is projected to increase in winter across all regions, with an increase of up to 25% by 2080, in contrast to other seasons which all show decreases in surface runoff. The results of the Sanderson et al (2012) investigation utilising UKCP09 data, shows significant losses in water resources in Southeast England during the 21st century. The paper concludes that adaption to these changes will be required before any formal climate change signals are made (Sanderson et al., 2012).

Kay (2021) discusses the potential future that will be manifested on the natural environment through climate change implications. The application of similar estimation of streamflow using UKCP18 data demonstrates falling summer flows of up to -45% by the year 2050 and possible increases of 9% in winter flows by 2050.

These papers represent a range of available literature on climate change implications on streamflow but are important examples of UKCP data being used as main data sources for their investigation. The key strand linking all the papers is the less than optimistic view of the impact that climate change will have on flow regimes in the UK. There is evidence that there will be overwhelmingly negative effects of climate change on flow regimes in the UK. In an all but obvious sense, there is little beneficial impact of climate change on continual standards of water supply in the UK.

2.10 - Environmental Impacts of hydropower

The development of renewable energy from sources, such as hydropower, however positive the development may be, generates constant controversy surrounding associated environmental impacts (Pahl, 2007; Pahl, 2012; Bakken et al., 2014). Any form of renewable energy carries the requirement for a potential site to be recast to harness potential energy. This occurs in the adaptation of roofs for solar power, hillsides for exploitation of wind energy and even waste streams for biofuels (Armstrong & Bulkeley, 2014; Bakken et al., 2014).

2.10.1 - Pumped

Pumped-storage can be characterised as either open-loop (naturally flowing water) or a closed-loop (not connected to flowing water). The environmental implications of both closed and open loop are well documented (Saulsbury, 2020). There is a consensus that closed loop projects have generally lower environmental impacts than open loop systems. Closed loop systems are not located on flow regimes and therefore have minimal effects on riverine habitats (Saulsbury, 2020).

However, closed loop systems still influence their local environment. Closed loop systems impact their local environments through drawing surface water into the upper reservoir, which reduces the availability of surface water for other applications and habitats (Saulsbury, 2020).

2.10.2 - Impoundment

There are serious long-term implications from impoundment schemes, social impacts on local communities, water availability and changes to flow regimes and sediment transport; furthermore, greenhouse gas emissions from biomass decay in reservoirs (Richter et al., 2010; O'Neil et al., 2012; Zarlf et al., 2015; Gibson et al., 2017; Reid et al., 2018; Zarlf et al., 2019).

One major issue of Impoundment schemes is the effect on river dependent populations located directly downstream of the dam. Common implications on river dependent peoples are the instability of food supply and upheaval of livelihoods, which, in the developing world, can involve millions of people (Opperman et al., 2009; Richter et al., 2010). The damming process has implications on the migration and life cycle of fish populations. Despite the protections against flooding events, their livelihood may depend on the availability of fish (Richter et al., 2010). This reduction in availability of fish will increase competition for what remains, thereby forcing people to uproot their lives in search of a secure source of food and work.

Another considerable issue is the release of GHGs into the atmosphere (Song et al., 2018). Even discounting the idea of the amount of GHGs released through construction and raw material extraction for the creation of reservoirs, there are significant amounts of GHG production from the existence of the reservoir itself. The decomposition of submerged biomass and other organic materials creates carbon dioxide and methane (Song et al., 2018). Carbon dioxide and methane are emitted into the atmosphere through the processes of diffusion and ebullition at the water's surface (Song et al., 2018). A few studies into places that emit GHGs include Kemenes et al., (2007) and de Faria et al. (2015).

Kemenes et al. (2007) investigated emissions of turbine degassing and emissions of the downstream portions of the river immediately after the dam outlet. The study found that 39 Gg CO_2 eq. had been released annually from the Balbina Dam in Brazil. Furthermore, Kemenes et al., investigated the release of CO_2 from the reservoir surface and were able to estimate that a further 34 Gg CO_2 eq. had been emitted annually (Kemenes et al., 2007). Similarly, De Faria et al., (2015), estimated that GHG emissions were three times greater than GHG emissions from the reservoir surface. It has become more widely recognized as a significant source of GHG emissions but further research is required into this area of hydropower.

2.10.3 - Run-of-River

The major controversy surrounding micro-hydro generation is the contestation of water resources. The Environment Agency (2010) (Page 7) stated, 'Schemes can have an impact on other users including water abstractors, anglers, canoeists or those who enjoy the natural beauty of an area'. In this regard, many projects not on private land must get through the public planning process, meaning all those who 'share' a water resource must agree to a scheme's installation (Armstrong & Bulkeley, 2014). In most cases public waterways are used by a variety of stakeholders, ranging from local organisations such as fishing and boat clubs, to landowners holding riparian rights. Although highly beneficial, this process opens projects to criticism, potentially introducing otherwise unknown obstructions (Pahl, 2007; Pahl, 2012; Armstrong & Bulkeley, 2014). For example, the Hexham River Hydro, based on the River Tyne, met considerable opposition from people using the river for fishing and angling and from the Tyne Rivers Trust, who are directly responsible for the Tyne (including fish stocks) (Armstrong & Bulkeley, 2014). The disquiet of the Tyne Rivers Trust was the potential impact of the micro-hydro scheme on ecology of the river and subsequently impacts on course and migratory fish stocks (Armstrong & Bulkeley, 2014).

2.10.4 - Impacts of river species

The amount of water abstracted from rivers through the penstock for the generation of electricity in a run-of-river hydro scheme must also be considered. In addition, in-channel barriers utilised by small-scale hydro schemes impact longitudinal connectivity of rivers. The presence of a barrier alters the in-channel environment and thus the ecological habitat of a river (Anderson et al., 2014). Papers such as Anderson et al., (2014) and Bakken et al., (2014), discuss the effect of small and micro-hydropower on migratory fish stocks. However, few papers discuss impacts of barriers in the context of run-of-river hydro schemes.

A major consideration in planning a hydro scheme is the potential effect of water abstraction. Abstraction creates a section of river which has a reduced water or depleted flow compared to the natural flow. In hydro schemes in upland catchments, these depleted sections feature a significantly reduced riverine habitat (McIntosh et al., 2002; Riley et al., 2009; Anderson et al., 2014). Many studies show that within these depleted zones, changes to habitats occur, as well as to the chemical make-up of the water. Reduction of water supply confines habitat areas, increasing competition for food and space, potentially forcing species to migrate downstream (McIntosh et al., 2002; McKay & King, 2006; Anderson et al., 2014). Investigations by Elderd (2003) & Greet et al., (2011), observed a reduced number of species in these depleted areas. This was confirmed by authors including: Kubecka et al., (1997); Habit et al., (1997); McIntosh et al., (2002); and Riley et al., (2009) who showed reductions in species of invertebrates and fish.

Issues surrounding fish migration are discussed in academic literature when considering the impact of micro or small-scale hydro schemes. The issues surround species of fish, which follow the main flow of a river for migration, such as the diadromous family (*i.e.* Salmon) and potamodromous family (i.e. trout and catfish). As a result of the nature of these fish migratory patterns, when traveling downstream, fish may follow water being diverted into the hydro scheme resulting in injury or mortality (Anderson et al., 2014). There has been significant improvement to the safety of run-of-river hydro schemes, through introduction of fish passages such as rock passages, natural diversion channels and coverings on intakes of penstocks of small and micro hydro schemes. Fish passages have significantly improved migration of fish stocks (Arnekleiv, Kraabol, 1996; Dodd et al., 2018). However, little is known about the impact of fish passages on the invertebrates and other riverine species (Anderson et al., 2014).

2.11 – Summary:

Hydropower could be and has demonstrated through history to be a clean and efficient form of renewable energy. Hydropower relies on the kinetic energy of water passing through a turbine, in essence a ‘low-tech’ form of renewable energy. Hydropower schemes have been deployed globally and are excellent, efficient generators of electricity (Paish, 2002; Safarik, 2019). There is a myriad of application due to the large variety of generation capacities and mechanical setups (i.e., impoundment, pumped and run-of-river). The applications in the modern world could fit into any economy and operate as an effective method of generating sustainable electricity (Hamududu & Killingtveit, 2012; Palomino Cuya et al., 2013; IEA, 2021).

There are limitations to the development of hydropower: most notable are significant environmental implications and, for the development of larger hydropower schemes, the extreme financial burden (Pahl, 2007; Pahl, 2012; Bakken et al., 2014). The environmental implications have been weighed up extensively in academic literature with specific investigations into local hydro schemes, not just general investigative work (Pahl, 2007; Pahl, 2012; Bakken et al., 2014). Impoundment schemes are having the greatest impact on the greatest number of people, as presented by Kemenes et al., (2007) and de Faria et al., (2015)., discussing the enormous amounts of GHGs being emitted from the stagnant reservoirs to the extent of no true understanding of global implications recorded (Kemenes et al., 2007; de Faria et al., 2015). At the other end of the spectrum, run-of-river schemes have localised impact, there is understanding of increased competition created in the river between the inlet and outlet of the scheme. Lower areas of flow inhibit development of local species of flora and fauna (McIntosh et al., 2002; McKay & King, 2006; Anderson et al., 2014).

From the literature gathered in the above literature review, there is a clear criterion for practices to calculate hydropower potential, as demonstrated by papers such Purdhomme et al (2012), Christierson et al., (2012), Sanderson et al., (2012), and Kay (2021). There are distinctions between all these papers, with variety in the hydrological modelling practices and the scale of their investigation. The variety of areas studied presents an interesting opportunity to understand local potential for hydropower, with studies focusing on two catchments to studies focusing on entire basins. For each of the papers presented there are limitations and benefits to the approach, albeit more positive than negative.

Through the presentation of literature, there is a need for further understanding of impact of climate change on streamflow in Wales. Although there is no new research brought to the field, contributors, such as Dallison et al., (2021), imply the addition of further investigation would be beneficial. This study will aim to contribute through the investigation of EXP-hydro hydrological model to simulate streamflow in accordance with UKCP18 data (RCP8.5) and provide a theoretical understanding of hydropower potential for seven catchments, each with unique population density and land-use. This is an opportunity for the investigation into EXP-hydro performance and to further understand implications of climate change on streamflow in Wales.

3 - Methods

The aim of this research project is to assess the long-term hydropower potential in Wales by utilising a combined hydrological and GIS-based approach. The hydrological model used in this project was EXP-Hydro. For validation of the modelling output, Kling-Gupta Efficiency and Sum-Squared Regression were utilised. The simulated streamflow created from the modelling process, was then utilised in ArcMap to generate values for stream flow and from this hydropower potential for the period of 2040-2080. The climate scenario chosen for this investigation was the RCP8.5, to provide the worst case for flow regimes. The catchments selected for this investigation offer a range of land-use and population densities, which for the investigation of EXP-hydro's ability to simulate streamflow should provide a good test.

3.1 - EXP-Hydro:

EXP-Hydro (single-run lumped version is displayed in appendix 2) (exponential bucket hydrologic model) is the name given to the rainfall-runoff model, developed by Dr Sopan Patil. The model is designed to estimate streamflow in ungauged catchments on a daily time-step. There are spatially distributed and lumped versions of the model, both of which were examined in the initial investigation by Patil and Stieglitz (2014). EXP-Hydro was initially used for the estimation of streamflow in 756 catchments in the US. The model relies on the calibration of parameters for each catchment based one a chosen goodness-of-fit metric, in this case Kling-Gupta Efficiency, from the literature available Nash-Sutcliffe has been chosen frequently.

The data were collected for a gauging station as close as possible for each of the catchments. However, the catchments investigated are of a significant scale and therefore a single gauging station may be insufficient to give an accurate representation of the entire model. The model solves two differential equations, which can be seen below.

$$\frac{dS_{\text{Snow}}}{dt} = P_{\text{Snow}} - Q_{\text{Melt}}$$

$$\frac{dS}{dt} = P_{\text{Rain}} + Q_{\text{Melt}} - \text{ET} - Q_{\text{Bucket}} - Q_{\text{Spill}}$$

Fig. 6: showing the differential equations that are solved in EXP-Hydro (Patil and Stieglitz, 2014).

The values S and S_{snow} represent stores of water described in mm. The two S values represent the total amount of water in the catchment, in both liquid and solid forms (Patil et al., 2014; Patil & Stiglitz, 2014). P_{snow} and P_{rain} are the values for precipitation as either rain or snowfall, both being represented in mm per day. ET is the value for evapotranspiration, given in mm per day. Q_{melt} is the value for snow melt in the catchment, calculated using the snow accumulation equation and is represented in mm per day. Q_{Sub} and Q_{Surf} are representations of flow within the catchment. Q_{Sub} is the representation of subsurface flow, which is generated using the catchment equation, similarly, Q_{Surf} is the representation of surface runoff. Both Q_{Sub} and Q_{Surf} are in mm per day for use in EXP-Hydro (Patil et al., 2014; Patil & Stiglitz, 2014).

EXP-Hydro requires the calibration of six parameters, which are representations of climate variables, thereby allowing for the prediction of daily streamflow. Similarly, as for any modelling process, the calibration of the EXP-Hydro, involves using historical data for a given period and comparing the output of the model to the historical dataset. The parameters are calibrated using EXP-Hydro PSO, which is a version of the modelling using Particle Swarm Optimization. From this is it possible to have parameters for EXP-Hydro, which will give accurate values for future streamflow. In addition to this, assessing the accuracy of the calibration is carried out using goodness-of-fit metrics, such as Nash-Sutcliffe efficiency or Kling-Gupta efficiency (Nash & Sutcliffe, 1970; Patil & Stiglitz, 2014; Patil et al., 2014).

3.2 - Kling-Gupta Efficiency:

Kling-Gupta Efficiency has become a standard tool for validating hydrological models. Developed in 2009, Efficiency calculation is based on the mean squared error, derived in parts from the Nash-Sutcliffe Efficiency. Efficiency calculations use the mean squared error between the observed flow and simulated flow, which can be dissected into variability, mean and dynamics (Gupta et al., 2009; Pool, Vis, and Seibert, 2018). Model parameter estimation is a vital aspect of hydrological modelling especially considering there has to be a demonstration of model performance to achieve highly accurate simulations (Gupta et al., 2009; Pool, Vis, and Seibert, 2018). KGE follows a criterion of thought within the academic community, that utilising multiple parameter calibration for the potential of avoiding overfitting of parameters to the hydrograph (Gupta et al., 2009; Pool, Vis and Seibert, 2018). Through multiple parameter calibration there are opportunities for reducing uncertainties in the simulation, as well as provide more trustworthy predictions without the consideration for parameters being uncorrelated (Gupta et al., 2009; Pool, Vis, and Seibert, 2018). KGE calculates efficiency of simulations on the basis the data is linear and has normality, an absence of outliers (Gupta et al., 2009).

Kling-Gupta Efficiency (KGE) is a validation tool utilised in hydrological modelling. There are multiple objectives of KGE, which allow for calibrated data to not overfit model parameters to a particular hydrograph aspect (Liu, 2018; Pool, Vis, and Seibert, 2018). KGE is used to reduce the number of simulation uncertainties, while maintaining accurate predictions for individual objectives (Liu, 2018; Pool, Vis, and Seibert, 2018).

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}$$

Fig. 7: equation for KGE calculation as demonstrated in Knoben, Freer and Woods (2019).

In the KGE calculation, R, represents the linear correlation between observed values and simulations, ɑ is the measure of flow variation error and β is the bias of the equation (Liu, 2018; Pool, Vis, and Seibert, 2018). KGE uses an integer as the basis for demonstrating model efficiency, KGE is measured on a scale of 0 to 1, with KGE = 1 being a perfect result. Values > 0 demonstrates the modelling is running efficiently, however, based on the value there would be consideration to improve the calibration to obtain a greater KGE value. For KGE = < 0, this would identify to the user the model is not running efficiently for the use of generating simulated data (Pool, Vis, and Seibert, 2018).

3.3 - Methodology:

The methodology presented in this project was approached in two stages – firstly the data preparation and the modelling process for the creation of future streamflow data from EXP-Hydro. Secondly, using ArcMap 10.7.1 for the calculation of hydropower potential and for generating the micro-hydro portfolio of potential generating locations.

3.3.1 - Data Collection

The observed streamflow and climate data were collected from the Centre for Ecology and Hydrology (CEH) and the National River Flow Archive (NRFA). CEH provided data for precipitation, potential evapotranspiration, and temperature. NRFA provided the observed streamflow. The Met Office was the source for the projected data for the variables of temperature, precipitation, and evapotranspiration for the years from 2040 to 2080. The surface data used in this investigation was the OS Terrain 5, which is a 5 m resolution Digital Elevation Model (DEM), sourced from EDINA Digimap.

The data collected from the CEH and Met Office were provided in a NetCDF format, the utilisation of which required extraction and conversion from NetCDF to a more manageable file type; in this case text files were chosen. To achieve this, an extraction script was used, which allowed for the extraction and conversion for given coordinates (see appendix 1). Furthermore, the data for temperature required conversion from Kelvin to Celsius and the precipitation data conversion to mm/day for use in EXP-Hydro. These conversions were carried out as part of the extraction from the NetCDF file type (see appendix 1).

Spatial reference data was also required for this investigation. The river network for each of the seven catchments were gathered from EDINA Digimap. The river network data, OS Water Network, was converted to a polyline feature class from the format in which it was provided - the Geography Markup Language (gml). In addition to this, the locations of electrical substations were required. This data was gathered from OS Points of Interest, provided in CSV formatting and then filtered through ArcMap to extract electrical substations within the seven catchment areas.

3.3.2 Running EXP-Hydro

Utilising EXP-Hydro requires a two-step approach. Firstly, a Particle Swarm Optimisation (PSO) version of EXP-Hydro is used for the optimisation of model parameters. This was completed using the observed historical period of 2000-2009. This process was carried out for each investigated catchment. PSO is a calibration method for rainfall-runoff modelling, developed by Kennedy and Eberhart (1995). The model is based on the analogy of animal swarms, giving explicit examples of fish or flocking birds. This provides excellent examples for demonstrating the method for solving nonlinear optimisation problems (Mandal et al., 2008; Jiang et al., 2013). PSO works by assigning values for parameters to a particle; with each iteration of the model being run, the particle is tested for model suitability (Mandal et al., 2008). The PSO runs of EXP-Hydro aim to achieve the best possible parameters based on the KGE value. The model achieves this once a desired KGE value has been reached or the number of runs has been completed. The PSO run of EXP-hydro was carried out for each individual catchment, as opposed to running the entire investigation area. The EXP-Hydro PSO was run for individual catchments to improve the accuracy of optimisation and thereby improve the predictions of streamflow.

Once the best possible parameters had been generated, the single-run version of EXP-Hydro could be employed. The data used for this is the collection of variables from the Met Office UKCP18 dataset;

the data spans the 2040-2080 investigative period. Only the single-run version was required for this section of the modelling procedure because the validation of the model running capabilities had been expressed from the running of the PSO EXP-Hydro.

The output from this hydrological modelling process was the generation of streamflow from the period of 2040-2080 with the model giving average flow per annum for each year. These values were aggregated to allow analysis of decadal variations in streamflow. The values were then exported into plain text files and into csv format.

3.3.3 Calculating Hydropower Potential

This section of the methodology was carried out in ArcMap, utilising the model builder function in ArcMap to streamline the process of calculating potential hydropower locations. Two key characteristics were required for consideration of hydropower in this investigation: distance from electrical substation and potential wattage. The following is a description of the processes taken to complete the spatial investigation of hydropower potential.

The process in ArcMap included the calculation for conversion from streamflow to wattage. However, there were pre-processing requirements before these processes were carried out. The first stage involved extracting the electrical substations from the OS Point of Interest dataset in ArcMap. This was completed using the 'select by attribute' tool and selecting only those that were named as electrical substations and then exported as a new layer. Following this the clipping tool was then used to extract river networks for each individual catchments from the OS Water Network data. Again, this was carried out for each study catchment.

The first tool used in the ArcMap process was 'Extract by Mask', which is similar to the clipping tool but works by extracting data from a raster layer within the bounds of the mask. Two inputs are required for this tool: the 5m DEM and mask of the catchment area, which is the catchment boundary as a shapefile. The output of this tool is elevation surface data for each catchment.

The following three tools are the initial stages of catchment delineation: fill, flow direction and flow accumulation. The 'fill' tool removes any imperfections from the surface raster. 'Flow direction' has multiple options utilising various algorithms, which can be utilised based on the user's preference. In this investigation, the D8 option was chosen. This algorithm calculates change in elevation based on the surrounding eight cells. 'Flow direction' identifies potential routes for overland flow based on the algorithm chosen (Krause & Bronstert, 2005). ‘Flow accumulation’ tool is used for understanding the drainage boundaries of an investigation area (Krause & Bronstert, 2005). These are important stages of the methodology, as the surface raster is utilised in the subsequent raster calculations as head (in metres).

The final section of calculating hydropower potential involves two raster calculations, which adjust streamflow based on the future flows generated in EXP-Hydro. The first raster calculation utilises the output of the flow accumulation (FA) tool and multiplies this by the ‘Future Flow Value’ (FFV) (see fig 9). The FFV is an aggregated value, which represents the potential flow for a given decade. The aim of this investigation is to assess decadal changes in hydropower potential; therefore, the aggregate has been taken as an average of the potential flow values for each year within the decade.

The flow data generated from EXP-Hydro modelling process currently only represents the grid coordinates used for extracting data from the UKCP18 dataset. This is a key aspect of the first raster calculation, taking these values for single points and creating a full surface raster for each catchment area.

$$P = p \times g \times H \times Q \times n$$

Fig. 9: The equation for hydropower potential (in Watts) as taken from the paper by Hatata, El-Saadawi and Saad (2019).

The second raster calculation, as seen in fig. 9, is the calculation of hydropower potential in Watts. This equation was taken from the Hatata, El-Saadawi and Saad (2019) paper, investigating the feasibility of small-scale hydropower in Egypt. As in figure 9, the terms represented are: P power in Watts, p water density (1000kg/m^3), H net head, Q water flow rate in m^3/s, g gravity constant (9.8 m/s^2), and n turbine efficiency (90%). One adjustment has been made to the equation, which revolves around potential energy losses in energy transfer and component efficiency (Hatata et al., 2019). Hatata et al., (2019), propose there are three key potential losses in a hydropower system: turbine efficiency (estimated to be 85%), drive efficiency (estimated to be 95%) and finally the generator efficiency (estimated to be 93%). By multiplying the efficiencies, it would be possible to estimate a total component loss and give an estimate for system efficiency in small-scale hydropower. This estimate equates to 75.1%, which for the purposes of the hydropower calculation is represented as 0.751 (Hatata et al., 2019).

The output of the final raster calculation is a surface raster, which is then clipped to the river network for each catchment, using the ‘extract by mask’ tool. Following this, a 500 m buffer was created around the electrical substations. 500 m was chosen as the maximum distance from the river to electrical substation because of the inherent increases in infrastructural costs for community owned schemes, as presented by Paish (2002). The sections of the river networks that fall within the bounds of the electrical substation buffers were then extracted and filtered to only show the cells of the rivers, which have a wattage value within the desired range of 5 kW to 1 MW. These cells were then exported into a spreadsheet, where patterns for hydropower potential could be calculated.

4 – Results:

The following is an overview of the generated data from the methodology presented previously. In this section, the results of the data will be presented for analysis, which will be followed by a discussion of the implications and how this data will be able to answer the research questions:

1. How accurately, through the assessment of Kling-Gupta efficiency values, could a combined method of geographical information systems and hydrological modelling estimate the hydropower potential of seven catchments across North Wales, between 2040-2080?
2. What effect will climate change have on the number of potential micro-hydropower locations across Wales?

The combined method of using hydrological model and GIS was able to locate 760 locations, which fall within the 500 m bound of essential grid connection through electrical substation. However, once the additional filter was applied for the wattage for these points being between 5 kW and 1 MW, the number was reduced to 74 potentially viable locations.

An important aspect of this investigation is understanding whether the output of the modelling process is similar or follows the trends and observations of potential change in the UK. The UKCP18 worst case scenario, demonstrates an increase in rainfall intensity, which is predicted to be in the form of increased frequency of severe downpours (Met Office, 2021). The UKCP18 predictions show, during summer months the average conditions will be much drier but with a significant increase in the number of severe rainfall events (Met Office, 2021). From the same scenario, the Autumn and Winter months will see an increase in rainfall intensity up to 2070 (Met Office, 2021).

The data presented in this study outlines and increasing output of hydropower, albeit at an uneven rate, for example, 2060 is the peak period of output. It can be assumed that with the increasing rainfall predictions, there will be an increase in the discharge in Wales and as a result it could be assumed there would be an increase in the rate of hydroelectricity production within the investigated catchments.

4.1 - General Observations:

The general observation for the data presented, is there is an overall increase in hydroelectricity generation over the period of 2040-2080. The decades of 2060, 2070 and 2080 all show to have increases in hydroelectric output on the values presented as aggregate for 2050. However, despite the increasing output, the peak period of output is 2060, which is synonymous across all the catchments investigated. In addition to this, there is significant drop in the hydroelectric output from 2060 to 2070, which is observed in the catchments Alwen, Clwyd, Dee and Vrynwy.

The peaking period of 2060 could be due to the increase in GHG emissions that are part of the scenario chosen for this investigation, which in this case is Representative Concentration Pathway 8.5 (RCP8.5). RCP8.5 is the worst-case scenario for a continued rate of GHG emissions for a world that would not stop the use of fossil fuels. This scenario represents an increase in temperature of 3.2-5.4˚C (IPCC, 2014).

One concern is the lack of modelled viable sites, once criteria were applied, in the catchments of Dee and Dyfi. There were a significant number of potential cells throughout, both Dee and Dyfi, before the limiting factor of distance to electrical substations was applied to the catchments. For this investigation limiting factors were based on the datasets available. Utilising on pole transformers for this investigation would have been a much more appropriate dataset, which would have provided a greater number of potential hydropower points. This is due to on-pole transformers being widely utilised in rural areas. However, this dataset was not readily available at the time of this investigation, therefore using electrical substations was chosen as an appropriate alternative.

4.2 – Individual Catchments:

This study investigated seven catchments in Wales, generating futuristic stream flows for each catchment individually and then an assessment of hydropower potential, based on discovering potentially untapped hydroelectric resources. The following section will present the data in a spatial context as well as demonstrate the variations between hydroelectric output for each of the catchments.

The spatial scale of the study area can be seen in figure 10, the distribution of electrical substations can be seen in this figure as well as the watersheds that make up the total catchment area. Furthermore, the elevation variability of the investigation area can be seen in figure 11.

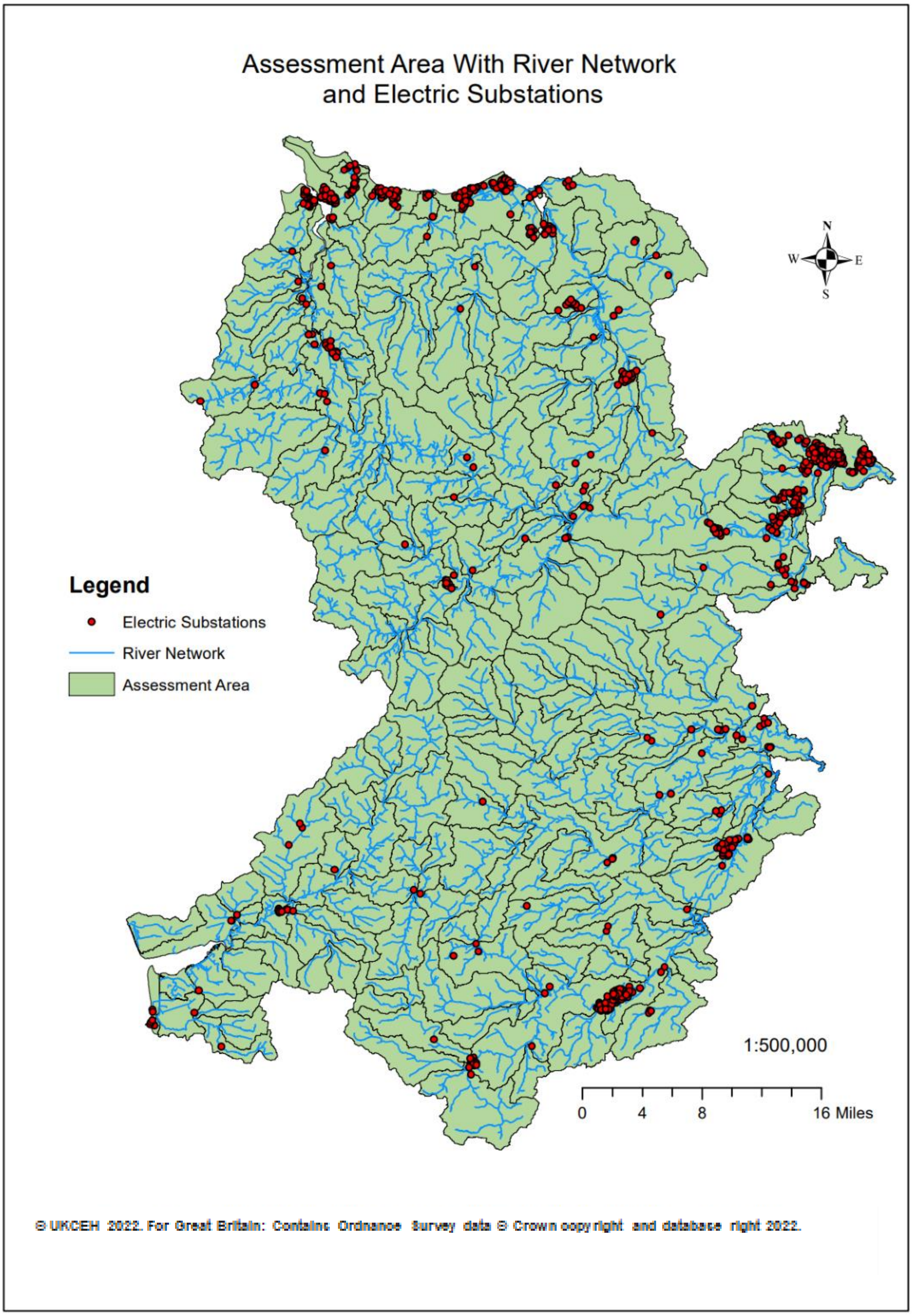

Fig. 10: Map showing the distribution of electrical substations and the river network of the investigation area.

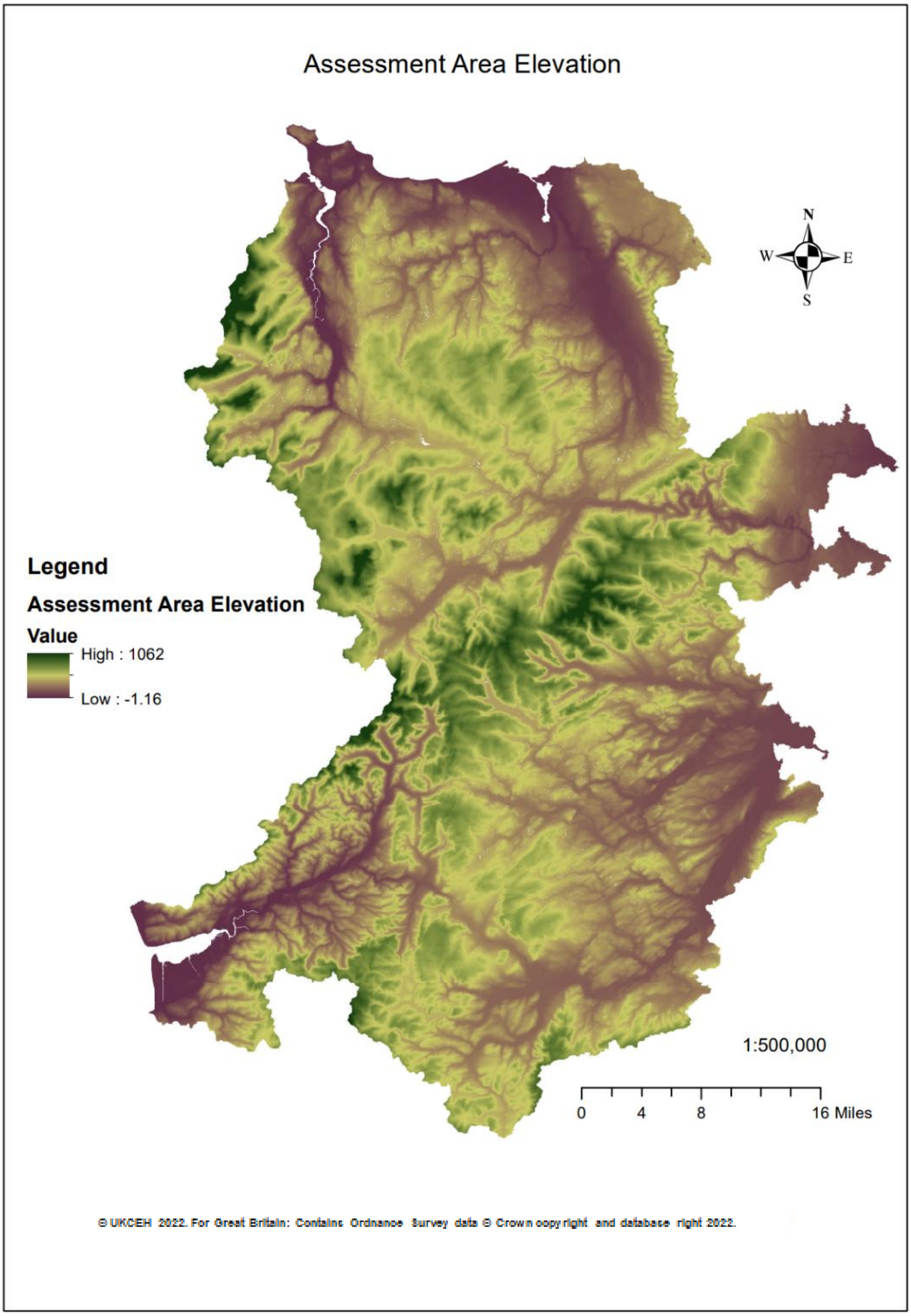

Fig. 11: Map demonstrating the variability in elevation throughout the investigation area.

4.2.1 – Alwen and Lower Dee:

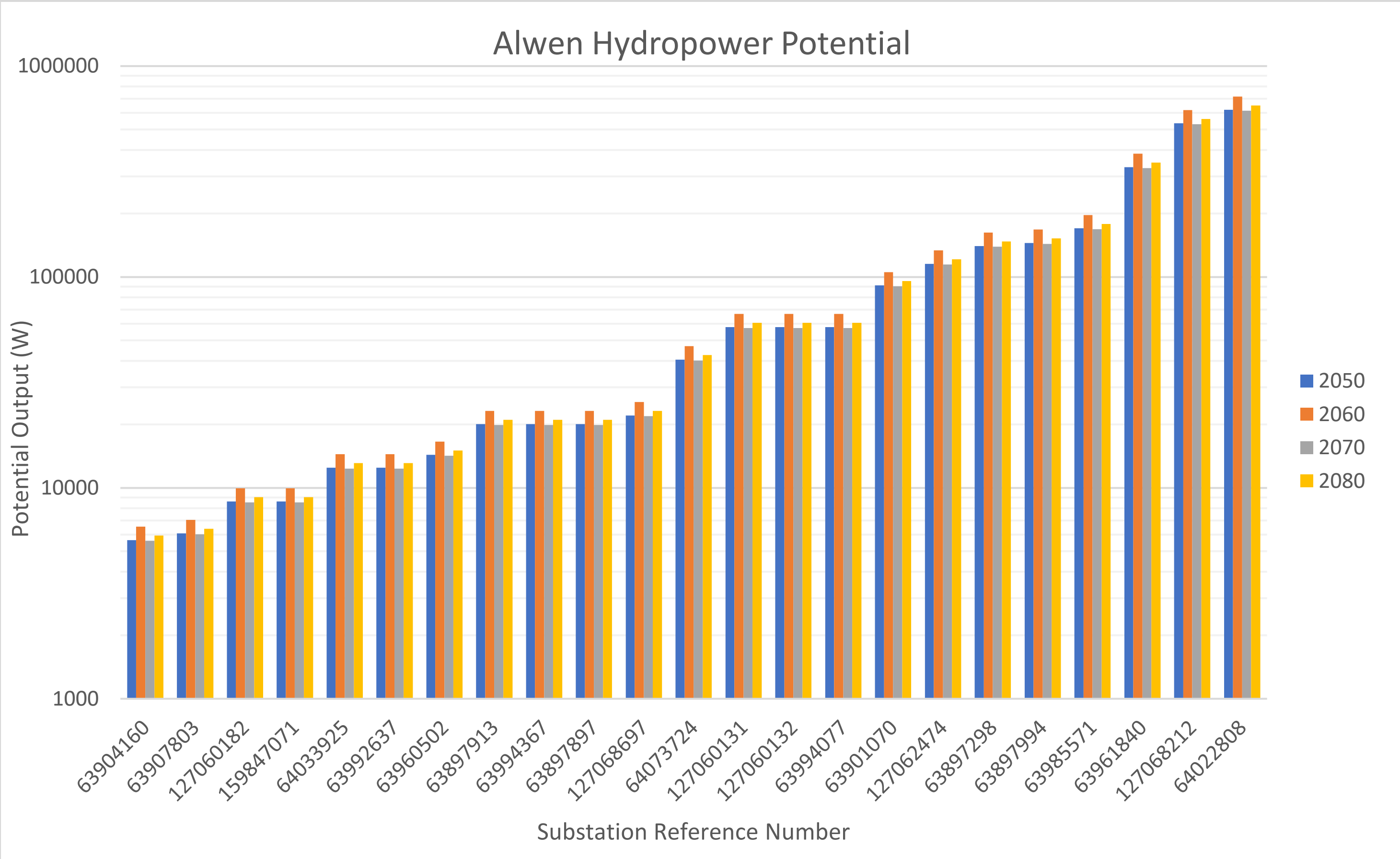

Fig. 12 – Histogram showing the variability of output in potentially viable locations within Alwen and Lower Dee Catchment area.

In the Alwen and Lower Dee catchment, there were 23 potential sites found to fall within the constraints of distance from the electrical substation and within the bounds of 5 kW output to 1 MW. The average value of output for potential sites in Alwen is 126 kW, which demonstrates there are a greater number of lower output sites compared to high output locations. This can also be seen in Fig. 12, where the histogram shows that 16 of the 23 sites are below 100 kW. There are no potential locations in Alwen that fall within the higher percentiles of the micro-hydropower range. The histogram in fig. 12 demonstrates clearly that the peak output for the catchment is 2060, which could be explained by the rise in GHG emission as part of RCP8.5. It is a substantial difference between 2060 and the other decades being investigated. The change in output based on the decade of 2060 to 2070, is a 16% reduction in total output. An example in this catchment is the viable location at electrical substation 127060182, which has an output of 67 kW in 2060 to then a reduced output in 2070 of 57 kW.

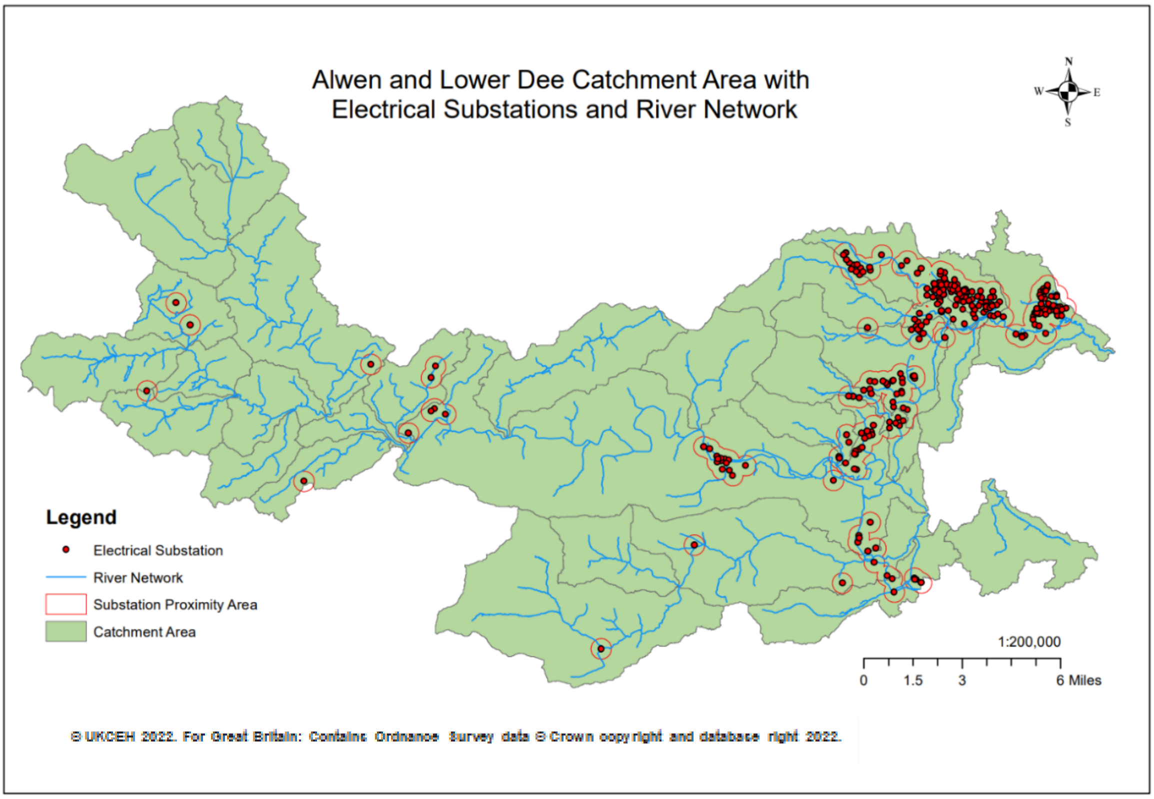

Fig. 13 – Visual representation of the spatial distribution of electrical substations in Alwen and Lower Dee Catchment area.

The distribution of electrical substations in the Alwen and Lower Dee catchment area is heavily biased around the Wrexham, in the West of the catchment. There is another smaller grouping around the town of Llangollen and then extremely rural examples of an electrical substation in the south of the catchment area in Llanarmon Dyffryn Ceiriog.

4.2.2 – Clwyd:

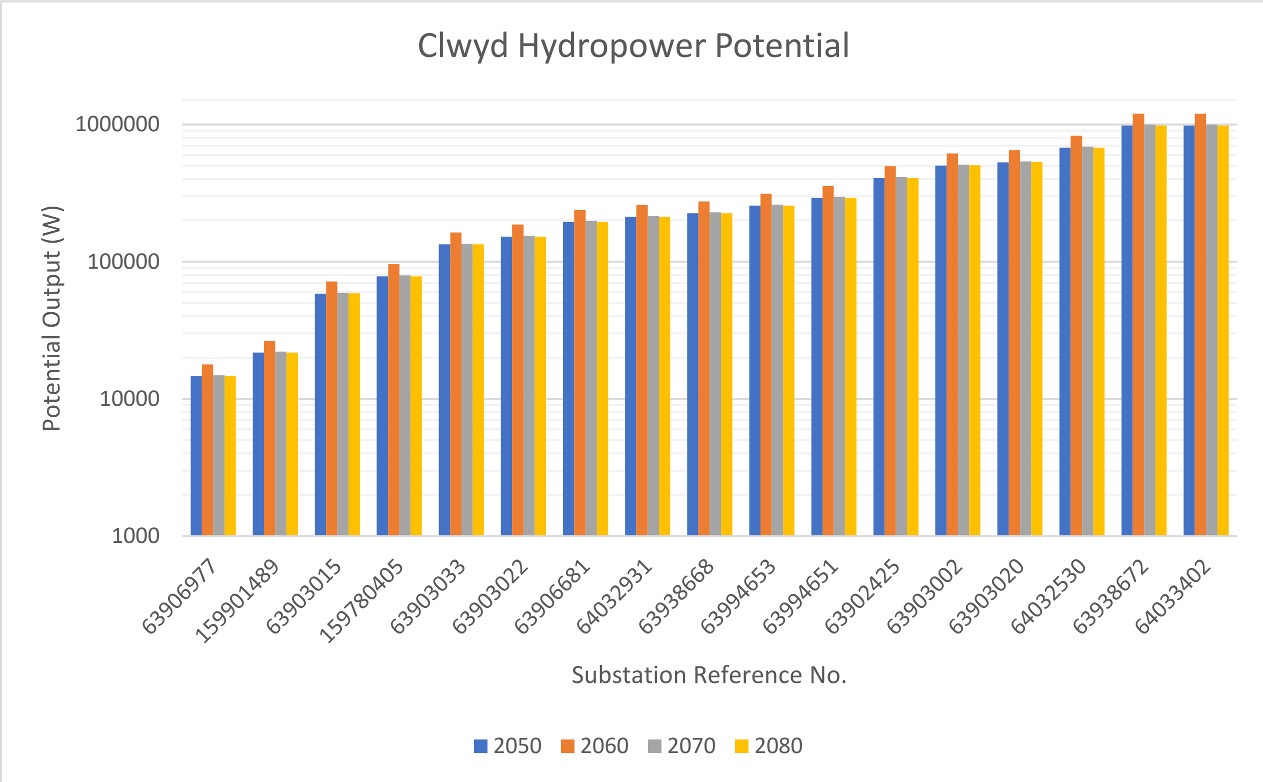

Fig. 14 - Histogram showing the variability of output in potentially viable locations within Clwyd Catchment.

In the Clwyd catchment area, there are 17 sites that may generate between 5 kW and 1 MW. There are similar trends observed in Clwyd and the Alwen catchment. There is a significant increase generating capacity by 2060 compared to 2050 levels. In addition, the lowest production period is 2070 to 2080. The difference in output from 2060 to 2070 is a 20% change in output, with the given example of electrical substation 63903002. The potential output 615 kW by 2060 and then by 2070, the generation capacity falls to 511 kW. The comparison between Alwen and Clwyd catchment begins with the number of potentially viable locations, with 23 for Alwen and 17 for the Clwyd. This catchment has a higher proportion of viable sites that have a greater generation capacity. There are 9 sites in the Clwyd catchment area with a production over 100 kW, within in this number there are 2 potential locations that are on the edge of being 1 MW. These two sites are 63938672 and 64033402, which are neighbouring electrical substations, both of which producing, power output of 982 kW in 2050 and then peaking over 1.2 MW in 2060. The larger output locations could provide better financial returns for large corporate investors, such as potential use similar to those of the hydro scheme in Durham. The Durham hydro scheme is an example hydropower being utilised for electricity generation of workspaces, Archimedes screw generated 100 kW and is supplying the County Hall and the passport offices (Mark, 2014).

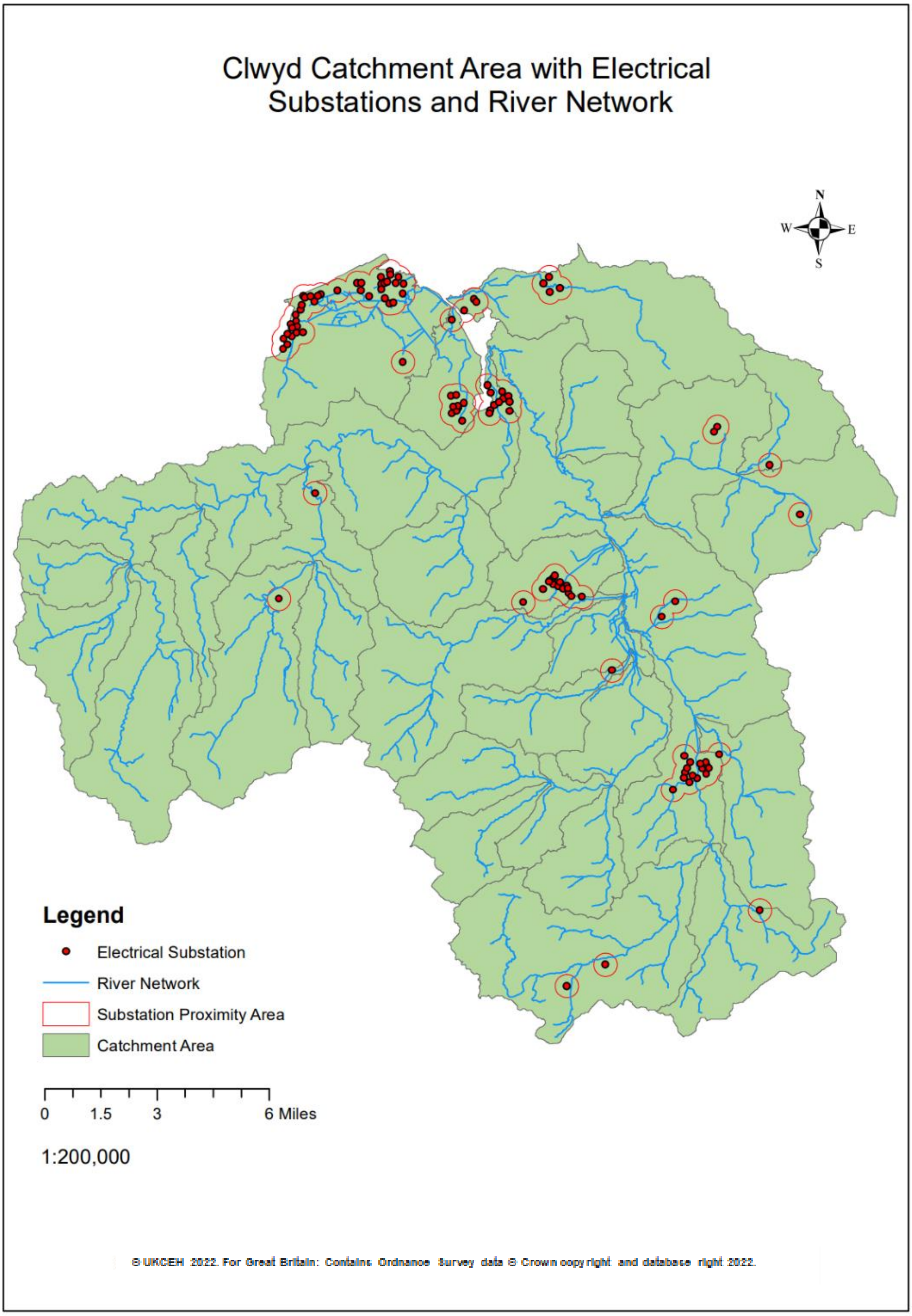

Fig. 15 - Visual representation of the spatial distribution of electrical substations in Clwyd Catchment.

4.2.3 – Conwy:

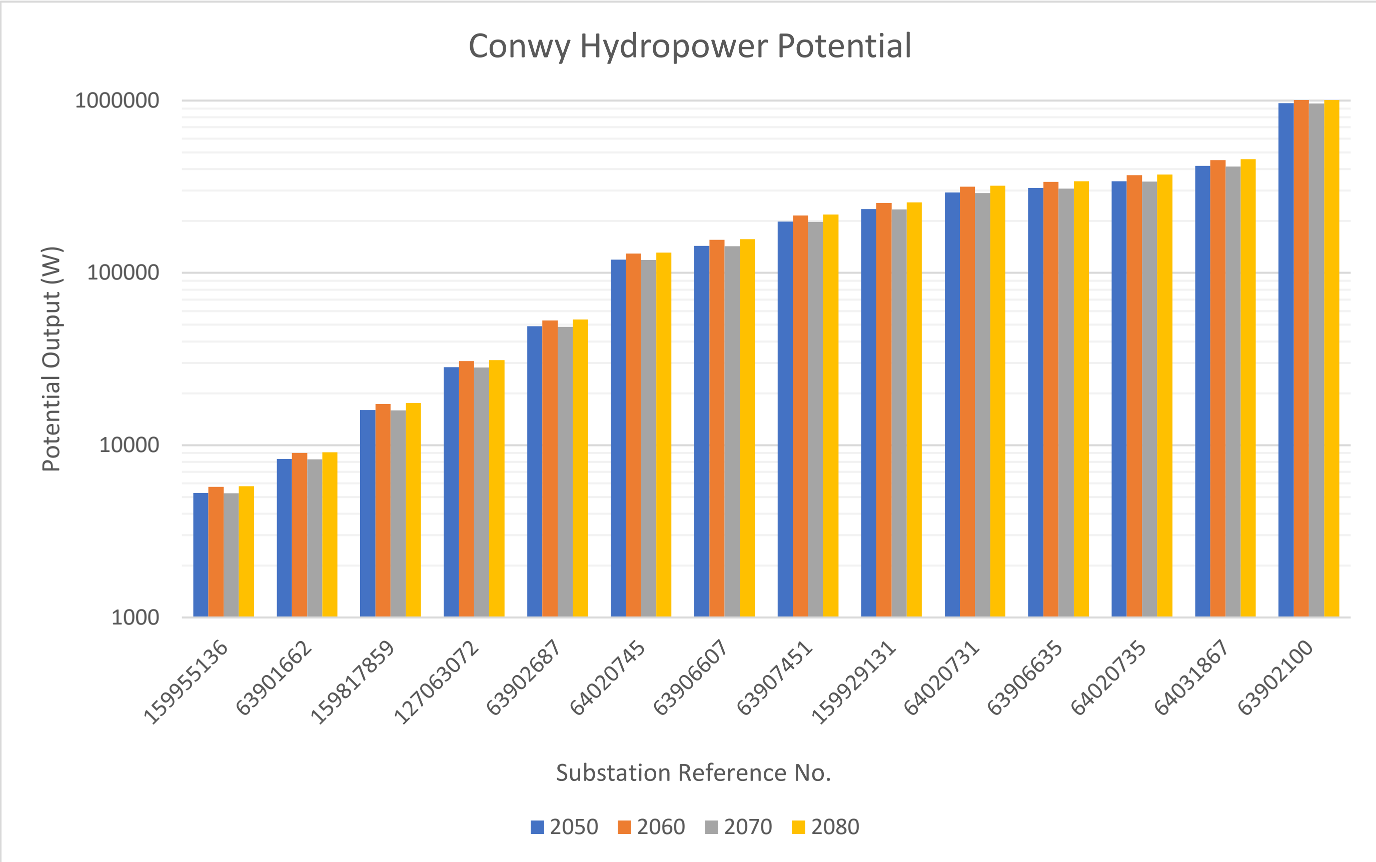

Fig. 16 - Histogram showing the variability of output in potentially viable locations within Conwy catchment.

Conwy catchment only produced 14 potentially viable locations within the range of 5 kW and 1 MW. The mean output for Conwy 254 kWin 2050. There is a significant range between the viable locations based on output, the lowest is at substation 159955136, producing an average of 5.5 kW over the investigation period. This is opposed to point 63902100, which produces an average output of 1 MW. Of the 14 potentially viable locations 63902100 has the most consistent output in the catchment, with the largest percentage difference being between the decades of 2070 to 2080, with a 10% change in output. This can be seen in the graph below (Fig. 16). In addition to this, Conwy has an observably different fluctuation in output compared to the other catchments. There are similarities between Conwy, Dee and Dyfi catchments, where the lowest years of output are 2050 and 2070.

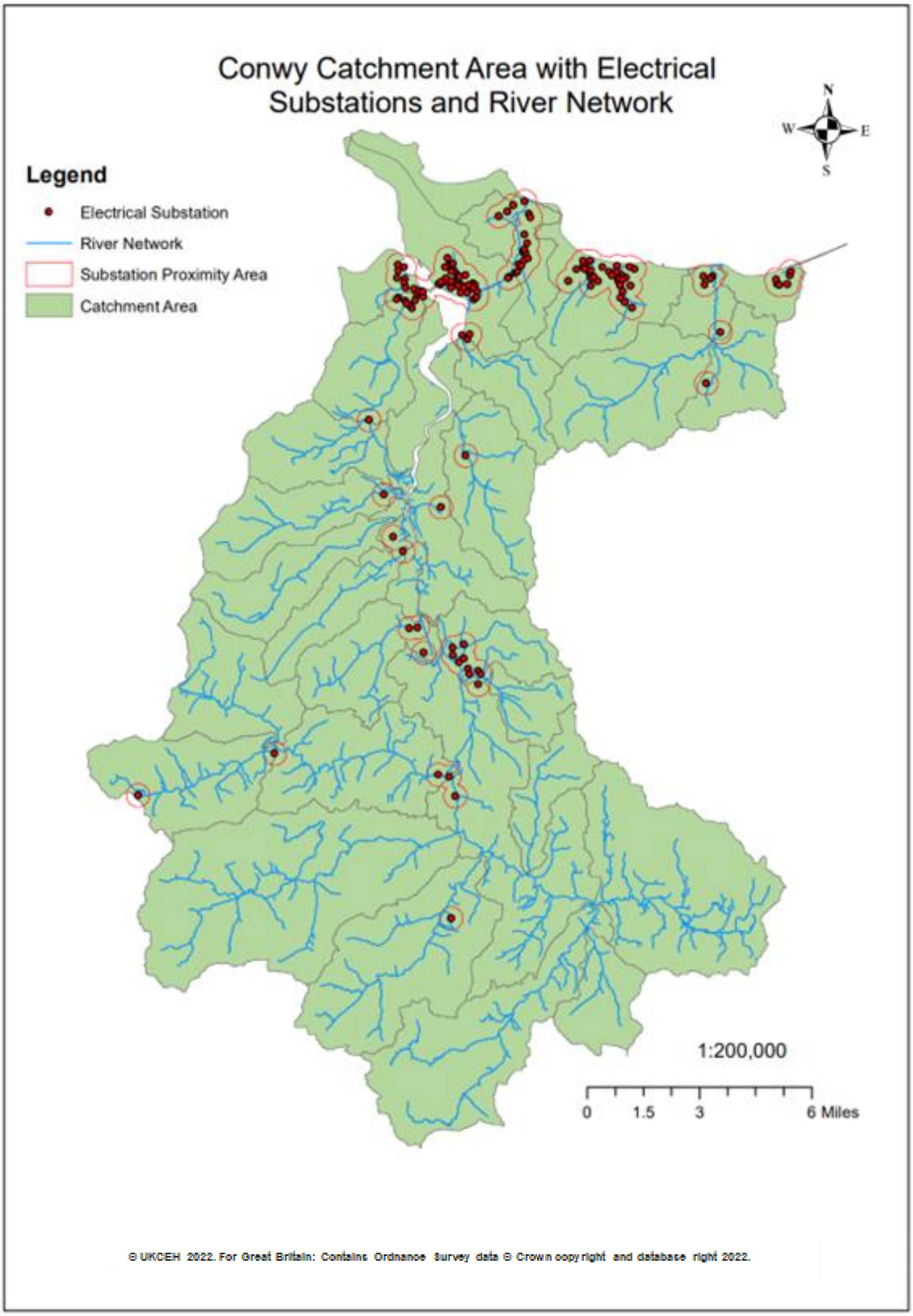

Fig. 17 - Visual representation of the spatial distribution of electrical substations in Conwy catchment.

4.2.4 – Dee:

The Dee catchment does not demonstrate much hydropower potential. It is an extremely rural catchment, which before the filtering process will have had significant numbers of potential locations. However, due to the chosen methods of the investigation, there were only two locations that meet the criteria of distance to electrical substation and are within the range of 5 kW to 1 MW. The greatest modelled value for the Dee catchment is 69 kW in the decade 2060, with the lowest in 2050, at 60 kW. The mean value for this catchment is 46 kW.

As seen in the graph, which depicts the two potential locations in the Dee catchment area. The pattern of outputs for the catchment, clearly show that the lowest output occurs in 2050 followed by the 2070, as the next lowest output period. 2060 shows the greatest potential output decade for the Dee catchment area. There is little variation between output periods (2050 – 60 kW; 2070 – 60 kW; 2080 – 63 kW), with the exception being 2060 (69 kW).

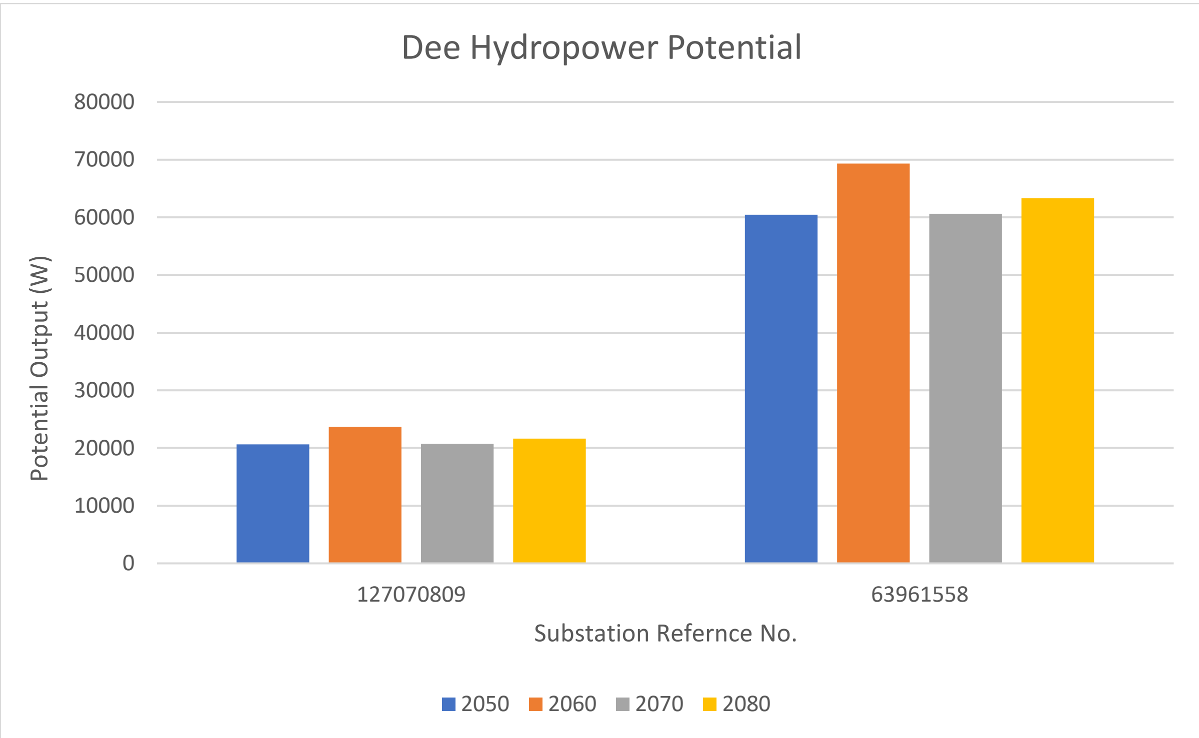

Fig. 18 - Histogram showing the variability of output in potentially viable locations within Dee catchment.

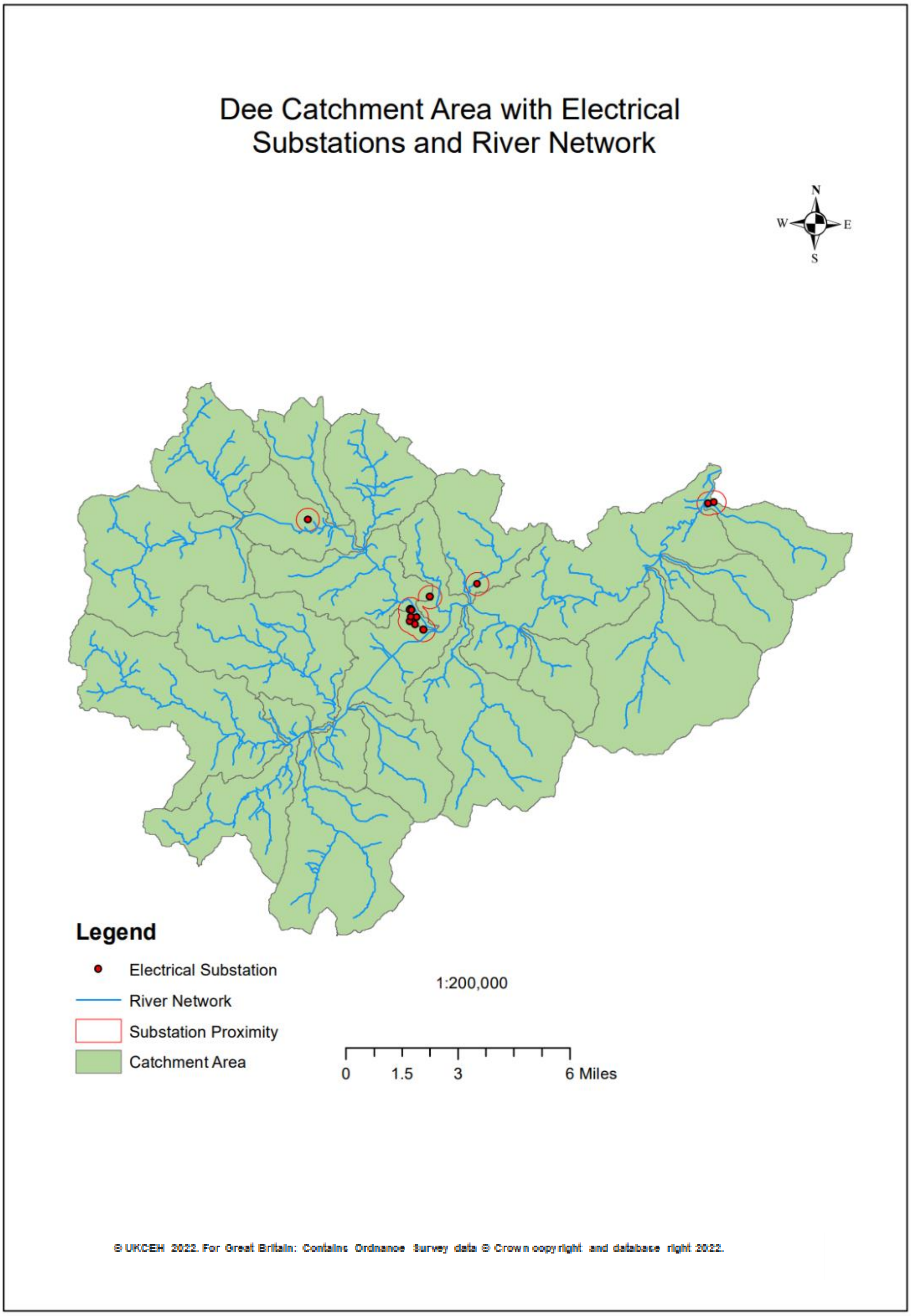

Fig. 19 - Visual representation of the spatial distribution of electrical substations in Dee catchment.

4.2.5 – Dyfi:

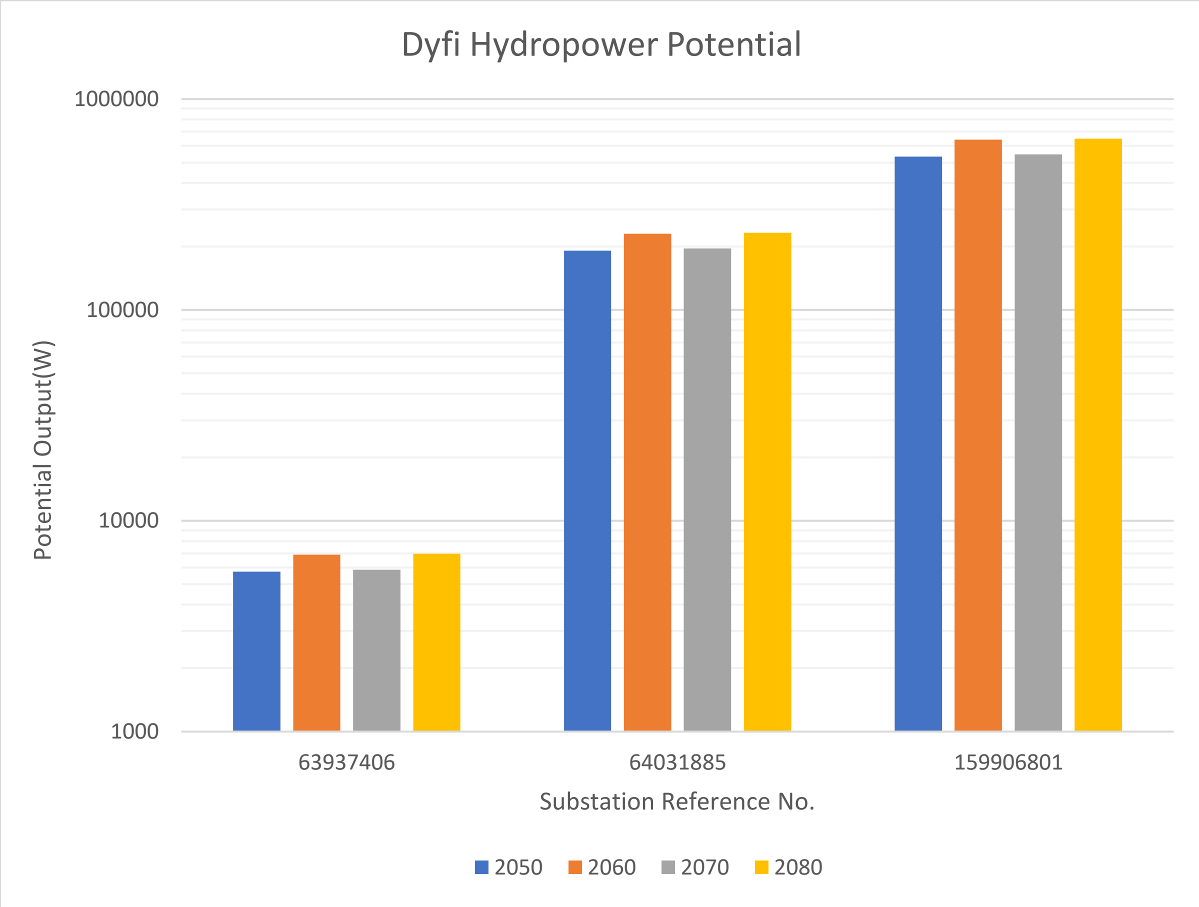

Fig. 20 - Histogram showing the variability of output in potentially viable locations within Dyfi catchment.

The Dyfi catchment is another low potential output area, as a result there are only 3 potentially viable locations within the catchment.). The mean modelled output from this catchment is 296 kW, which is a higher mean value than larger catchments such as the Alwen and Clwyd. 2080 is the decade for greatest potential output from this catchment, the highest output value for Dyfi is at the substation, 159906801, which has a maximum output of 650 kW. The lowest point for this catchment is at substation 63937406, which has a peak output of 7 kW. Fig x below clearly outlines the maximum outputs for each decade. It is important to remember there will have been more locations, which would have potentially generated significant generation. However, the issue remains that there is a lack of pre-existing infrastructure or become too expensive to utilise beyond the 500 m radius from the substation (Paiash, 2002).

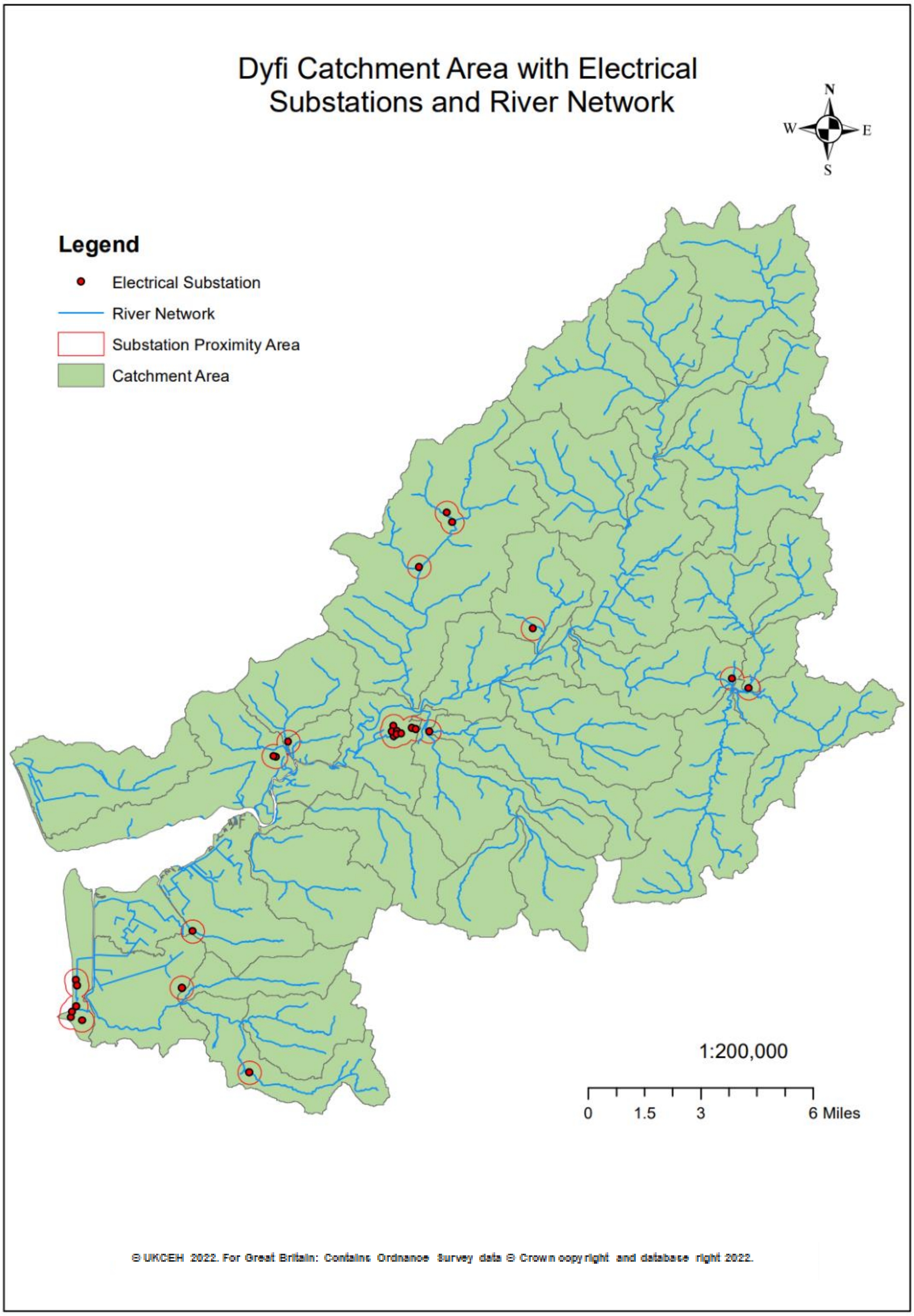

Fig. 21 - Visual representation of the spatial distribution of electrical substations in Dyfi catchment.

4.2.6 – Severn:

The Severn catchment area is the greatest catchment area investigated in this study. Therefore, it is surprising to see the lack of potentially viable locations within the catchment. There were 121 locations within the 500 m radius of existing electrical substations. Once the filter is applied to find the sites within micro-hydro power output range (5 kW to 1 MW) there remains only 10 potentially viable sites. Of these sites, 1 is below 100 kW, 9 sites fall between 100 kW and 1 MW. 3 of these sites reach a final output maximum in 2080 over 1 MW. The mean value for the Severn Catchment is 598 kW. In this catchment, there is a potentially served by two substations, meaning either substation could be utilised for the purposes of developing hydropower. In the graph below, both substations are represented (substation; 64068524 and 64037409).

As seen in the graph below, there is a steadily increasing output across all sites over all four investigation periods. The maximum outputs are reached in 2080, which can be seen to have a significant increase on the previous decades. When looking at the substation, 63982704, the increase from 2070 to 2080 is 204 kW. This magnitude of increase is witnessed through all sights in the Severn catchment. It is important to note this catchment is the only example exhibiting continual decadal increases in output.

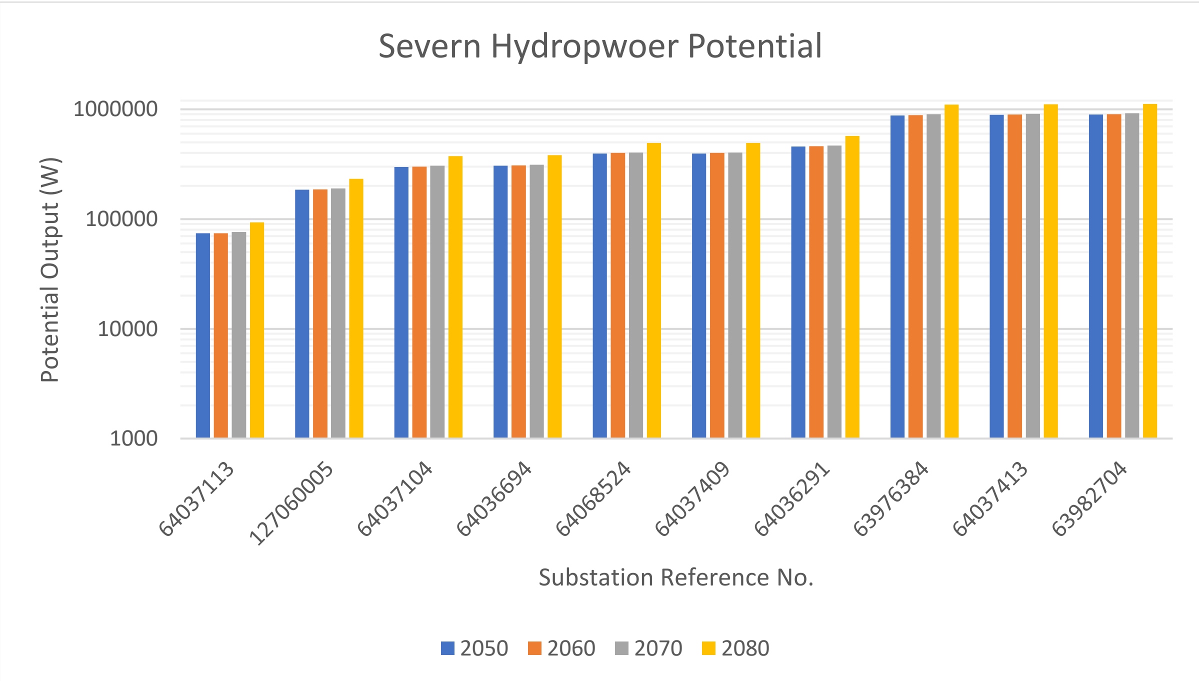

Fig. 22 - Histogram showing the variability of output in potentially viable locations within Severn catchment.

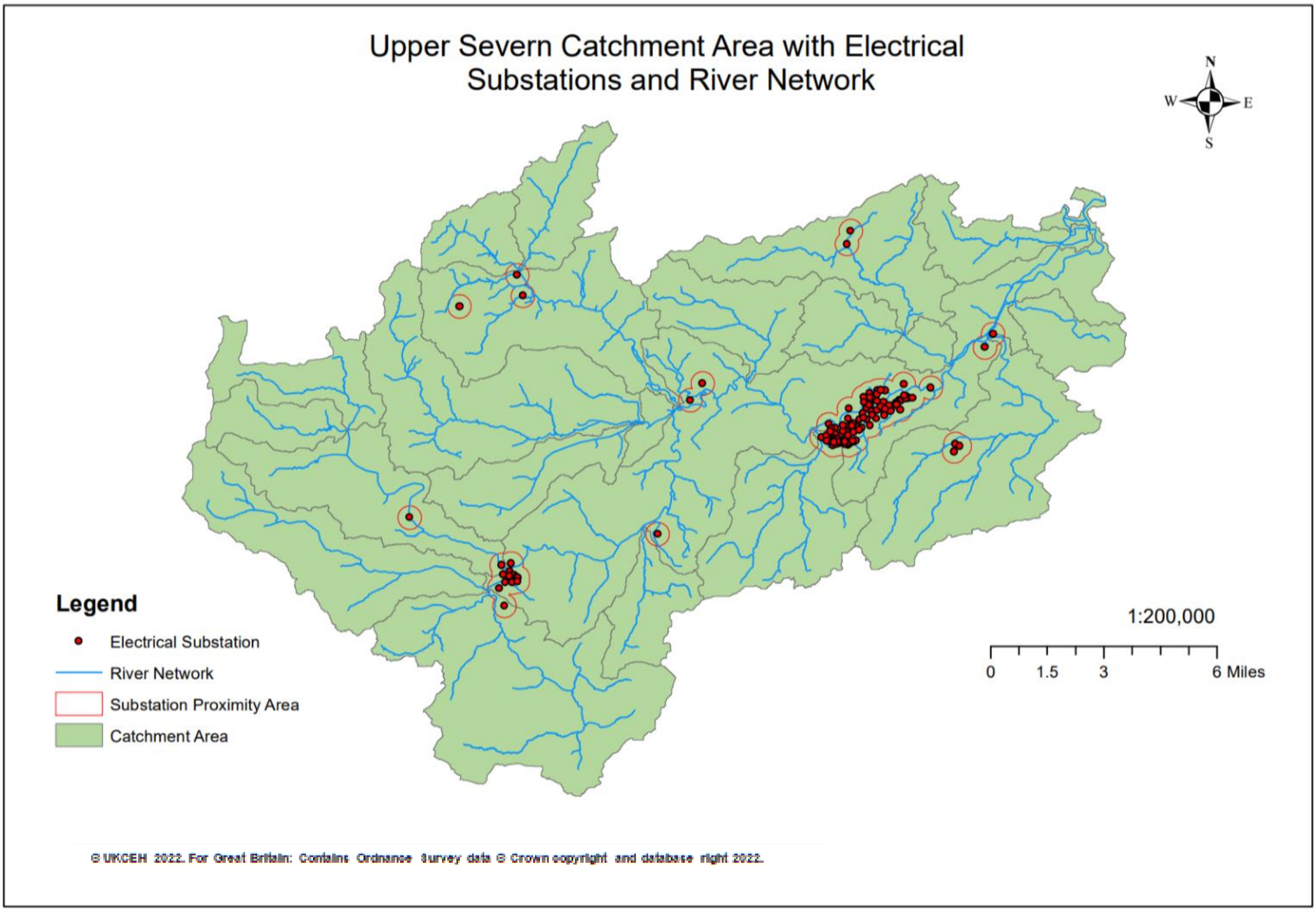

Fig. 23 – Visual representation of the spatial distribution of electrical substations in Severn Catchment

4.2.7 – Vyrnwy:

The Vyrnwy catchment has locations for which there is a theoretical hydropower output. However, once the limitation of distance to existing electrical infrastructure are applied, there is a significant reduction in the number of potential locations within the 500 m radius there were 68 points and once these have been filtered to the micro-hydro power capacity (5 kW to 1 MW) only 5 potential locations remain. The locations range from the smallest being substation 64015713, which has a potential output of 7.1 kW at its maximum. The highest output for this catchment is substation 63901081, which has a maximum output of 670 kW at peak output. The mean potential output for the catchment is 192 kW.

As seen in the graph below (fig. 24), the trend for output in the catchment is varied, there isn't an overall increase, and the lowest output occurs in 2070 and the maximum in 2060. This pattern is synonymous with the catchments Alwen, Clwyd and Dee.

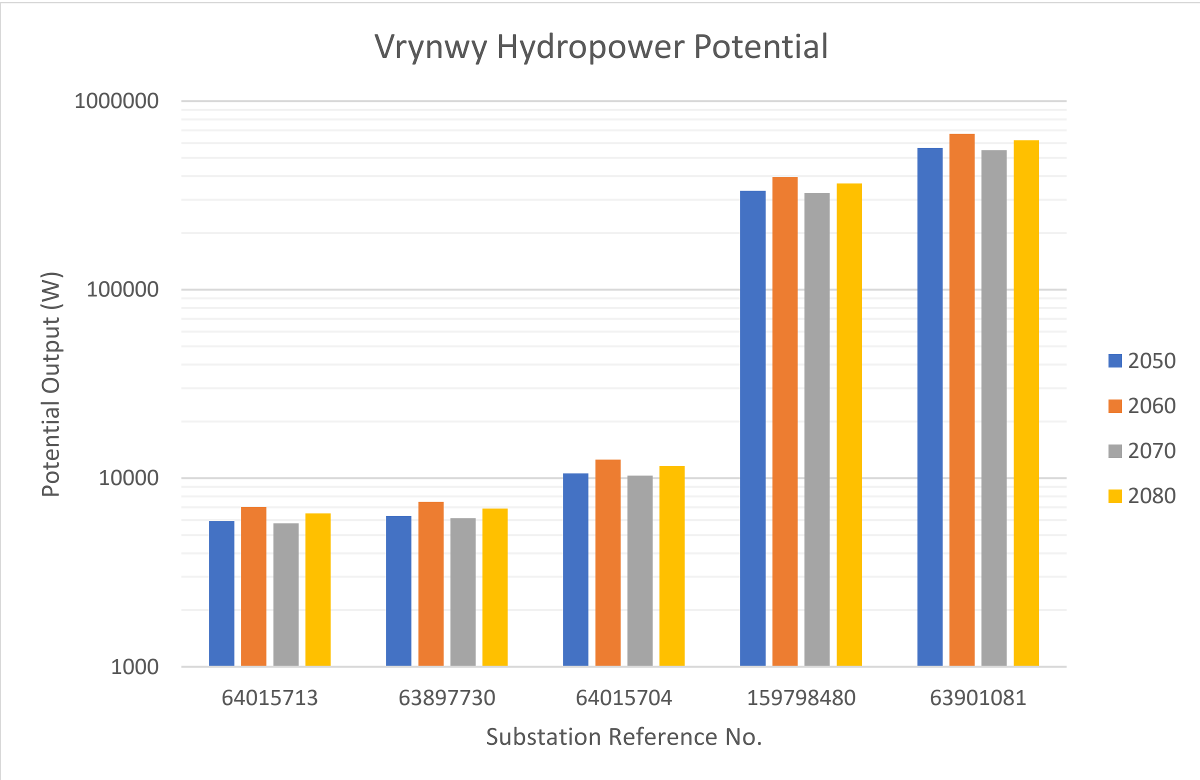

Fig. 24 - Histogram showing the variability of output in potentially viable locations within Vyrnwy catchment.

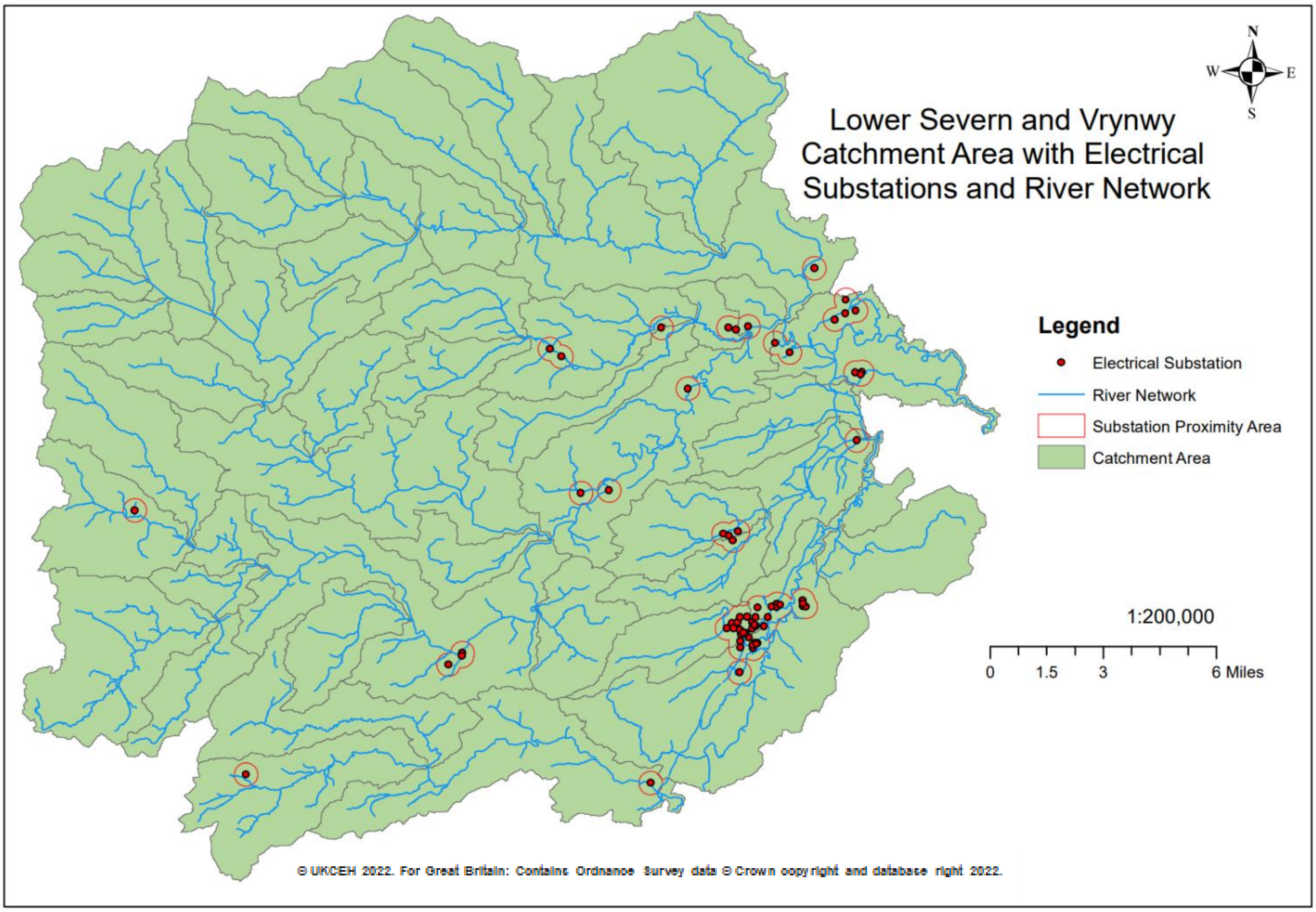

Fig. 25 - Visual representation of the spatial distribution of electrical substations in Vyrnwy catchment

	KGE Value			
	2050	2060	2070	2080
Alwen	0.41	0.38	0.39	0.42
Clwyd	0.32	0.36	0.34	0.35
Conwy	0.48	0.48	0.47	0.48
Dee	0.36	0.37	0.36	0.38
Dyfi	0.43	0.41	0.45	0.42
Severn	0.41	0.43	0.42	0.42
Vyrnwy	0.31	0.33	0.31	0.34

Table. 1 – Seen above are the KGE values for each catchment as when run in EXP-hydro.

The KGE values presented here demonstrate the goodness-of-fit of the modelled streamflow compared to observed values taken from CEH. The values presented were taken during the modelling process and for the given parameters they were the best KGE values possible, this was due to the number of runs being completed. Measures were taken to improve the KGE values. For example, the number of decimal places was increased and double checking of calculations for conversions. However, as seen in the values in table 1 the values are still what could be deemed 'sub-par'.

Here it is important to consider the work of Knoben, Freer and Woods (2019), discussing the inherent benchmark of using KGE for streamflow. The key observation from this work is that KGE cannot be considered on a perfect scale, such as Nash-Sutcliffe (NSE). Where NSE can be considered NSE = 0, the same catchment appeared to have KGE values of KGE = -0.41. Therefore, the understanding must be that values for KGE are considered differently. Thereby n this investigation of hydropower potential of catchments in Wales, although the KGE values for the modelled output appear low when comparing to KGE = 1 (the ideal value). The values could be considered viable for the purposes of this investigation.

These results were surprising and not the expected given the rigor put into the data management and the modelling process. One explanation for these results could have occurred during the parameterisation of the model. EXP-hydro model relies on the parameters such as min and max temperatures. The parameters for the catchments could have been beyond the physical bounds of the catchments causing several inaccuracies. To further this a repeat of the study could be used to check the results gathered here.

5 – Discussion:

This thesis aims to investigate the ability of EXP-hydro to simulate streamflow, using KGE as the validation tool for measuring performance. A secondary aim was to use simulated streamflow for the years 2040 to 2080 to calculate hydropower potential for seven catchments. The results of this investigation are not of the expected standard, when compared to other published findings. The KGE values range from 0.31 to 0.48, which are not an accurate outcome for modelling. Explanations for this outcome may lie in data management and/or inaccuracies in the modelling process due to oversimplification. However, the outcomes lead to limitations for the values and data generated in this investigation. The discussion section answers the research questions laid out at the beginning of this thesis:

1. Demonstrate the ability of EXP-hydro to simulate streamflow by using Kling-Gupta Efficiency as the benchmark validation tool.

2. How will climate change impact hydropower generation capacity in the seven catchment areas of Wales between the years of 2040-2080?

5.1 – Demonstrate the ability of EXP-hydro to simulate streamflow by using Kling-Gupta Efficiency as the benchmark validation tool.

This is a vital question as evaluation and validation of the hydrological model is crucial to the credibility of the research. Validation of the model allows for comparison of this study with earlier work. Then, once this is achieved, allows for the possibility that this research can be categorised and compared with other studies, as well as indicating future research opportunities. KGE is a criterion for validating hydrological models; it allows for cross-comparison of model performance without the necessity of the same model to be used. Modelling practices need a method for assessment, as these act as a 'measuring stick' from which hydrological models can be discussed and critiqued.

The conceptual rainfall-runoff model, EXP-hydro, calculates streamflow on a daily time-step, and treats a catchment as two storage buckets, through solving two differential equations (See Method section: 3.1 and 3.2.2). This concept was utilised in attempting to model streamflow for the years 2040 to 2080. To achieve this, the UKCP18 dataset was employed to accurately simulate streamflow. The validation methodology chosen was the Kling-Gupta Efficiency: an efficiency calculation evaluating goodness-of-fit of a hydrological model through assigning a value to the representation of three aspects of the Nash-Sutcliffe Efficiency of model errors. These aspects are correlation, coefficient of variance and correlation biases (Pool, Vis, and Seibert, 2018).

The output of the modelling process produced singular values for each year for the individual catchments. From extrapolated values, streamflow was calculated for each individual year from 2040 to 2080. These streamflow values were used to calculate hydropower potential for the entirety of each catchment, thresholds for distance from stream to electrical substation and minimum and maximum values for kW. This filtered the number of potential locations to 74.

Comparisons can be made between this investigation of streamflow with other studies using KGE, UKCP18 data in Welsh catchments. One such study with which significant comparison can be drawn is Dallison et al. (2021). This investigation modelled implications of climate change on streamflow and water quality for 2021 to 2080 for 5 catchments in Wales: the Clwyd, Conwy, Dyfi, Teifi, and Tywi. These catchments enabled Dallison et al to investigate a variety of land uses and soil types in this study. This study used the semi-distributed hydrological model Soil and Water Assessment Tool (SWAT). Similar to this thesis, Dallison et al. (2021) utilised UKCP18 data for simulating streamflow. Dallison et al. (2021), demonstrated a potential decline in average annual flows frin -4% to -13%. Futhermore, the study reports large variation in seasonal streamflow, comprising increases of up to 41% in spring and 52% lower flows in autumn (Dallison et al., 2021). The paper also reports an increase in high flow events in spring and an increase in the number of low flow events in autumn (Dallison et al., 2021).

Nonetheless, there are important differences between Dallison et al. (2021) and this thesis, namely the modelling approach and resolution of elevation data. Additionally, in an obvious sense, findings of the implications of climate change on streamflow differ. There are opportunities for common analysis as both studies investigate streamflow for the catchments, Clwyd, Conwy and Dyfi.

Results gathered in this investigation set out an optimistic view for the future of streamflow in the years of 2040 to 2080, compared with Dallison et al., (2021), which laid out a negative future for streamflow. This contrast could arise because of the severity of the climate projection that was used, which provides an explanation for the variability in streamflow. Dallison et al.'s (2021) investigation utilised the same RCP 8.5 data as this investigation. As both studies yield different outlooks for the future of streamflow, it is important to question the accuracy of the application of EXP-Hydro. Comparison of KGE values for both investigations reveals a distinction between them. Dallison et al., (2021) utilise the complex and higher variable demand of SWAT to simulate streamflow, generating KGE values in the range of 0.7-0.8. In this investigation, utilising EXP-hydro was only sufficient for KGE values ranging from 0.31-0.48.

The methodology was not chosen as an approach to redevelop calculation of hydropower potential. The methodology was chosen as a possible criterion in hydropower potential assessments. There is support for this methodology (Pandey et al., 2014; Hallouz et al., 2018; Dallison et al., 2021). Utilisation of KGE in this scenario does not indicate automatic generation of 'good' results. Possible reasons for lack of production in KGE values include data handling. This issue can arise due to an inability to remove extreme values from the calibration dataset. The failure to remove outliers from the calibration dataset would increase variance and the mean value. Consequently, this negatively impacts the accuracy of calibrations, which could be an issue in this investigation.

There are several papers that discuss the effectiveness or the influence KGE should represent on the value of the modelling process, most notably Knoben, Freer and Woods (2019). Their findings imply there is sufficient argument for what can be considered as credible, acceptable values when calculating efficiency of flows. Knoben, Freer and Woods (2019) interpret Kling-Gupta Efficiency (KGE) in the same way as NSE values, with the notion that negative or low values are 'poor' and positive or higher values are 'good' indications of model performance (Knoben, Freer and Woods, 2019). Unlike NSE, KGE does not have an inherent benchmark with which flows are compared. Based on the formation of KGE, there is no meaning to be derived from KGE = 0. Therefore, when using KGE for understanding mean streamflow, all model simulations exceeding $-0.41 < KGE \leq 1$ surpass the benchmark, meaning they can be considered viable data (Knoben, Freer and Woods, 2019).

Limitations of the chosen modelling approach:

The modelling approach taken in this investigation has points for improvement. One improvement is to minimise the number of aggregations. Aggregating is a method of combining values to represent a greater whole, resulting in loss of accuracy. In the methodology for this investigation, values for streamflow were aggregated from daily to annual values, which were calculated to provide annual hydropower potential. Then each value was amassed to provide decadal averages for hydropower potential. These aggregates of decadal hydropower potential are presented in the data chapters (See

Results section). Presenting decade averages creates an oversimplification of outputs from the modelling process and steps taken to calculate hydropower potential. The aggregation process reduces variability of any results, which reduces effectiveness and, in this case, relinquishes the purpose of using high resolution data.

A second improvement is making changes to the approach to removing inaccuracies in the modelling stage caused by utilising a single value to represent a large catchment area. In this study, single values represent large areas, such as the upper and middle Severn. Splitting the catchment into smaller areas would be a better method of simulating streamflow. This would have produced a greater number of data points for the catchment and meaning data would represent its characteristics with enhanced accuracy.

Thirdly, utilising a proxy for electrical transformers as access into the national grid would be helpful. This investigation made a compromise to achieve completion. This involved using electrical substations in place of a proxy for on-pole transformers. The electrical substations provided a simple solution to understanding locations of electricity distribution locations for the catchments investigated. However, community hydro-schemes use on-pole transformers as their connection to the national grid (Manitoba Hydro, 2022). This allows hydro installations to be adopted in rural locations compared to the immediate vicinity of housing areas. A potential complication of attempting to use transformer locations, particularly pole-mounted, is the difficulty of obtaining their precise location data. No dataset or data package to which the University had access demonstrated locations of pole-mounted transformers, so this information was not available to this study. Therefore, a proxy for transformers was created in the catchment areas that may not have been accurate, with consequences for subsequent accuracy of modelling data.

The creation of a suitable proxy required a significant amount of work, beyond the time constraints of the current project. A compromise, the use of electrical substations, was available in OS data. Using electrical substations limits coverage of rivers across the entire project. This means there are locations that could have been optimal locations for micro-hydro installations, which were missed. A proxy for transformers would increase coverage of the investigation and increase the estimates of Welsh hydropower potential.

A fourth limitation of the methodology used is the absence of hands-off flow, which is a factor used for setting the flow rate below and above which abstraction cannot occur (NRW, 2014). By using hands-off flow, an appropriate or adjusted value of streamflow would be presented. This could be an improvement on the methods presented. However, an adjusted value of wattage was calculated through the addition of a multiplication of wattage based on mechanical losses (Hatata et al., 2019).

5.2 - How will climate change impact hydropower generation capacity in the seven catchment areas of Wales between the years of 2040-2080?

Understanding the future generation capacity of rivers in Wales will be essential to realising the potential contribution run-of-river hydropower to the energy mix in Wales, thus aiding meeting of climate change targets set by the Welsh Assembly for 2030. The Welsh Assembly target is 70% of electricity generated by renewable energy sources (Welsh Assembly, 2017). Answering the question of how climate change impacts hydropower generation capacity offers an argument for inclusion of run-of-river hydro into the Welsh energy mix.

The Met Office in the UKCP18 outlines the future of rainfall in Wales as “not uniform”. This provides an uncertain outlook for hydropower developments. By 2070 UKCP18 stipulates a change in the sum of rainfall through the summer period, with a potential increase in the frequency of severe rainfalls yet a decrease in rainfall in total. UKCP18 predictions outline a decrease in rainfall within the range of -47% to +2% by 2070. In addition the winter season is predicted to produce an increase in rainfall, with projections estimating a range of -2% to +35%. UKCP18 describes an increase in seasonal extremes, including greater intensity of rainfall in the autumn and winter months (Met Office, 2018). This outlines the potential for the UK’s future seasonality, which may reduce to a two-season year: a wet and a dry season. This is especially evident in predictions for seasonal extremes and significant reduction in summer rainfall. Despite the effects of changes of rainfall on hydropower, this future will have implications for life in the UK.

The UKCP18 estimates for future rainfall are based on a two-degree increase in global mean temperature. This means the implications for hydropower generation in Wales is uncertain. As UKCP18 predicts dry months in the summer and an increased frequency of seasonal extremes, smaller rivers could be dry in periods. This means that micro- and small-scale hydro schemes would not generate meaningful amounts of electricity for periods of the year. However, an abundance of electricity generation would occur over the autumn and winter months as UKCP18 predicts a potential increase of +35% in rainfall by 2070 (Met Office, 2018). From utilising predictive datasets, future flows are predicted, which will be contentious, when considering abstraction of water resources for generation of hydroelectricity.

Catchments selected for this investigation suggest an uncertain future for generation capacity in Wales. The Alwen, Conwy, and Clwyd catchments provided the greatest KGE values, which suggests a reasonable assumption of the accuracy of their calculations for hydropower potential. There is a consensus between all three catchments that increased generation capacity will occur in the years 2050-60 followed by a fall-off for 2060-2070. In the Alwen and Conwy catchment areas, the model predicts 16% and 10% reductions respectively in generation capacity. Histograms for the three catchments how variability from one decade to the next.

Projections of future flows in academic literature flows a similar trend as that stated by the UKCP18 climate predictions. An important, recent study by Dallison et al. (2021), investigated the future of water availability in Wales for utilisation in hydropower and public water supply. This paper discusses the future of flows and the potential impact on abstraction. Similar to this study, Dallison et al., (2021) utilised a combined methodology for investigating future flows of two catchments in Wales, the Conwy and Twyi catchments. The hydrological model used was a semi-distributed version of the Soil and Water Assessment Tool (SWAT) on a continuous time-step. The study investigated the years 2021-2079. The calibration method utilised by Dallison et al., (2021) was the Particle Swarm Optimisation (PSO) for calibration of the modelling process and KGE for goodness-of-fit. The output of the modelling process regarding hydroelectricity found a total of 16 sites in the Conwy catchment, which compared to this assessment, found 14 sites in Conwy, with nine in the Twyi catchment. Over the investigation period of 2021-2079, Dallison et al., (2021), demonstrate a trend of overall decreases in annual abstraction for mid-term and long-term predictions. Dallison et al. (2021) outline a future of fewer days of potential abstraction for hydro schemes but greater abstraction volume on those days, which overall led Dallsion et al. (2021) to conclude a lower rate of hydroelectric output will occur in the future.

The results of this investigation into seven catchments in Wales, albeit not the most accurate, fall in line with expectations of uncertainty for future generation capacity of micro-hydro and small-scale hydropower (Dallison et al., 2021; Kay, 2021).

Although UKCP18 demonstrates and outlines implications of GHGs on the environment, there is an important aspect of understanding how population changes and expansion of urban areas will impact water resource availability (Hoekstra et al., 2018; Alamanos et al., 2020; Dallison et al., 2021). It is widely expected that human populations will increase over time. This increase will inevitably create demand for greater amounts of electricity, for which hydropower could be a potential solution. However, increases in population will generate pressure on available resources (Bildirici and Gökmenoğlu, 2017; Hoekstra et al., 2018; Alamanos et al., 2020). This includes the natural expectation that larger populations will lower river flow and by extension hydropower capacity of run-of-river schemes. This raises the question of the suitability of run-of-river hydro schemes as a potential source of renewable electricity. Construction of impoundment schemes, mentioned in the literature review, would solve multiple issues simultaneously. Impoundment schemes generate great amounts of electricity while acting as water storage for meeting the joint public demand of water and electricity (Berga, 2016; Zarlf et al., 2019).

6 - Conclusion

It is important to consider the effectiveness of EXP-Hydro in this study and if the outcomes warrant further work. The project set out to answer research questions stated previously through the means of presenting meaningful data. This is partially achieved. Data presented allow for understanding the future of hydropower in seven catchments, but limitations to the method or with the available data led to inaccuracies. Hence, results of this investigation are unclear.

Patil and Stieglitz (2014) suggest that EXP-Hydro may be an effective tool for simulating streamflow. However, little evidence exists in wider literature of its utilisation to achieve effective simulations of streamflow. Utilising EXP-Hydro in this study shows issues with validation of modelling practices. The KGE values for this investigation, which ranged from 0.31 to 0.48, are low compared to other studies following the same methodology.

Using a conceptual model is sufficient for estimation of streamflow, but a more complex approach may be required for greater in-depth assessment. Conceptual hydrological models are convenient because they provide short computational times and easier data handling, because fewer variables are involved. Conceptual models provide accurate estimations, but in this case issues with data normalisation led to inaccuracies of simulated streamflow. A more complex modelling approach such as a semi-distributed model would require much more computational time and significantly more data input. However, the added complexity of including more variables would have permitted a much more robust simulation of streamflow.

In conclusion, further investigation to assess the suitability of EXP-Hydro to simulate streamflow is worthwhile. There is significant potential for models with the ability to simulate ungauged catchments, but for the purposes of improving this investigation, allowing additional computational time would ultimately have been a small price to pay to achieve a robust modelling approach.

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Appendix:

Appendix 1 – python script for extracting data from NetCDF files to txt file type.

```
infile = #input NetCDF
outfile = #output to new data

# Reading the NetCDF file
dst = xr.open_dataset(infile)

# Co-ordinates of your pixel; remember to change for each grid
x1 =
y1 =

#Extract the data for the chosen pixel
fp=dst.pr.sel(projection_x_coordinate=x1,projection_y_coordinate=y1,method='nearest')
pcp = fp.values
pcp1 = np.transpose(pcp)
pcp2 = pcp1*86400 # for converting Precip
pcp3 = (pcp1-273.15) # for converting temp
#Writing the data
np.savetxt(outfile, pcp1, fmt='%.9f')
```

Appendix 2 – Exp-hydro single run version

```
# Programmer(s): Sopan Patil.

""" MAIN PROGRAM FILE
Run this file to perform a single run of the EXP-HYDRO model
with user provided parameter values.
"""
import statistics
import datetime, pyeto
import numpy
import os
import matplotlib.pyplot as plt
from exphydro.lumped import ExphydroModel, ExphydroParameters
from hydroutils import ObjectiveFunction
from pyeto import thornthwaite, monthly_mean_daylight_hours, deg2rad

######################################################################
# SET WORKING DIRECTORY

# Getting current directory, i.e., directory containing this file
dir1 = os.path.dirname(os.path.abspath('__file__'))

# Setting to current directory
```

```
os.chdir(dir1)

##########################################################################
# MAIN PROGRAM

#Load meteorological and observed flow data

P = numpy.genfromtxt('P_test.txt') # Observed rainfall (mm/day)
T = numpy.genfromtxt('T_test.txt') # Observed air temperature (deg C)
PET = numpy.genfromtxt('PET_test.txt') # Potential evapotranspiration (mm/day)
Qobs = numpy.genfromtxt('Q_test.txt')  # Observed streamflow (mm/day)

# Converting Discharge from m3/s to mm/day

Qobs = ()*1000.0*60.0*60.0*24.0


# Initialise EXP-HYDRO model parameters object
params = ExphydroParameters()

# Specify the parameter values
# Please refer to Patil and Stieglitz (2014) for model parameter descriptions
f =
smax =
qmax =
ddf =
mint =
maxt =

# Assign the above parameter values into the model parameters object
params.assignvalues(f, smax, qmax, ddf, mint, maxt)

# Initialise the model by loading its climate inputs
model = ExphydroModel(P, PET, T)

# Specify the start and end day numbers of the simulation period.
# This is done separately for the observed and simulated data
# because they might not be of the same length in some cases.
simperiods_obs = [365, 3285]
simperiods_sim = [365, 3285]

# Run the model and calculate objective function value for the simulation period
Qsim = model.simulate(params)
kge = ObjectiveFunction.klinggupta(Qobs[simperiods_obs[0]:simperiods_obs[1]+1],
                                   Qsim[simperiods_sim[0]:simperiods_sim[1]+1])
print('KGE value = ', kge)
```

```
# Displaying averages for each year

a = statistics.mean(Qsim[366:730])
b = statistics.mean(Qsim[731:1095])
c = statistics.mean(Qsim[1096:1460])
d = statistics.mean(Qsim[1461:1825])
e = statistics.mean(Qsim[1826:2190])
f = statistics.mean(Qsim[2191:2555])
g = statistics.mean(Qsim[2556:2920])
h = statistics.mean(Qsim[2921:3285])

print ('Mean for 2031 =', a)
print ('Mean for 2032 =', b)
print ('Mean for 2033 =', c)
print ('Mean for 2034 =', d)
print ('Mean for 2035 =', e)
print ('Mean for 2036 =', f)
print ('Mean for 2037 =', g)
print ('Mean for 2038 =', h)

#print ('Hargreaves =', C)

# Plot the observed and simulated hydrographs
plt.plot(Qobs[simperiods_obs[0]:simperiods_obs[1]+1], 'b-')
plt.plot(Qsim[simperiods_sim[0]:simperiods_sim[1]+1], 'r-')
plt.show()

numpy.savetxt()
numpy.savetxt()

#########################################################################
```