Climate change mitigation: Learning from the past to unlock the hydropower potential of the Derbyshire Derwent catchment.

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Thesis submitted to the University of Nottingham
for the degree of Doctor of Philosophy
Environmental Geography (Science)

School of Geography

September 2024

Abstract

For Derbyshire communities seeking climate change mitigation opportunities, the hydropower (HEP) potential of the historic water-powered textile mills of the Derwent Valley Mills World Heritage Site (DVMWHS) is an obvious starting point. Waterpower is a core story of the DVMWHS, in the heart of the Derbyshire Derwent catchment (DDC), but there is limited understanding of how the early industrial watermill owners overcame the natural and man-made challenges they faced, many similar to those faced today. This research aims to improve our understanding of the harnessing, management and use of waterpower, particularly during the Georgian period, to identify what lessons we can learn to repower the remaining HEP opportunities on revitalised DDC waterways, supporting our climate change mitigation efforts.

DDC waterpower sites, by waterway, were identified using historic OS maps and a gazetteer created. Individual watermill timelines were produced, capturing each mill's use, power and water management development. The gazetteer included historic mills, non-mills (e.g. Chatsworth House) and man-made water sources for power (e.g. lead mine drainage soughs). External factors were also considered, capturing the wider impacts of political, economic and legislative changes on 'milling power' over time.

Historically, government support has been critical for waterpower, with parliament repeatedly listening to the industrial watermill owners, protecting their milling power, including in the *Salmon Fishery Act* (1861). However, run-of-river (small) HEP collapsed in the 1950s-70s, with the government focussed on building the fossil-fuelled electricity grid, and the newly formed water authorities charging the mills for 'borrowing' water for power. From the 1990s, the climate change driven need for renewable energy saw a mini revival in small HEP, but the ending of government subsides supporting small, local, renewable energy in 2019, paused this.

This research uncovered the millowners' wider influence on river stewardship, using the mills' weirs, floodgates and sluices to control the waterways, including flood management, maintaining fisheries and river morphology, issues critical to HEP development today. Following the closure of run-of-river HEP from the 1950s, many weirs, floodgates and sluices were no longer used or maintained, and today are viewed as redundant barriers by river ecologists. Much of this infrastructure remains, providing historic watermill sites with an opportunity to be repurposed as green power stations, and to play a role in current river stewardship challenges, as they did in the past.

Acknowledgements

I would like to take this opportunity to thank the many individuals who initiated and supported my passion for communities repowering historic watermills, acting locally to help tackle the global challenge of climate change, which ultimately led to this research project. Craig Scott's invitation to the Transition Belper community group, led to the question 'are Belper's Mills producing renewable energy?' Adrian Farmer (Derwent Valley Mills World Heritage) and Jon Needle (Derwent Hydroelectric Power) answered the first question, yes, but ignited my interest and raised further questions, leading to many years of research and projects, culminating in this PhD research at the University of Nottingham.

I must thank, my fellow directors, Richard Keighley and David George for their efforts in setting up Amber and Derwent Valley Community Energy, to try to deliver the Ambergate Hydro community energy project, Kate Gilmartin (community hydro) and Olly Paish (hydro expert), who have continued to be a sounding board throughout my research and Pauline Latham, my local MP, who, interested in repowering the Derbyshire mills, has facilitated access to ministers. There are too many researchers in the Derbyshire Derwent valley, and holders of archives (especially the Derbyshire Record Office team), to thank individually, but three I must mention are Alan Gifford who so willingly, and ably, shares his mill knowledge and continues to inspire, Rosemary Annable who repeatedly asked my favourite question 'is this of interest?' and finally Joan d'Arcy who I was only fortunate enough to meet once, who first encouraged me to talk to a university about formalising my research.

I am indebted to Susanne Seymour, my primary supervisor, who took the 'risk' of encouraging and facilitating my PhD, despite my having left academia (polytechnic) 35 years earlier. Susanne also encouraged me to apply for the AHRC funding, which removed some of the concerns about spending retirement funds and allowed trips, book purchases and visits, that would not have taken place without the much-appreciated M4C support. Steve Dugdale, my second supervisor, showed interest and support in my research from day one, despite sometimes conflicting interests his area of expertise. I have been challenged academically, especially during the covid years, so I must acknowledge the efforts and patience of both supervisors through my struggles with the process, and their constructive criticism that helped to develop the thesis in its current form. Throughout my research the School of Geography team have shown interest and support, especially Professor Charles Watkins in our annual reviews.

In hindsight, my approach to the research and thesis has been heavily influenced by the workplace training and development I received by supportive managers throughout my 25 years working, as a chartered mechanical engineer, in metal packaging manufacturing, including the lean six sigma (black belt) development programme, and the following 10 years as an independent lean and green business improvement consultant.

The one solid rock and inspirational supporter of my ‘passion project’ is my wife, Helen, who I do hope is as genuinely interested in the research as she acts, who encouraged me to give up the day job and follow this path, and then offered every form and level of support possible (including listening to my ideas and proof-reading every word written). I promise that we will go on a holiday and not accidently discover a watermill or hydroelectric power generator at some point in the future. My final thank you must be for our much-missed Blade, my home study companion who took me for much needed, reflective, walks during those challenging Covid years.

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Chapter 1 Introduction

1.1 Context

The Derbyshire Derwent Valley Mills site 'is significant for its pivotal contribution to the development of the modern factory system and the workers' communities that grew alongside the mills in the late 18th century' (D Wilson [Historic England] cited in Knight, 2016 6), and was inscribed as a World Heritage Site by UNESCO in 2001. It was the development of the water-powered cotton spinning mill at Cromford, Derbyshire in 1771, by Richard Arkwright and his partners Jedediah Strutt and Samuel Need, powered by a lead mine sough (drainage channel) to directly drive his water spinning frame, that led to the development of the 'Arkwright system', a new efficient and profitable model of mass manufacture, which was replicated hundreds of times before the end of the century (Fitton and Wadsworth, 2012, Newman, Rodríguez et al., 2018, Strange, 2008). The Arkwright system substituted capital for labour, machines for skill, factory for home and mill discipline for family work routines (Jeremy, 1981). The '*Derwent Valley Mills World Heritage Site (DVMWHS) Management plan (2020-2025)*' states that 'one of our core stories is the use of waterpower to mass produce cotton – the first mechanised mass production of any commodity in the history of the human race' (DVMWHS, 2020 4), at the heart of the Derbyshire Derwent catchment (DDC).

This research improves our understanding of the core story of waterpower and the wider impacts of the industrial watermill owners on the river. It addresses the problem that, despite the current urgent need to decarbonise the electricity supply network, as 'We are dangerously close to tipping points at which climate chaos could become irreversible' (Guterres, 2022), hydroelectric power (HEP) reinstatement and development in the UK has stalled (Needle, 2020) due to the lack of ongoing financial certainty and difficulties in obtaining environmental licences, grid connections and planning permission (Wilson, Day et al., 2022). 'As we seek out new power alternatives, we believe we have an important message: when it comes to providing the world with a carbon-free, inexhaustible power source, the Derwent Valley shows that you don't have to reinvent the (water) wheel' (Chair of the DVMWHS partnership, B Lewis, cited in DVMWHS, 2020 4).

In the late 19th century many mills converted their waterwheels that provided mechanical power to turbines, to 'self-generate' hydroelectricity for electric lighting or power. The number of sites self-generating electricity reduced significantly in the mid-20th century in the UK, with the leading UK HEP turbine manufacturer, Gilbert Gilkes & Gordon Ltd, reporting that by the 1960s their business relied on exports to survive, following the establishment of the national grid (Slee, Whitfield et al., 2011, Wilson, 1974).

The UK's response to the threat of climate change led to a mini revival in HEP development (1990 to 2018), as the government introduced a series of fiscal incentives supporting renewable energy, decarbonising the electricity generation industry (Needle, 2020, Walker, 1997, Woods, Tickle et al., 2010). Removal of one subsidy, Feed in Tariffs (2010-2019) that supported small-scale renewables, led to HEP deployment across the UK (Figure 1.1) halting, including at least three projects in the Derbyshire Derwent catchment. References to current UK government policy in the thesis reflects the research being completed during the term of the Conservative government, 12 December 2019 to 4 July 2024.

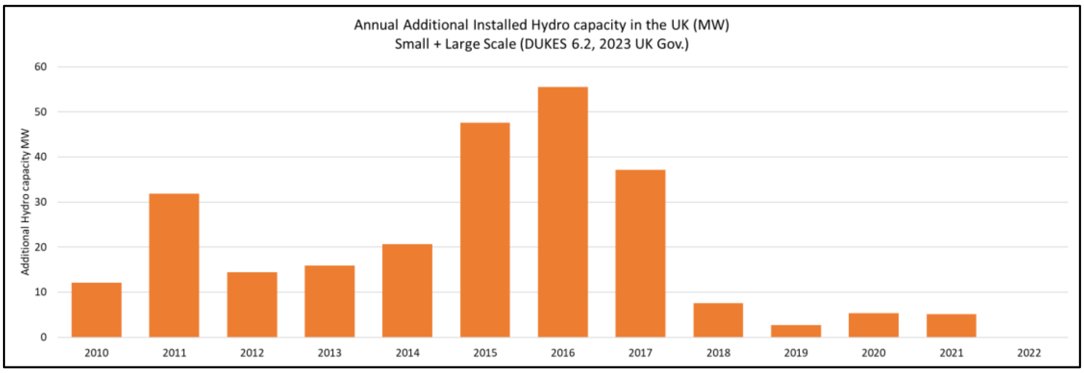


Figure 1.1 UK Hydropower additional installed capacity (2010 to 2020) DUKES 6.2 (DESNZ, 2023)

For three generations (1770-1830), water was the primary fuel that powered the Industrial Revolution, enabling the transition from domestic to factory manufacturing systems (Chapman, 1971). Suitable locations to build industrial water powered factories were at a premium and by 1818 'Upon most rivers in this country [England] all the falls of water are fully occupied, and at every mill there is a weir which pens up the water as high as the mill above can suffer it to stand without inconvenience' (Cossons and Rees, 1972 V.5 363, Getzler, 2004).

A common misconception is that steam replaced water to power industrial mills during the 19th century (Hannah, 1979, Reynolds, 2006, Wilson, 1957). It wasn't until the mid-1830s that steady improvements in steam engine design and construction produced an engine whose motions were as consistently smooth as the water wheel, making the two sources of power economically interchangeable, dependant on location and resource (e.g. water or coal) availability (Chapman, 1971 12). However, whilst steam became the primary power source across the country, especially in regions such as Lancashire (Phelps, Gregory et al., 2016), industrial watermill owners and innovators, such as the Strutts of Derbyshire, continually improved the harnessing of waterpower throughout the 19th century (Hills, 2008 141), with steam added to the waterpower baseload in a hybrid arrangement, to meet additional demands for power. The need to optimise the power from the water available led to challenges and conflicts for watermill owners; with other watermill owners, competing water abstractions, neighbouring communities, navigation and those with fishery interests.

The industrial watermill owners invested significantly in their waterwheels, weirs, floodgates, sluices, channels, tunnels and controls to harness the 'free fuel' (Hills, 2008 30). These historic waterpower attributes help define the outstanding universal value (OUV) of the DVMWHS (DVMWHS, 2020). In addition to the generation of renewable energy, the restoration of waterpower in historic mills can contribute to and promote cultural heritage and social activities, and improve local economies (Hognogi, Marian-Potra et al., 2021, Quaranta, Aggidis et al., 2021), sometimes exceeding the value of energy generated (Punys, Kvaraciejus et al., 2019 1108). Historic England (HE) studied the threats and opportunities of the wider watermill landscape, including weirs, dams, sluice-gates, leats and ponds, that ranged from global (e.g. climate change) to local (e.g. development) (Alexander and Edgeworth, 2018). Within the DVMWHS, of the six major weir complexes, five are associated with the main river Derwent and one with a tributary valley (the Cromford Mill basin weir), with the most important of these weir structures having grades II or II* listed building status (Howard, Coulthard et al., 2017 40). Today, the Environment Agency (whose duties include the regulation of rivers) identifies the industrial revolution weirs as a major cause of the decline of migratory fish in the wider Trent catchment (including the Derbyshire Derwent catchment) (Brailsford, 2016). Driven by the Water Framework Directive (WFD), the heritage structures are under increasing pressure to be modified (installing fish passes) or removed altogether (Alexander and Edgeworth, 2018 48, Howard, Coulthard et al., 2017). The Historic England study makes no reference to the opportunities afforded by reinstatement of the waterpower assets regarding climate change mitigation, or the river management (e.g. flood management) provided by the watermill landscape owner, instead, viewing the development of HEP at a historic watermill site as a potential threat.

Cowx and O'Grady (1995) found evidence of salmon in the Trent and its Derbyshire tributaries, the Dove and the Derwent, up to the mid-19th century. They concluded the salmon stock was lost mainly because of pollution and the building of large weirs (Cowx and O'Grady, 1995 70). However, by the start of the 19th century most of the 'industrial revolution' weirs were already built, suggesting that for several generations, the watermill and weir owners were able to facilitate fish passage. The discovery by Belper North Mill researcher Rosemary Annable, of an 1817 report describing the Strutts' weirs at Belper and Milford, suggests some industrial weirs (including all the downstream weirs of the Trent and Derwent) had facilities to enable salmon migration c.1800 (Section 3.5.3.1). Many of the watermill assets are still in place and may offer an opportunity to generate HEP and improve fish migration through the catchment's waterways today.

In 2016 the '*DVMWHS Research Framework'* was developed (Knight, 2016) to help identify the gaps in our understanding of this period. This research will improve our understanding of framework Agenda Theme 4 (The low-carbon industrial revolution) and research objectives, 8D (Investigate the harnessing of hydropower from rivers in the Derwent catchment and the reconciliation of competing interests) and 10C (Investigate the impact of human modifications to the hydrological landscape of the Derwent Valley and identify strategies for improved water management). The outcome could also form the basis of strategic objective 11D (Investigate the potential to develop the Derwent Valley as a model for the development of sustainable low-carbon economies). The research touches on many other aspects and identifies further gaps in our knowledge, such as the chronology, engineering design, function and impacts of the many weirs along the length of the River Derwent. The use of waterpower in the earlier lead mining industry, including the use of sough (mine drainage) waters, still flowing, overground and underground is also a gap in our current knowledge.

1.2 Aims and objectives

Faced with today's challenges of climate change, the ecology crisis and water security concerns, the question this research seeks to address is, are there lessons we can learn from the last 250 years of waterpower usage to help the unlock the hydroelectric power (HEP) potential of the Derbyshire Derwent catchments (DDC) sustainably, along with that of other similar catchments across the United Kingdom?

The overarching aim is to identify and understand what we can learn from how the early 'factory masters' harnessed waterpower so successfully during the second half of the Georgian period (1771-1837). The research also investigates the issues that caused the decline in the use of waterpower post WWII, identifying the common causes that are preventing HEP development today. My research looks to develop a collaborative approach to HEP development, to overcome the current challenges faced, unlocking the river's power potential using a replicable, sustainable, approach to generate hydroelectric power, mitigating climate change, on revitalised waterways.

This overarching aim will be achieved via the following research objectives:

1. Understand the key success factors that enabled the early industrialists in the DDC to develop mass production factories, powered by industrial scale waterpower, despite being faced with challenges similar to those we see today, (water-rights, floods, drought, impact on local communities, alternative power sources and fisheries).
2. Identify the main cause(s) of the 20th century decline in waterpower use to generate electricity, despite the apparent availability of 'free' fuel from the rivers.
3. With the current stagnation in HEP development, deduce the lessons to be learnt from the past, including the recent 1990 - 2019, mini revival in HEP generation.
4. Assess the hydroelectric power potential of the DDC and wider Derbyshire area utilising the information collated during this research, including past and present waterpower application and generation.

1.3 Literature review: Waterpower discourse

1.3.1 Power

Waterpower, and more recently hydroelectric power (HEP), reigned as the most significant prime mover for around 1,500 years (Vince, 1985), up to c.1830 (Chapman, 1971). Over this time, it has proven to be a reliable source of energy (Brown, 2011, Munro, 2002, Reynolds, 2006, Wilson, 1972). Waterpower has played a significant role in the development of civilisation, with Forbes (1995) identifying five phases of technological advancement: human muscle; human and animal power; waterpower; steam power; and the nuclear age (cited in Brown, 2011 12), published before the low carbon energy phase. Watermills played an important role in communities, whether they were resident-run, built within the fortifications of a castle, within the grounds of an abbey and grange or were the Lord's manorial mill that tenants were obliged to use to raise an income for the manor (Brown, 2011 20, Watts, 2000). With each community harnessing the power from their local waterways, there remain thousands of historic waterpower sites, many with weirs still in place.

1.3.1.1 Pre-18th century waterpower

The 1086 Domesday survey identified approximately 6,000 watermills in England, with 98 mill sites identified in Derbyshire (Morris, Morgan et al., 1978). The survey examined villages, so the exact location of mills is not known; for example the land including Duffield, Bradeli (Belper), Holbrook, Milford and Makeney in Derbyshire had two watermills (ibid). Communities harnessed the power of water for a variety of applications, primarily corn mills originally (e.g. Mill in Bonsall Dale, Figure 1.2) (Vince, 1993), but also industrial use, such as rolling and slitting mills, as used during the 16th century in Makeney (Figure 1.2) (Donald, 1961).

Understanding the power capacity of the early mills is difficult, nonetheless, it is possible to estimate power usage retrospectively by looking at the application and use of the power, e.g. the number of mill stones driven in a corn mill (2 to 5 HP [1.5 to 3.7 kW]) (Vince, 1993), or 1,000 spindles driven in a cotton mill (10 HP [7.5 kW])

(Chapman, 1971 6, Hills, 2008). Whilst the power levels appear low today, 1 to 3HP (0.8 to 2.2 kW) in a small corn mill would have liberated anywhere from 30 to 60 persons from the laborious task of grinding grain into flour (Munro, 2002 230).

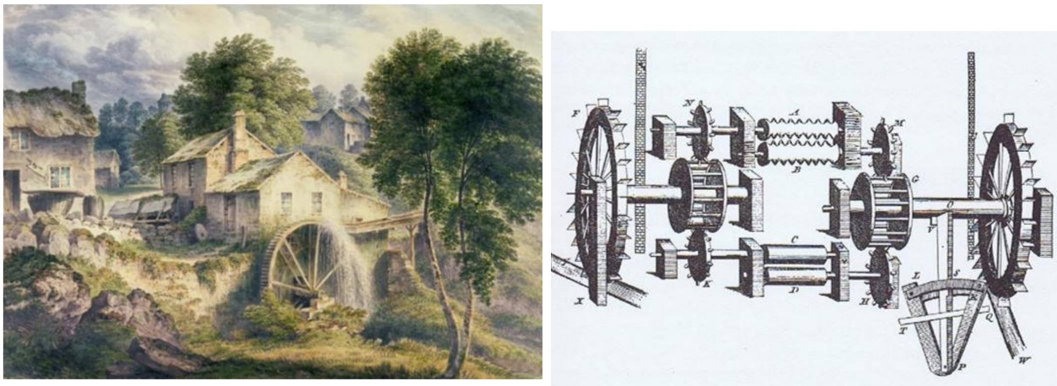


Figure 1.2 Typical corn (J Glover, date unknown) and industrial (slitting) mill found in the DDC pre 18th century (Emerson, 1758 Plate XX).

Medieval mills overcame the challenges of intermittent water supplies by using mill ponds and sluices for power control, when grinding was to be done, rather than relying on the flow of the stream. Collecting water in a mill pond overnight also effectively doubled the power available during the day. Early watermills' ability to harness power was limited by the wooden construction of the water wheel, gears and shafts, and the wheel design, typically undershot adjacent to the watercourse (Figure 1.2 right), or overshot, when water could be conveyed using an aqueduct from a water source with a higher head (Figure 1.2 left) (Wilson, 1955 25). Having harnessed the power of the water the sites could be used for multiple, seasonal applications, such as corn and fulling (Watts, 2000), corn and paper (Hickling, 1964) or paper and forge (Alexander and Edgeworth, 2018). Mills located on smaller streams could only work part time, when sufficient water was available, such as the seasonal 'winter mills' (Brown, 2011).

1.3.1.2 18th and 19th century waterpower

Waterpower became critical as the industrial revolution gathered momentum (Reynolds, 2006). The first British civil engineer, John Smeaton (1724-1792), realised it was wasteful to use inefficient waterwheels and, as a trained mathematical instrument maker, built models to carry out scientific experiments (Figure 1.3). Smeaton read two papers to the Royal Society in 1759 and was awarded a gold medal for the 'most masterly' report ever published on the subject (Smiles, 1891 94): *An experimental Enquiry concerning the natural Powers of Water and Wind to turn Mills, and other Machines, depending on circular Motion*, J Smeaton FRS, was read on May 3 and 10 1759 (Wilson, 1955). Many future developments, including what was to become standard in industrial watermills, the Breastshot Wheel, were derived from his study (Lewis, Cimbala et al., 2014). John Smeaton also first introduced the use of iron for water wheel shafts in 1769 (Wilson, 1955).

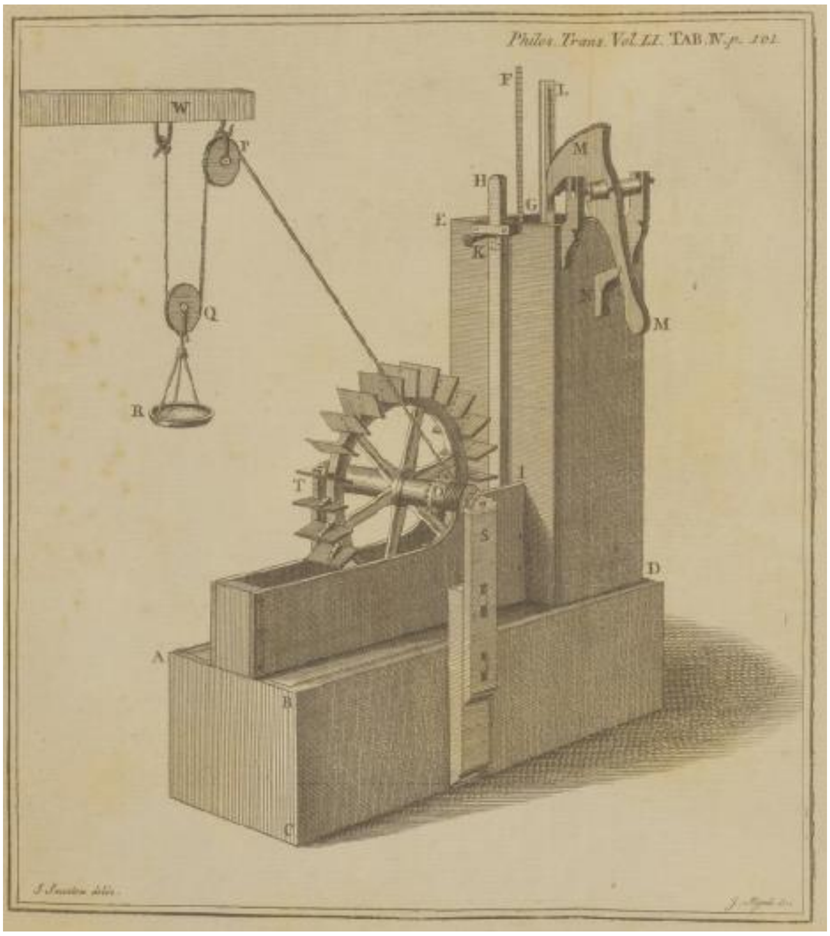


Figure 1.3 Plate showing the machine for experiments on waterwheels. (Smeaton, 1759 101)

Following the development, patenting (1775) and licencing of the 'Arkwright Cotton Spinning System' in Cromford, Derbyshire, there was a dramatic growth in industrial watermill development (including converted or rebuilt corn mills). Compared to 10 to 15 Arkwright Type mills in 1780, a total of 124 water-powered cotton mills were recorded in England and Wales by Colquhoun in 1787, a number revised up to 182 in a later study (Chapman, 1981 8). Mills with Arkwright licences were built in units of 1,000s of spindles (Chapman, 1971), with output being dependant on the waterpower available. The expansion of the cotton industry is indicated by the raw cotton import figures, with imports rising from 6 million lbs in 1775-6 to 621 million lbs in 1849-50, when the UK possessed 60% of the world's cotton-factory spindlage (Maw, Wyke et al., 2012).

After Arkwright's first water powered cotton mill (1771), similar mills quickly developed in England, France and slightly later in the US (Viollet, 2017). In Pawtucket, North America, conflicts arose between the mill owners, including with the new industrial cotton spinning mill weirs built in 1792 by Samuel Slater (Kulik, 1985), a former apprentice of the Strutts in the Belper and Milford Mills, Derbyshire. With his knowledge of cotton spinning gained in his six-year apprenticeship with the Strutts (1783-1789), Slater became the 'Father of the American Industrial Revolution' (as referenced by President Andrew Jackson) (Peake, 1982 125, White, 1836).

Waterpower innovation continued to meet the additional power requirements of the growing industries and site expansions in the late 18th and early 19th centuries (Reynolds, 1984). Buchanan (1823) recorded the transition from the use of timber shafts to cast-iron in millwork, largely due to the cotton industry: 'After Arkwright's invention, it became a great object with them to save time in the erection of machinery, and to render it as durable as possible; for every stoppage was attended with great loss, by throwing idle the numbers of people necessary in cotton mills' (Buchanan and Tredgold, 1823 252).

The introduction of cast iron created a new era in the history of mills, with the material significantly increasing the productivity of Great Britain (ibid 254). The iron suspension wheel came at a time of cost-effective iron production and competition from the alternative energy source, steam (Hills, 1970, Rees, Blake et al., 1819, Reynolds, 1983, Wilson, 1972). Its development and associated infrastructure, such as the close-fitting stone apron, first installed in the Belper mill complex c.1808 (Section 3.2.2.2), allowed a maximum power per wheel increase from around 40 hp

(30 kW) to 200 hp (150 kW) (Smith, 1969). The potential power in the river became the constraint, rather than the waterwheel and transmission systems. It was the introduction of light wrought iron rods, acting like spokes (Wilson, 1972), with power take off from edge of the wheel, rather than the axle, that allowed a much lighter, efficient wheel to be constructed. The wheels were described as remarkable for their simplicity, strength and lightness of appearance (Glover and Noble, 1833).

Rees's thirty-nine volume Cyclopaedia of 1819 (Cossons and Rees, 1972) included many references to the work of William Strutt in harnessing and controlling waterpower in the Belper Mills, such as the governors familiar on steam engines, to control the large wooden and then iron waterwheels, during this period of industrial growth (Manufacture of Cotton [Vol. 22], Mill-Work [Vol. 23], Water [Vol. 38] and Plates 2, 3 and 4, [Rees, 1819]). An investigation into the work of T C Hewes, the Manchester engineer who built and installed the first iron suspension wheel in Belper, discovered activity across several textile mill clusters, including the Derbyshire Derwent Valley, working with the Evanses at Darley Abbey and Arkwright at Bakewell (Figure 1.4), as well as exporting one suspension wheel to the US (Smith, 1969). The design of waterwheels in the early US textile mills was also influenced by the Strutts' work on waterpower, with Slater's mill at Pawtucket, erected in 1793 using a breast wheel (Reynolds, 1984 69), and 'the unprecedented axial alignment at Lowell' (suspension wheels side by side) that may have been influenced by Francis Cabot Lowell visiting Belper (visited Britain 1810-12) (Reynolds, 1984 74). The plentiful access to rivers and timber (for water wheels) (Kulik, 1985) meant the US adoption of the iron suspension wheel was very different to Britain.

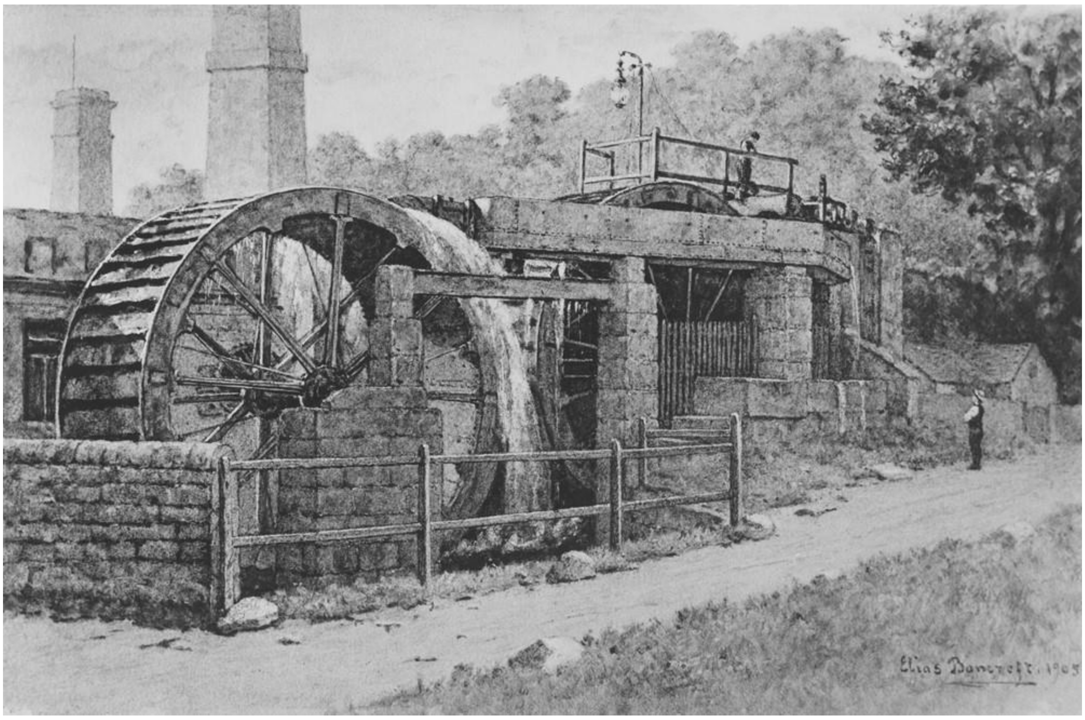


Figure 1.4 Two iron suspension wheels, Lumford Mill, Bakewell, Derbyshire. 1827 Wren and Hewes (rear) and 1852 Kirkland of Mansfield (front) water wheels (Picture the Past DMAG000291, 1905).

Whilst there is no data for Britain as a whole, a number of individual river studies show a saturation of mills on British streams between 1750 and 1850 (Reynolds, 1983). Over 200 reported cases of waterpower overcrowding litigation between 1770 and 1870 were identified by Getzler (2004). One example of 'congestion' was the River Leen in Nottinghamshire, a 12 mile (c.19 km) 'sluggish' stream that had 17 mills in 1784 (Reynolds, 1983, Walker, 2017). By 1789 there were complaints that the flow of the River Leen was unpredictable due to the numerous mills and water works on it (Walker, 2017). Increased congestion of water users along English rivers saw a return to a land-based principle of water law, similar to that which had governed water use in medieval England, but which had become obsolete by the beginning of the seventeenth century (Scott and Coustalin, 1995). Similarly, in Scotland, the period 1730–1830 has been described as the age of waterpower and, in addition to the longstanding milling of grains and sawing of timber, new industries, especially textiles, mineral processing and paper making, led to the water-side construction of large numbers of new water mills, with over 850 historic waterpower sites in Aberdeenshire (Shaw, 1984, Slee, Whitfield et al., 2011). By the late 18th century three areas with suitable water resources became major industrial regions; the midlands (Birmingham, Nottingham, Sheffield and Derbyshire); central Scotland (Glasgow, New Lanark, Paisley and the Clyde Valley) and southern Lancashire, including Manchester (Getzler, 2004). A project recording the historical journeys of British rivers is capturing all post-1750 watermills and their original purpose(s). As of May 2024, 12,185 commercial and farm watermills had been recorded on the 51 British rivers researched (Robertson and Robertson, 2024), but not including the Derbyshire Derwent.

1.3.1.3 Steam Power

Steam engines were erected to pump water from coalmines as early as 1712 (Trinder, 2013) and by the mid-18th century steam engines were a common sight in coalfield and ore-mining regions, such as Cornwall and the lead mines of Derbyshire (Trinder, 2013, Willies, 2004). During the 18th century 871 steam engines (40% of the total) were being used to pump water from mines (Kanefsky and Robey, 1980). Newcomen steam engines were used in 1743 to pump water that had passed over the water wheels at Abraham Darby II's ironworks, back up to the mill pond (Trinder, 2013), applying steam power to indirectly produce mechanical power. In the same year that Arkwright patented his water spinning machine, 1769, Watt patented his separate condenser steam engines, initially used to pump water from lower mill ponds to upper mill ponds to supply continuous waterwheel power (Hills, 1970). Boulton and Watt's Soho Manufactory recycled water over their waterwheel using a James Watt steam pump, to drive the first purpose-built steam engine manufactory (1795) (Demidowicz, 2022). At least 150 steam engines were used in conjunction with waterwheels in the 18th century (Kanefsky and Robey, 1980).

Whilst the development of the steam engine is often referenced as being a primary driver of the UK's industrial revolution (Reynolds, 1984), this research argues that developments in the harnessing and control of water meant that waterpower retained its position as the primary driver for the first sixty years of the industrial revolution (1770-1830). The first (1785-6) directly powered steam mill was the cotton factory in

Papplewick, Nottinghamshire (Pierson, 1949). Whilst the first rotative steam engine wheels were used to directly power mills in the 1780s-90s (Hills, 2008), they were originally used where continuous operations were needed, such as furnace bellows (Kanefsky and Robey, 1980). By the 1790s rotary steam engines were widely used but waterpower was generally preferred, whenever it was available, as it gave steadier motion and had lower working costs (ibid). The development of steam power gradually transformed the siting of new cotton-spinning mills, shifting the industry from the rural river valleys, such as the Derbyshire Derwent Valley, to urban centres (Phelps, Gregory et al., 2016 20). With the abundance of labour and cheap coal the early 19th century boom concentrated on Manchester, Lancashire, earning the title of 'Cottonopolis' in 1854 (ibid). Whereas the watermills returned water back into the waterway once the power had been captured, water abstracted from the river for steam engines would be evaporated and lost. Losses of water due to feeding boilers and condensing steam (Maw, Wyke et al., 2012) were an important aspect of steam engine development. Steam powered mills requiring water had a significant influence on the location of mills in cities such as Manchester, with more than half of the mills being located on man-made waterfronts, the newly built canal feeders, compared to the natural watercourses (ibid). Mills located by canals benefited from enhanced transportation of raw materials (e.g. cotton), coal and finished goods, in addition to the canal companies offering rights to access to water to produce steam (ibid).

Hills (2008) compiled estimates regarding the usage of wind, water and steam power in Britain between 1760 and 1907. Whilst it is clear steam eclipsed waterpower in the second half of the 19th century in the percentage of power used (Figure 1.5), waterpower usage continued to grow (Figure 1.6) as a baseload until the 20th century, suggesting the common narrative, that steam caused a decline in waterpower use in the 19th century (Reynolds, 2006, Wilson, 1957), is incorrect.

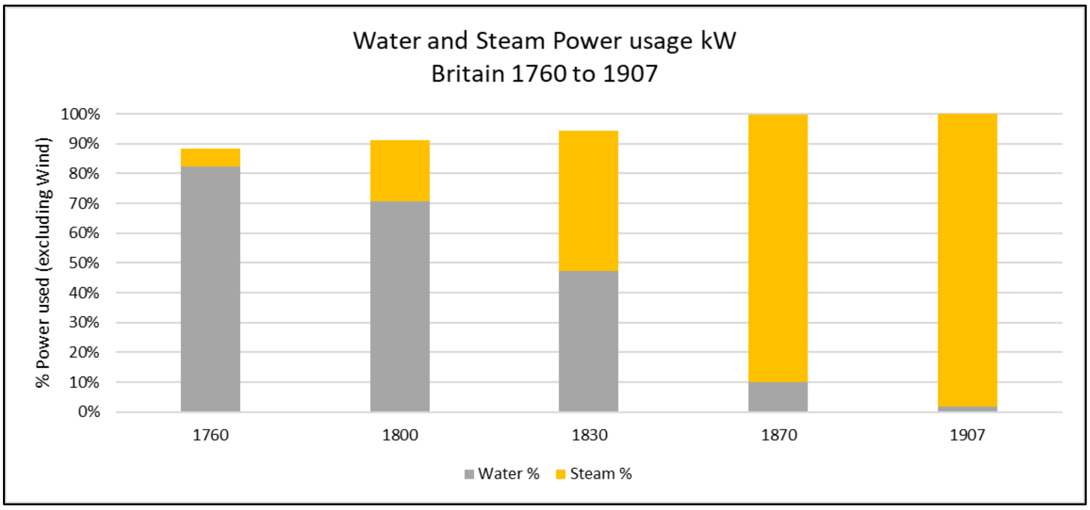


Figure 1.5 Type of power use in Britain % (Data: Hills, 2008 185)

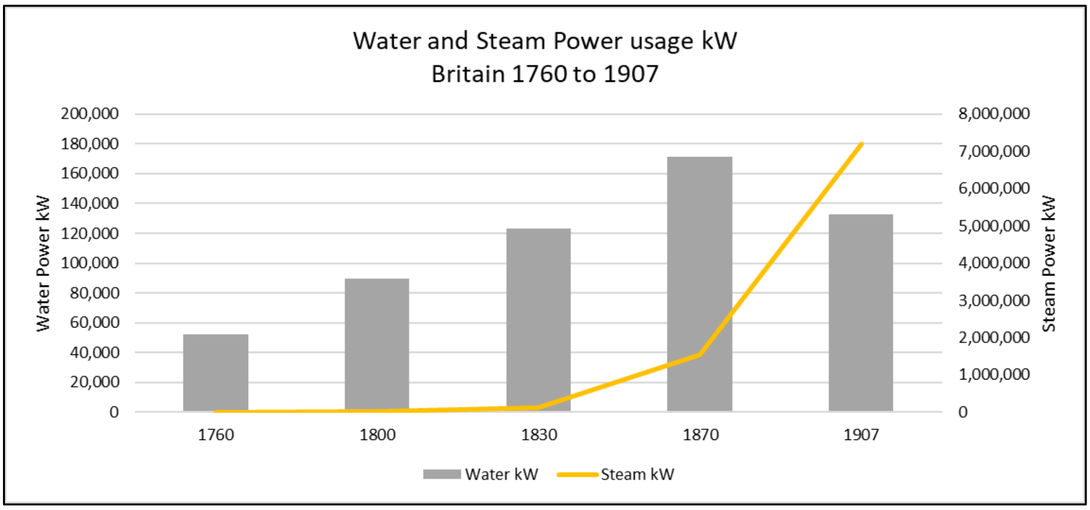


Figure 1.6 Type of power use in Britain kW (Data: Hills, 2008 185)

1.3.1.4 Use of fossil fuels

In Britain, at the start of the industrial revolution, coal had replaced wood as the main source of domestic heat (around 1700), but this was not an event that registered markedly on the atmosphere (Stephenson, 2018). It was the take up of coal industrially that was more important: from using natural falling water to generate power to spin cotton, to using the coal-powered steam engine (ibid). This was a big moment in human history, where 'human society stepped beyond natural limits and began to register on the composition of the 18th-century atmosphere' (ibid).

Traditional sources of energy were still important; in 1760, firewood, human and animal muscle, water and wind power accounted for about one-third of energy supply in England and Wales, but only 4% by 1913 (Kennedy, 2020). In a study looking at long-run CO_2 emissions in Europe, North America and Japan, it was found that only 14% of the total energy consumed in 1800 by the twelve countries studied resulted from the burning of coal, most of it attributable to the UK (Henriques and Borowiecki, 2017). However, by 1876, coal already accounted for about 50% of the total energy consumed in these countries, not only due to the influence of the UK where the industrial revolution was well underway, but also to Germany and France, which also markedly increased their coal consumption (Figure 1.7) (ibid 543).

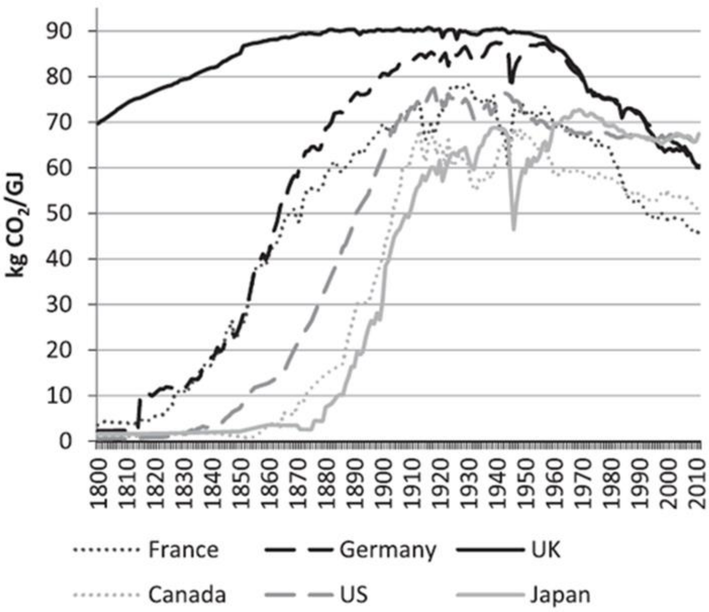


Figure 1.7 CO_2 intensity of all forms of energy (kg CO_2/GJ) (Henriques and Borowiecki, 2017 544)

1.3.1.5 Water turbines

Whilst in England coal (steam) became the primary energy source for cotton spinning mills c.1830, water remained the main source of energy for cotton spinning mills in France and the USA (Viollet, 2017). In 1825 France awarded a prize for water wheel innovation, won by Jean-Francois Poncelet. Developments with waterwheels and later water turbines continued across Europe, with the first successful turbine built by Benoit Fourneyron in 1827 (Wilson, 1957) and industrial turbines (delivering mechanical power) being installed in France and Germany in the 1830s (Viollet, 2017).

In Britain, engineers in Scotland and Ireland introduced the water turbine, often developing the technology proven abroad, such as the MacAdams who built their early turbines, based on the French Fourneyron design, at their Soho works in Belfast in the 1850s (Wilson, 1957). Another early manufacturer was the Glasgow engineer James Whitelaw, whose turbines were proving to be cost effective compared to water wheels and were in use in mills across the UK, including Pleasley near Mansfield, according to an article in the Mechanics Magazine of 1854 (ibid). In the Great Exhibition of 1851 there were no British turbine manufacturers exhibiting, but by 1862 four British manufacturers exhibited, including Williamson Bros. of Kendal, who still operate today in the form of Gilbert Gilkes & Gordon Ltd (ibid).

1.3.1.6 Hydroelectric power (HEP)

Mechanically driven water powered (wheels or turbines) machinery relied on direct drive via gears, belts, shafts and pulleys, and the machinery was immobile, located adjacent to the prime mover, the river, brook or stream (Munro, 2002, Reynolds, 2006). Following Michael Faraday's discovery of electromagnetic induction in 1831, the possibility of converting mechanical power (water or steam) using a rotating shaft into electricity arrived (Hannah, 1979). The development of generators followed, with the first generators (converting rotation power into electricity) on the market in 1857, producing light in lighthouses (ibid). Electrical power transmission developments in the 1880s allowed waterpower to be optimised, in location and size, with manufacturing plants able to draw on hydroelectric power (HEP) from multiple sites (Reynolds, 2006, Tucker, 1988). Long distance electricity transmission came later, so HEP sites only provided power to local houses, their communities and cities (Viollet, 2017).

Lord Armstrong, a significant industrialist and innovator, had a long interest in the production, use and conservation of energy, and in the 1860s warned of the over-exploitation of Britain's limited coal reserves (Irlam, 1988). Taking a similar approach to Smeaton, in 1835 Armstrong watched a waterwheel powering a quarry whilst fishing and, seeing the small percentage of the water's energy being converted into power, became interested in waterpower innovation and development, building his first water pressure engine in 1840 (Figure 1.8) (Bamburgh Museum, 2023). The power harnessed from water continued to be used purely for mechanical power drive until 1878 when a dynamo was attached to the shaft of a water turbine located in a sawmill on Lord Armstrong's estate to generate electricity at Cragside House in Northumbria, powering two arc lights in Armstrong's library. Further improvements allowed the 'powerhouse' to electrically drive the sawmill by day and the world's first 'Swan' incandescent lights in the house by night (Hannah, 1979, Irlam, 1989).

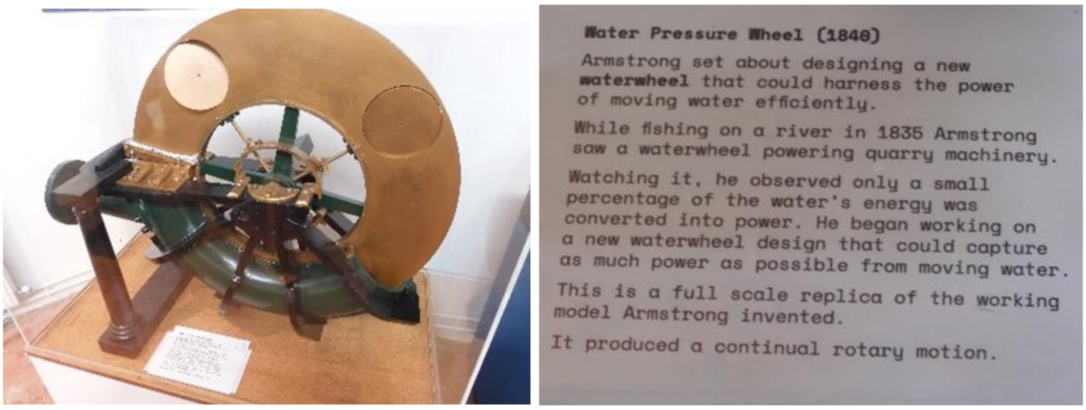


Figure 1.8 Armstrong's water pressure engine (1840) (Photographs: Author, 2023)

As the world's first house to be lit by HEP Cragside is a major site in the National Trust's collection (Dixon, 2007). Similar country house owners, with access to a watermill or flowing waterway, who wanted to introduce electric lighting at the turn of the 20th century, would have to generate the electricity themselves, with no local or national electricity grid available. Derbyshire had 'early HEP adopters', such as the 8th Duke of Devonshire at Chatsworth, who diverted water from his Emperor Fountain to power two Gilkes turbines to light the house in 1893 (Strange, 2001). The Country House Technology Project (https://le.ac.uk/country-house-technology) which looked at the adoption of technologies into country houses, proposed that at least 400 houses in Britain had their own electricity generating plant (Palmer and West, 2013), although some of these may have been steam powered.

1.3.1.7 Public supplies of electricity

Both businesses and local authorities could see the potential and growth in electricity usage, which forced parliament to act, resulting in the *Electric Lighting Act* (1882). With no public electricity supply available the Act gave local authorities the powers to break up streets and lay cables, to supply lighting for their communities (Hannah, 1979). In Britain, the pioneering HEP station was at Westbrook Mill on the River Wey, Godalming in Surrey, in 1881, using a breastshot wheel to drive a dynamo (Strange, 1979, Tucker, 1977). It was used to light streets, as well as supplying private consumers, but demand for the new light from consumers was inadequate, making the scheme economically unviable and gas lighting was restored in 1884 (Gardner, 2008, Strange, 1979, Watts, 2000). Before the turn of the century a further 14 HEP schemes were opened (Gardner, 2008), but there were no known public HEP supply systems in Derbyshire. At the end of the 19th century, public ‘town gas’ supply (produced from coal) was already extensively used to produce artificial lighting and was comparatively cheap, so, as electricity became more cost effective, there was competition between the two industries (ibid). Town gas was cheap and by 1881 there were 1 ½ million gas consumers, compared with 6 million dwellings. In 1878 the gas companies were so concerned about electric lighting that they set up a committee to investigate the threat (Hannah, 1979). In Britain gas lighting remained generally cheaper than electric lighting until WWI (Byatt, 1979).

In the early twentieth century demand for electricity grew, and whilst HEP had been an ideal solution for initial local generation projects, the traditional challenges of hydropower, such as high first costs, immobility, inflexibility and unreliability (water flow), restricted its development (Reynolds, 2006). HEP sites tend to be non-standard, with variability of flows and geographical challenges making sites’ output difficult to predict (Munro, 2002), and the hydraulic structures (dams, reservoirs and powerhouses) were capital intensive (Reynolds, 2006). The larger HEP developments also raised sensitive social and political issues: land rights, water rights, people displacement, fisheries protection, navigation rights and urban water supply demands (ibid).

In 1902 Halford Mackinder, an eminent geographer, prophesised that if the energy of the tides around Britain could be harnessed, a supply of electrical energy from the rhythmical pulsation, would supply more energy than is available from the world total resource of coal, whose costs were rising (Gardner, 2008). The only large-scale HEP project given serious consideration in England, and revisited many times since, was the Severn estuary barrage, which, if completed when originally planned (1933), would have supplied 7.5% of British electricity requirements by 1940. The initial reason for ruling out the project was increased stringency in government expenditure (Gardner, 2008, Hannah, 1979), with other environmental impacts not considered at that time. During the 1920s Scotland could see the potential and economic importance of the region's natural resources, with H. F. Campbell, a Fellow of the Royal Scottish Geographical Society, asserting that 'the future of the Highlands depends largely on afforestation and the development of waterpower' as a prescription for the regeneration of the Highlands (cited in Gardner, 2008 40).

The early 20th century saw the electricity supply industry focussing on the development of 'off the shelf', cost predictable and relatively reliable coal powered steam engines (Reynolds, 2006). The influential engineer, Ferranti, was the first to develop a large-scale coal fired power station in Deptford (1891), taking advantage of the coal being delivered by river and the Thames water being used for cooling (Hannah, 1979). Local networks were developed, often in competition, by corporations, local authorities and private enterprises, including syndicates of large manufacturers, such as the proposed General Power Distribution Company (1898) in the Chesterfield, who planned to supply electricity over an area with a million inhabitants, with only 1,546 taking electricity at the time (ibid). Within Derbyshire the local electrical grid was developed by the Derbyshire and Nottinghamshire Electric Power Company, with Chatsworth House turning off their self-generation in the 1930s when the electricity supply became available in rural Derbyshire (Strange, 2001).

Despite the UK government of the day wanting to shelve the issues of electricity generation, transmission and supply during the World War II, the appointment of Labour MP Tom Johnston as Secretary of State for Scotland initiated a review aimed at resolving acrimonious debates in the 1930s, to investigate the possibilities of developing hydropower in Scotland (Gardner, 2008, Hannah, 1979). Many of the parliamentary debates described by Hannah (1979) relate to the proposals to rationalise the many municipal and commercial electrical supply undertakings and the electricity supply markets, but there were other forms of HEP discourse, particularly for the large-scale HEP schemes.

This research primarily focusses on the smaller run-of-river hydro (small HEP) available in England due to its natural topography. In Scotland and Wales, and globally, the terrain and hydrology allow the development of large-scale HEP generation in moorlands and mountains (Brown, 2011) often leading to protests. In the 20th century developments in these landscapes and areas of natural beauty created new forms of opposition to HEP development, from different bodies with different priorities. The development of HEP in Scotland also coalesced the Scottish landscape protection movement, with the Association for the Protection of Rural Scotland and the National Trust for Scotland both forming post WWII, both associated with the landscape protection-linked opposition to the large-scale HEP development in the Highlands (Payne, 2008). Sportsmen in the Highlands wanted the wild landscape preserved and fishermen were concerned about the impact on their salmon fisheries from the construction of dams and the abstraction of water from rivers to create reservoirs. The 1949 proposal for large-scale schemes in North Wales prompted protests from the Council for the Protection of Rural Wales and the Welsh nationalists, that most of the power would be exported to England (Brown, 2011).

Whilst the creation of the North of Scotland Hydro-Electric Board, and subsequent nationalisation, enabled the development of over 50 large-scale HEP power stations from the late 1940s to mid-1960s (Slee, Whitfield et al., 2011), by the late 1950s steam generation became more competitive in Scotland (Hannah, 1982). A study of the UK's largest water turbine manufacturer (Gilbert Gilkes & Gordon Ltd) from 1853 to 1975, noted that their business was impacted 'with the spread of the [national electric] grid throughout the United Kingdom, and particularly in the North of Scotland, the business in domestic Hydro-electric plants dropped off rapidly and had virtually disappeared by the 1960s, relying on exports for their business to survive' (Slee, Whitfield et al., 2011 56, Wilson, 1974 83). The government's decision, to build a series of large-scale coal fired power stations, distributed around the UK to supply a national network, led to the discouragement of self-generation of electricity (Hannah, 1979, Hannah, 1982), by water or steam.

Whilst there is evidence of decline in the self-generation of HEP during the mid- 21st century there is little understanding of the carrots that encouraged sites to purchase grid electricity or the sticks that discouraged local HEP generation (both existing and new). Before WWII, many large industrial sites invested heavily in local electricity generation, using available HEP resources, and coal powered steam generation plants (Hannah, 1982). Post WWII, for the nationalised electricity board to sell electricity from its newly built power stations, tariffs, pricing structures and incentives were used, offering favourable terms for large users such as ICI, who would accept interruptible supplies, to encourage the switch to national grid supply (ibid). The British Electricity Authority, and later Central Electricity Generating Board, prevented smaller generators connecting their supplies to the national grid (Brown, 2011, Wilson, 1974), a regulation only changed as part of the privatisation of the electricity industry in the 1980s. A common theme impacting on small power generation, seems to be the policies relating to nationalisation and the resultant regulation of the water (Brown, 2011, Sheail, 1991) and electricity utility industries (Hannah, 1982).

Stowers, giving his closing remarks in his 1957 Newcomen Society presidential address said, ‘It is unwise to predict the future, but I submit that we may assume that, when the available coal and oil in the world have been used up in a few hundred years and when the supply of uranium and thorium is failing, the wind will continue to blow, the rivers and waterfalls will still be flowing and the tides still working. Engineers will have to make the most efficient use of them for civilisation to exist’ (Stowers, 1955 255). By 1978 the advent of cheap and reliable energy supplies, mainly from coal-fired power stations, had seen the demise of small HEP, with possibly only 300 sites across England and Wales still operating (Francis, 1978). In the early 1980s the National Association of Water Power Users produced a report identifying the many legal and institutional barriers as ‘factors inhibiting development’ for the Watt Committee on Energy. However the Energy Act 1983 altered the situation significantly, with many of the obstacles to the private generation and sale of electricity removed (Reed, Hinton et al., 1985 51).

1.3.1.8 Electricity alternative fuel options

A significant challenge to the development of HEP, as the electrical power industry grew, was the need for the government to pacify the coal industry, owners and unions (Hannah, 1979 130). In the late 19th century hydroelectricity was seen as a threat to the coal industry (Tucker, 1988), partly as a result of electric lighting's impact on 'town' gas lighting, which was produced from coal (Gardner, 2008). During the 20th century England exploited its coal reserves (Kennedy, 2020), whilst elsewhere in the world the natural resource of waterpower was viewed quite differently, with Germany referring to HEP as 'white coal' (Brown, 2011 169). In North America an international design competition was started in 1890 to develop the Niagara Falls' HEP installation, leading to the 3,750 kW, 10 turbine system, running from 1896, supplying electricity to Buffalo 43 km away (Reynolds, 2006).

The extraction and use of coal in the UK peaked in 1913, with an output of 292 Mt, and the industry was economically and strategically critical with over 1.2 million workers (7% of the total labour force) by the 1920s (Smil, 2017 272-3). In 1947 the UK Labour government nationalised the coal industry and created the National Coal Board, with a post war, 1950s, peak output of 228 Mt. However rising imports of crude oil and the availability of North Sea oil and gas in the 1970s halved the UK's coal dependence by the 1980s (Figure 1.9) (ibid).

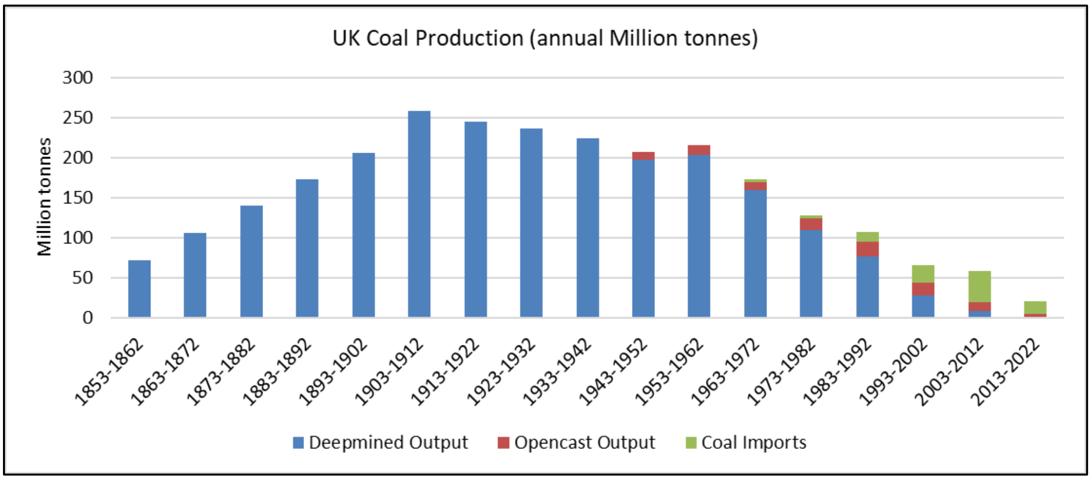


Figure 1.9 UK: Historical coal production data DUKES, 2023 (DESNZ, 2023)

Prior to the discovery of natural gas in the North Sea (1965) Britain had used 'town-gas' produced from coal or oil. By 1967 a national gas pipeline transmission system was under construction, but it was not anticipated that the fuel would make a significant contribution to electricity generation; rather, as stated in successive White Papers in the 1960s, nuclear power was expected to dominate (Winskel, 2002). Development of the combined cycle gas turbines changed the role of gas (Section 5.3). Today in the UK, faced with transitioning away from gas central heating to low carbon electrical heating, such as air source heat pumps, there may be lessons to learn from the UK's introduction of gas central heating, 1966 to 1972. The *Fuel Policy White Paper* (Ministry of Power, 1967) outlined the challenges and opportunities for moving from a two fuel (coal and oil) to a four fuel (coal, oil, natural gas and nuclear) system and stated that 'the discovery of natural gas in the North Sea is a major event in the evolution of Britain's energy supplies' (cited in Hanmer and Abram, 2017 8). By 1972, 75% of all new housing had gas central heating (ibid) (Section 4.6.1).

Despite the 1970s arguably being the nadir for HEP generation in the UK, energy supplies during this period were insecure and there was concern over the impact fossil fuels and nuclear fuels have on the environment (Francis, 1978). HEP was described as an indigenous secure renewable energy source, with its value recognised around the world (ibid), although only Scotland and Wales had the mountains and rainfall on a scale large enough to offer opportunities for HEP development of tens of MW (Wilson, 1985). However there were hundreds of sites across the UK, in the 1980s, where modest amounts (tens of kW) of HEP could be generated (ibid). The UK government focussed only on large-scale options, with funding prioritising the development of the nuclear industry (Gardner, 2008, Lees and Eyre, 2021, Walker, 1997), and one large-scale HEP potential project, the Severn Barrage, being considered and ruled out again (Gardner, 2008).

Air pollution and incidents, such as the sinking of the oil tanker Torrey Canyon in 1968, raised the awareness of environmental issues in society. The early 1970s saw the creation of the Department for Environment, the start of the Ecologist journal, the launch of Friends of the Earth and the establishment of the forerunner to the Green Party in 1973 (Wilson, 2018). The same year also saw the foundation of the Centre for Alternative Technology in Wales, a project experimenting with alternative energy technologies and communities to develop and demonstrate a self-sufficiency model (Gardner, 2008). This counter-cultural movement was heavily influenced by the work of E F Schumacher, *Small is Beautiful* (1973), with his new eco-philosophy based on decentralised, small-scale, simplified technologies, appropriate to the economic and physical environments (ibid).

Two major rises in oil price, in 1973 and 1979, caused significant, temporary, reductions in energy consumption, both through the resulting recessions and incentivised increased energy efficiency (Lees and Eyre, 2021). These raised the profile of energy consumption politically and started the search for solutions to fossil fuel depletion and the need for energy self-sufficiency. It also led to the creation of a separate Department for Energy in 1974 (ibid). Following the second oil crisis new non-OPEC oil and gas reserves were developed (Winskel, 2002). Both dominant electricity generating technologies, coal-fired power and nuclear, were experiencing chronic technical and economic difficulties in the 1980s. Following the Three Mile Island incident 1979, the industry became very aware of nuclear power risks and coal-fired power plant emissions were also being restricted (ibid). The development of a more flexible, cost effective, form of electricity generation, the combined cycle gas turbine (CCGT) in the 1980-90s, combined with the recent privatisation of the UK electricity supply industry (1990), led to the abandonment of all new coal and nuclear power plant developments (ibid).

1.3.1.9 Climate change: renewable energy

The first UK governmental encounter with climate change was the review of the global science of climate change, completed by the Interdepartmental Group on Climatology, commissioned by the Labour government in 1979, but received by the Conservatives who were in power by its completion (Mahony and Hulme, 2016). Governments around the world responded to this scientific research and, following an initial United Nations (UN) meeting in 1985 recommending an international programme on Climate Change, it was agreed in 1988 to set up the UN Intergovernmental Panel on Climate Change (IPCC) to collate current knowledge, understanding and programmes relating to climate change globally (IPCC, 2024). In 1988 Margaret Thatcher, UK Prime Minister, spoke to the Royal Society, raising her concerns about global warming and environmental change (Mahony and Hulme, 2016).

Tasked with reporting on the opportunities to reduce carbon dioxide emissions, the head of the UK government's Energy Technology Support Unit (ETSU) presented his findings to the cabinet in 1989 (Lees and Eyre, 2021). The presentation identified the key potential options for mitigation by 2020, including renewable electricity, which in 1988 was primarily hydroelectric power (HEP), with small amounts of power from wind and a negligible quantity of solar (ibid). Until 2009 (when it was overtaken by wind power) HEP was the single largest source of renewable electricity in the UK, with the vast majority of installed capacity located in Scotland (Duncan, 2012).

The need to decarbonise electricity generation saw the fragmentation of established spatial patterns of energy supply in the 1990s, including some localisation of energy generation in urban and rural locations (Walker, 1997). Much attention regarding energy utilities was focussed on the collapse of the UK coal industry and the controversial and problematic privatisation of nuclear power (ibid 59) but the renewable energy sector, including HEP, was developing quickly to offer part of the solution to future energy supplies, combatting the environmental problems faced (ibid). The Labour government introduced the 2008 Climate Change Act, requiring an 80% reduction of greenhouse gases by the year 2050, using a 1990 baseline, effectively transferring global policy into national legislation (Duncan, 2012, Pearce, 2013). Three fiscal packages were developed by the UK government (1990 to 2019) to support renewable energy generation (Needle, 2020) (Section 5.2.2).

A 2021 study investigating the ecological impacts of run-of-river HEP highlighted the essential role of HEP in global decarbonisation, meeting nearly 17% of the world's electricity demands (Kuriqi, Pinheiro et al., 2021 1). Among conventional renewable energy sources, large-scale dam HEP schemes account for 55% of the capacity and the small, run-of-river HEP 7% (similar to those found in Derbyshire) (ibid).

Across Europe, HEP is the largest, historically developed and well-advanced, mature renewable energy source (Wagner, Hauer et al., 2019 41). In some EU member states, for example, Turkey, Austria, Romania, and Greece, the status of hydropower has been comprehensively summarized by scientific reviews (Manzano-Agugliaro, Taher et al., 2017, Wagner, Hauer et al., 2019). HEP research on the European scale also addresses the state of the art and challenges of different hydropower technologies (Quaranta and Revelli, 2018), and considers the impact of climate change on the HEP potential. Other research addresses future HEP development in Europe based on technological, socio-economic, environmental, and policy aspects (Wagner, Hauer et al., 2019). Whilst HEP represents a considerable renewable energy source in Europe, it poses risks to river ecosystems and the downstream transport of sediments (Venus, Smialek et al., 2020).

Opposition continues today to large-scale HEP, where valleys flooded to create the head and storage for HEP generation have an ecological and aesthetic impact (Payne, 2008), with global campaigns from leading nature conservation groups such as the WWF. Whilst acknowledging that low impact HEP, such as refurbishing and retrofitting existing dams, and off-river pumped storage, has a role to play in tackling climate change, it states that 'the days of high impact hydropower [particularly in South America, Asia and Africa] – both big and small -must come to an end' (WWF, 2022). Whilst there is great potential for developing large-scale dam HEP schemes in less economically developed countries, the economic, political and environmental impacts have prevented development at a significant rate and public perception now sees one of the oldest power generation technologies, run-of-river HEP, as a sustainable energy source (Kuriqi, Pinheiro et al., 2021).

However, few studies take an historical perspective on HEP. One example is the EU RESTOR project, which ended in 2015 and aimed to identify and restore suitable historical mill run-of-river sites to generate HEP (Punys, Kvaraciejus et al., 2019) (www.restor-hydro.eu). The study reviewed 65,000 historic small HEP sites in 21 countries, identifying 6.8 TWh/year additional potential at historic sites not currently generating HEP (ibid). Additional research suggests there may have been up to 135,000 watermills across Europe (Quaranta, Bahreini et al., 2022) but they may not have been repurposed in c.1900 for HEP generation. Dependant on the historic non-

HEP watermills range selected, studies have identified additional HEP generation capacity of between 1.6 TWh/year to 8.7 TWh/year (Quaranta, 2023). There may be an opportunity to build on the EU RESTOR model, applying findings from the project to an English river catchment. The European Cultural Heritage Green Paper (Potts, 2021) argues that the EU's 2020 strategy for energy system integration, achieving the goal of climate neutrality by 2050, must consider the cultural dimensions of powering a climate neutral economy. To achieve this goal, the paper suggests that heritage has a role to play in supporting traditional, community-scale renewable energy sources, such as geothermal and hydroelectric (Potts, 2021).

There has been a 'boom' in HEP development as part of renewable energy and climate mitigation strategies, globally (Kelly-Richards, Silber-Coats et al., 2017). In the UK, HEP developers, regional authorities and local communities reducing their carbon impact have utilised government renewable energy subsidies (Needle, 2020) to install HEP, often mill reinstatements, since 1990 (Armstrong and Bulkeley, 2014, Bracken, Bulkeley et al., 2014, Gallagher, Harris et al., 2015, Johansson and O'Doherty, 2017, Sample, Duncan et al., 2015). However, this growth effectively stalled in the UK following the withdrawal of feed in tariff support (announced 2015) (Wilson, Day et al., 2022).

This boom for small renewables proved challenging for UK planning departments as, until the early 1990s, 'energy projects' meant large-scale power stations with construction decisions taken at national level (Walker, 1997). When faced with public opposition to new schemes, such as air pollution from large waste energy recovery and visual and noise issues with windfarms, planning applications were delayed, impacting on their financial viability, and often refused (ibid).

1.3.1.10 HEP potential in the UK

Concerns over energy security (relating to oil), and the impact fossil and nuclear fuels were having on the environment in the 1970s, led countries around the world to identify HEP sites, with Sweden identifying 1,300 sites for development and the US identifying 9,000 (Francis, 1978). HEP potential assessments are difficult to produce due to the large number of potential sites (weirs) (Scene Connect, 2022); a 1989 study limited ‘the number of sites to be considered in the study to a level commensurate with available time and resources’ (Salford Civil Engineering Limited, 1989). The first (1978) UK government assessment focussed only on the HEP opportunities available within the water industry and identified three different levels of potential; gross river (highest), exploitable technical and exploitable economic (lowest) (ibid). The independent Centre for Alternative Energy (CAT) (1973) prepared an alternative energy strategy in 1977-78, concerned about the planet’s growing population, ever-increasing consumption of energy with finite reserves and the UK government’s plan of a large-scale development of the “plutonium economy”, nuclear power (Gardner, 2008, Todd and Alty, 1978).

In 2009 a study of potential small HEP sites in England and Wales was completed by the Environment Agency (EA, 2010), reporting to the Department for Environment, Food and Rural Affairs (DEFRA). Looking at hydraulic heads and river flows: the study identified 26,000 potential sites in England and Wales (Bracken, Bulkeley et al., 2014). The study also included an assessment of the key environmental sensitivities that needed to be addressed to unlock the HEP potential. This study was based on the river barriers’ location dataset developed by the EA fisheries group, and summarised the barriers by map, text and descriptions, identifying 564 Dams, 274 Mill sites and 16,735 Weirs (EA, 2010).

The most recent assessment of UK capacity was commissioned by the British Hydropower Association (BHA) and published in October 2022, proposing an additional deployment of 1 GW as an achievable target under a supportive policy framework, creating a total 3 GW HEP generation capacity or 1.5% of the increased annual electrical demand (Wilson, Day et al., 2022). This report was based on the Salford Civil Engineering (ETSU) report 1989, Scotland (2008) and England & Wales (2010) reports, which all used different assumptions and exclusion criteria, such as low thresholds, minimum heads, financial viability, flow and grid connection opportunities (Wilson, Day et al., 2022 12). The different approaches and inputs to past studies have led to differing estimates for the potential HEP in the UK (ibid) (Section 5.3.2).

1.3.2 Water abstraction

1.3.2.1 Pre-20th century

Petts (1990) describes the relationship between water, engineering and landscape as having three phases of development. After the initial use of water sources for local agriculture and domestic supplies, which included small watermills established on natural cascades, falls, knickpoints and meanders, the second phase (1600 until about 1900) involved the management of the rivers for navigation and waterpower. The third phase (post 1900) describes the regulation of rivers by large structures (Petts, 1990 203). Pre-1600 the common law of riparian rights was based on the customs that grew up around the use of rivers for mill power, but used Roman law which gave the owners of land adjacent to small (private as opposed to public) streams the right to use water to justify 'natural' land-based rights (Tarlock, 2004). Technological developments during the early industrial revolution brought about increased congestion of water users along English rivers. Scott and Coustalin (1995 871) identified changes (1851) in water law (e.g. riparian rights) following the early industrial revolution (1600-1850), as a result of the high volume of watermill water right conflicts. Within the DDC, a key aspect of the original land purchase for the 1776-8 development of the first Belper Mill by Jedediah Strutt, was the water privilege attached to the sale (Fitton and Wadsworth, 1958). Similarly, the all-important water privileges attached to the land at Cromford, purchased by Richard Arkwright, included Bonsall Brook and the water issuing from Cromford Sough, the lead mine drainage channel (Getzler, 2004). The lease for the land also included water protections for the downstream 13th century corn mill with an ambiguous existing water rights claim (Getzler, 2004 31).

An interesting characteristic, and complication, of the waterways of the Derbyshire Derwent catchment (DDC), and influential to the development of the industrial use of waterpower, are the lead mine soughs. Man-made channels have removed drainage water from mines since the 14th Century, but the first named lead mine sough in Derbyshire was developed in the 1620s (Ford and Rieuwerts, 2000 98). Lead mining was a major industry for Derbyshire and as a result in excess of 400 individual soughs (were built) across the region by the late 19th century (Rieuwerts, 2007 cited in Endfield and Van Lieshout, 2018 5). It was primarily the water from

Cromford Sough, described at ‘a great sough’ by William Woolley in his history of Derbyshire written before 1719 (Woolley, Glover et al., 1981), that Richard Arkwright utilised to build the first water-powered cotton spinning mill in 1771 (Newman, Rodríguez et al., 2018). Arkwright’s use and control of the sough water impacted on the mine workings in 1776, leading to an acrimonious dispute and legal challenge (Endfield and Van Lieshout, 2018). It was the loss of the sough water, with the water being drained via the deeper Mere Brook Sough, that led to the closure of the Cromford Mill site in the 1840s (Buxton and Charlton, 2013).

Arkwright also had issues with water rights with his cotton mill in Bakewell, which, when it came into operation in 1783, affected the water supply to the Duke of Rutland’s corn mill and damaged his trout fishing (Getzler, 2004 32). This three-year dispute was resolved out of the courts with an annual rent for water use and waters to the corn mill maintained (ibid). During the 1770s-80s hundreds of entrepreneurs were purchasing leases, including water privileges, with many former corn mill sites becoming the target for new industrial mills, with water rights attached (ibid).

In the pre-railway era, navigable waterways were the most efficient way of carrying low value, bulky, non-perishable goods (Satchell, 2017 2). The growth in water transportation follows a similar pattern to the usage of waterpower, with England and Wales having around 950 miles of navigable waterways in 1600, increasing to 1,400 miles by 1760 (ibid 4). By 1835 the waterways network, including canals, was approximately 4,000 miles (ibid 4). Whilst the primary role of canals was the movement of goods, they also provided access to water for the steam-powered mills. A mapping of mills, based on two 1851 maps in Manchester, highlighted the importance of access to water for steam powered mills, and the impact the man-made canals had on the location and capacity of industrial mills within Manchester (Maw, Wyke et al., 2012). Manchester’s waterfront consisted of the rivers Irwell, Irk and Medlock pre-canal development, but the development of five public and twenty-three private canal branches significantly increased the area of economically valuable ‘waterfront’ land (ibid). By 1851 94% of cotton mills were within 175 yards of a waterway, with 55% of the closest mills (<20 yards) adjacent to canals and 45% adjacent to rivers (ibid).

Whilst the mill owners were significant users of the canals to transport raw materials, fuel and finished goods, they also had concerns about the loss of waterpower due to canal builders abstracting water from their catchments and petitioned parliament. The parliamentary inquiry leading to the Cromford Canal Act (1789) gives an insight into the mill operations (Figure 3.20) and, ultimately, the compromises made regarding water being taken from the River Derwent to feed the new canal (Gifford, 1999, Schofield, 1981, Schofield, 1985). A study of the mills and waterwheels was presented to the Cromford Canal inquiry (Figure 3.20), that had identified 53 water wheels in total between Cromford Mill, the proposed abstraction point, and the Trent confluence at Wilne (Gifford, 1999).

1.3.2.2 20th century water abstraction

Petts describes the third phase, the 20th century, as a period with rivers becoming ‘completely regulated by large structures, often as part of a complex basin or inter-basin development, for HEP generation, water supply and flood control’ (Petts, 1990 203). Within the DDC, competition for water within the Peak District led to the creation of the Derwent Valley Water Board, to supply water to the cities of Leicester, Nottingham, Sheffield and Derby (Cosgrove, Roscoe et al., 1996, Street, 1950). The building of the Derwent Valley Reservoir System (Howden started in 1899, commissioned in 1912 and the final River Noe diversion completed in 1951), which receives its water through natural inflows and flow diversion schemes, left almost dry stretches of rivers for long periods of time (Cosgrove, Roscoe et al., 1996, Maddock, Bickerton et al., 2001). The Derwent Valley Acts, that enabled the building of the reservoirs and associated infrastructure, stipulated the compensation flow (water volume released per day) to be released to the river from the Ladybower Reservoir in a regular flow (Section 4.4.1).

The Derwent Valley reservoirs are described as water-engineering schemes (provision of improved sanitation and associated clean drinking and washing water), unlike similar reservoirs built in Scotland and Wales, which also generate HEP (Gardner, 2008, Gerard, 1963), or globally (e.g. Europe, Africa, US [Gerard, 1963]). Similar dams being built around the world in the early 20th century offered the dual purpose of water storage and HEP generation. Germany developed its drinking water infrastructure, including the dams in the Ruhr valley, to incorporate large-scale HEP generation in their design: they became the target of Operation Chastise to disrupt key German industries by impacting on their electrical supplies (Hastings, 2020). The Derbyshire Derwent dam was famously used for training during WWII for Operation Chastise due its resemblance to three of the Ruhr valley dams (Historic England, 2023). The later, 1940s, Ladybower reservoir incorporated HEP for energy recovery during water transfer pumping operations (STWA, 1978 4). Following changes in law, allowing the export of electricity from small local generation in the 1980s and renewable energy subsidies being made available in the 2000s, some of the HEP potential is now being captured by three turbines installed in the Derwent Valley reservoirs (Section 5.3.2.2). The DDC water utility network includes structures that create heads and flows, pumped storage facilities and an early 1900s gravity-based distribution network, that all have HEP potential (Gallagher, Harris et al., 2015, Jiyun, Hongxing et al., 2018, McNabola, Coughlan et al., 2014, Power, McNabola et al., 2014).

The 1963 Water Resources Act established river authorities and water resource boards, with powers to manage water abstraction and impose charges for water use, including for watermills that return water back to the river. The Act had the effect of restricting small-scale use of waterpower and stifled development of small-scale HEP generation (Brown, 2011, Sheail, 1991). Water abstraction licencing passed from the publicly owned River Boards to the National Rivers Authority and then the Environment Agency, during the transition of public to private ownership of the water utilities. Today, HEP projects may require up to four permits from the Environment Agency (Armstrong and Bulkeley, 2014). Commencing with the abstraction licence that includes the operational conditions (e.g. water allowance and need for fish pass), the permits also control the design, including fish pass if required, of any HEP scheme, in England (AMEC, 2010).

1.3.3 River ecology

1.3.3.1 Fisheries and weirs

It is not always appreciated how important a food source fish was in medieval times (Moore-Scott, 2009). In coastal areas sea fish were caught and fishing was a major activity near large rivers, pools and lakes. Fishponds were created for breeding or as stock ponds holding fish until they were needed (ibid). Landowners would deliberately dam up streams to create breeding and holding fish-ponds, that would act as a fish larder for the local country house or abbey consumption. The Rufford Abbey, Nottinghamshire, charters contain the rights to construct a vivarium for fish husbandry in 1268 (Law, 2016). Various methods were employed for catching fish including basket traps, nets and spearing. On the river, no less important was the use made of constructed fish weirs (or "fixed engines") the use of which on the Severn can be traced back to Anglo Saxon times (Moore-Scott, 2009). One of the often quoted references, highlighting the large number of salmon available in English rivers in the past, relates to the river Wye that runs from mid-Wales to the Severn estuary. Prior to the erection of weirs on the river, salmon and other fish were so plentiful ‘that hired Servants would condition with their Masters not to eat such fish above three meales in the week’ (cited in Willan, 1964 86). In addition to watermills being recorded in the 1086 Domesday survey, details of fisheries were also captured, with eels being the ‘choice fish’ and the currency for fishery rental (Buffery, 2017).

Individual rivers, catchments and countrywide waterways in the UK have been subject to legislation, often relating to the fisheries, for hundreds of years. One of the earliest mentions of conflict on the rivers is in the Magna Carta (1215), with clause 33 stating ‘All fish-weirs are in future to be entirely removed from the Thames and the Medway, and throughout the whole of England, except on the sea-coast’ (Buffery, 2017 3). Within the Magna Carta, a distinction was made between private and public rivers, based on the presence of tidal influence. King John dedicated to the public all rights of fishing in public rivers as in the seas and estuaries (Stroud, 1993).

Whilst some weirs were built to catch fish, fish-gates were also often incorporated into mill weirs (Johnson, 1996). An early 18th century community in North America, faced with the problem of a mill weir preventing fish migration, is described by Kulik (1985), highlighting the cooperation required to enable the earliest recorded purpose-built fish pass, called Sargent's Trench, constructed in 1714 (Hahn and Prude, 1985). In 1791, when the US Bill of Rights was ratified, nine states had laws compelling mill dam owners to modify their dams in order to allow fish to pass upstream (Hart, 2004). Early fish passage regulation in the US varied in requirements by state, with a Connecticut statute (1793) required opening 'a sluiceway' in such dam twelve feet in width, and within six inches of the bottom of [the] river' (Hart, 2004 294). This severe fish passage requirements sharply reduced the head of water available for mill power during the relevant seasons (ibid).

In the UK, pool and weir fish passes were common by the early 19th century (Katopodis and Williams, 2012). In 1869, Francis Francis, was commissioned by *The Field* newspaper to gather information on fish passes built on weirs in UK salmon rivers (not including the Trent catchment) that had proved successful, to develop some best practice guidance for corrective measures on existing poor passes and the development of future passes (Kidder, 2016). His final article concluded that the greatest cause of failures were the ladders being too steep and too great a weight of water opposing the fish. Unfortunately, Francis felt the question of best practise was 'confused and complicated, that the truth which lies at the bottom of the well has been nearly smothered by the heap of theories and rubbish that have been thrown in on top of it' (Francis Francis, 1869 524).

By the 1860s, salmon numbers were under threat across the whole country, with Charles Dickins writing in 1861, 'The Salmon are in danger. A few years, a little more over-population, a few more tons of factory poisons, a few fresh poaching devices … and the salmon will be gone – he will become extinct' (cited in Netboy, 1980 85). The earliest Salmon Preservation Act within the statute of Westminster created a closed season for salmon, in 1285 (Buffery, 2017). By 1860 there were 26 public statutes relating to salmon, leading to confusion and uncertainty and rendering the law 'practically inoperative' (Bund, 1873 1). A Royal Commission (1860) investigated the decline of salmon fisheries in England and Wales, including the Trent catchment, leading to the *Salmon Fishery Act* (1861) (ibid). Several elements of the original Act related directly to the watermill owner (e.g. no fish to be caught at mill weirs and the provision of fish-passes over dams). The Commission advocated the removal or adaption of blockages to allow free passage of fish (Buffery, 2017). The resultant Act's measures appear to reflect watermill operations of the time, with a 42 hour weekly close time introduced (Bund, 1873) that appears to align with the 'Sunday observance' closure of most watermills (Seth-Smith, 1973).

A considerable number of studies investigating the evolutionary impacts of man-made barriers on aquatic organisms have been carried out, with Zarri's literature review identifying 2,383 studies (Zarri, Palkovacs et al., 2022). In determining the 'passability' of weirs their appears to be minimal consideration of the facilitation of fish passage through the use of sluice or free gaps in the run-of-river industrial mill weirs, recognised in the *Salmon Fishery Act* (1861). Salmon population studies in the Trent catchment show a decline in the mid-19th century (Cowx and O'Grady, 1995 12), half a century after the construction of the industrial revolution weirs, suggesting some level of fish passage was achieved during this period.

1.3.3.2 20th century (river pollution)

A 1935 report by the Trent River Authority's biologist, looking at the history of the fisheries of the River Trent, identified the combined effect of the obstructions in the river and pollution for the poor salmon runs at the end of the 19th century (cited in Easton, 1979). The 1950 annual Buckland Lecture, titled 'River pollution', aimed to address a gap in government legislation, without 'any really large-scale attempt to stop the horrible and quite unjustifiable pollution of our rivers', leading to The Rivers (Prevention of Pollution) Act, 1951 (Sheail, 1998 117).

Early in the 1950s, the Trent Fishery Board and the Earl of Harrington's angling club, supported by the newly formed national Anglers' Co-operative Association, launched the largest ever fisheries legal action against four polluters on the River Derwent below Derby. Claiming this section of the river had previously supported several million fish of different types, the 'watercourse had become, since 1945, dirty, relatively hot, and carpeted with foul sludge and sewage fungus. No fish, nor other forms of normal fauna and flora, were to be found' (Sheail, 1998 125).

In the Trent catchment four major sources of pollution through the 19th century were identified: potteries effluent, domestic and industrial effluent of the West Midlands (via the River Tame), brewery effluent (Burton) and heavy metals from the copper mines in the Dove catchment (Easton, 1979). Easton didn't include pollution of the River Derwent as one of the major contributors to the decline in salmon abundance in the River Trent. In the 1980s biologists from Severn Trent Water Authority started feasibility assessments to reintroduce salmon into the Trent catchment. This early study confirmed that both the Dove and Derwent would support juvenile salmon, but the Derwent was ruled out as an option due to the uneconomic proposition of delivering fish passage by the large number of obstructive weirs (DCAC, 1986).

1.3.3.3 Environmental flows

Since the 1980s the imperative has been to protect freshwater-dependent ecosystems, with the concept of e-flows mimicking natural flow variations (Neachell and Petts, 2017) in heavily managed riverways (Petts, 1990). In the 1960s George Baxter argued that, rather than having a fixed rate compensation flow from a dam, his 'schedule' would yield flows that not only better met the seasonal requirements of fish, but also used less water, and the approach was adopted around the world (Neachell and Petts, 2017).

Despite working on a committee set up by the North of Scotland Hydro-Electric Act, Baxter's efforts were focussed on the preservation of species, especially the Atlantic Salmon (ibid), not referencing the flows required for HEP generation, which was the likely purpose of the original compensation flow agreement. In 2001 an e-flow study in the upper DDC, commissioned by the EA, only considered the water utility abstraction requirements and potential river ecosystem improvement opportunities (Maddock, Bickerton et al., 2001). No consideration of HEP existing generation or potential was considered, for the Derwent or its affected tributaries. Management activities aimed at restoring endangered fish species, such as dam removals, fish pass installations and periodic turbine shutdowns, all tend to decrease HEP generation capacities. E-flow designs often attempt to mimic natural flow, but this designer flow concept, to be used in human altered rivers, such as the River Derwent with the

Derwent Valley reservoirs at its head, can facilitate other factors, such as discouragement of non-native fish, flood and drought management, as well as optimal HEP generation (Chen and Olden, 2017).

One modelling exercise predicted a change in dam management strategies could effectively increase the spawner abundance by 48-55%, whilst preserving 65% of the hydropower generation capacity (Song, Omalley et al., 2019). Research is underway around the world (Comino, Dominici et al., 2020, Kuriqi, Pinheiro et al., 2019) (Spain & Portugal; Scotland; Italy) identifying opportunities to factor HEP energy production into the assessment of environmental flows. Taking a more dynamic approach, e-Flow assessments suggest a 10-35% increase in energy output could be achieved with little impact on hydrological parameters (Kuriqi, Pinheiro et al., 2019). Current reservoir compensation flows are set at a fixed and steady flow, but research into varying dam outflows to optimise river flows to suit different species of fish at different times of the year, could also include dams currently used for water storage only, which could release water at energy demand peak times (Zarri, Danner et al., 2019).

Globally e-Flows are being utilised and different frameworks developed to improve their effectiveness. McManamay (2016) compares the science-based process (typically 2 years) developed by Richter et al (2006), with the typical licensing process, taking 5 to 10 years to complete. The science-based process relies on public involvement, with a series of workshops reviewing a preliminary assessment informed by a literature review and existing knowledge review to optimise e-Flows in the catchment, that support maximum renewable energy generation with minimum ecological impact (McManamay, Brewer et al., 2016).

1.3.3.4 21st century river ecology

In the UK, many of the provisions of the Salmon and Freshwater Fisheries Act 1975, that originated in 1861, relate to the obstruction to the passage of fish by weirs and are viewed by regulators as ‘a relic of the last century’ (Carty, 2001). Today there appears to be no acknowledgement of weirs containing sluices, floodgates or free gaps (Salmon and Freshwater Fisheries Act, 1975) and they are simply viewed as solid obstacles, with all of the UK's 7,000 to 10,000 weirs classed as barriers (Carty, 2001).

A small number of projects have investigated the use of exiting sluices to facilitate fish passage. One project, led by Natural Resources Wales in the 2010s, looked at the impact of the historic Bala sluice gates and low head weirs on salmon migration patterns, with undershot sluice gates originally designed as fish locks, as well as their primary flood management function (Gardner, Rees-Jones et al., 2016). Recent research has confirmed that sluices (if available) co-located with a pumping station, offer a safe and low-cost passage for silver European eels, if combined with operational changes i.e. night-time openings (Carter, Wright et al., 2023). Bangladesh has produced a policy brief, based on earlier research (Ali and Alam, 2005), to operate existing floodplain sluice gates in a way to enhance fisheries (Centre for Natural Resource Studies, 2005).

HEP development is complex, with many conflicting interests, such as the conflicting EU Renewable Energy Directive and EU Water Framework Directive (WFD) (Abazaj, Moen et al., 2016) or the UN Sustainable Development Goals 7 (affordable and clean energy) and 14 (life below water) (Kuriqi, Pinheiro et al., 2021). Regulations such as the European Water Framework Directive, 2000, (WFD) are moving river basins beyond the 20th century constructed and managed systems (Petts, 1990), to a more balanced system. Responding to the deterioration of European Union (EU) water status, it aims to protect and ensure the good ecological and chemical status of all water bodies (WFD, 2000 art. 2.9).

The EU WFD does not 'explicitly consider the implications of climate change' (Kilsby, Large et al., 2006 4). Barrier removal has demonstrated effectiveness and potential to restore river connectivity, increase habitat availability, and re-establish suitable habitats for refuge, feeding, and fish spawning (Kuriqi, Pinheiro et al., 2021). Nevertheless, barrier removal may not always positively affect all species, e.g., macroinvertebrates (ibid 12). Furthermore, removing weirs will conflict with the purpose for which it was built, e.g., the case of run-of-river HEP plants (ibid). Faced with declining salmon populations and risks of local extinctions, researchers are recommending conserving key river habitats, and minimising additional stressors where possible (Nicola, Elvira et al., 2018), with no reference to the loss of climate change mitigation opportunity, e.g. HEP generation, through weir removal.

In a 2011 study of HEP in North East Scotland, despite there being significant government policy support for the development of low carbon economies, rural diversification and multifunctional rural land use, ecological discourse blocked reinstatement or development of HEP due to the rigorous interpretation of the EU's Water Framework Directive (WFD) by the Scottish Environmental Protection Agency (SEPA), with its central concern to maintain water bodies in a pristine ecological and morphological state (Slee, Whitfield et al., 2011).

In England and Wales, the WFD is implemented through The Water Environment (Water Framework Directive), Regulations 2017. Low-head run-of-river HEP schemes must be designed to incorporate best practice mitigation measures to protect fish passage, with the onus being on the HEP developer to maintain or improve passage at the site (Dodd, Cowx et al., 2018, EA, 2013). This currently includes having a co-located fish passage solution (where the discharge from the turbine and fish pass are parallel) (Armstrong and Bulkeley, 2014, Dodd, Bolland et al., 2018). The Hexham River Hydro project, which failed to progress in 2013, found the 'fish issue' to be the most contentious element of the scheme, with strong opposition from the local Tyne Rivers Trust, the national Rivers Trust (the umbrella organisation), and separately the local angling community. The Rivers Trust claimed they organised their arguments using 'scientific and best evidence' approaches, whilst the local trust focussed more on the fisheries. Ultimately it was the local angling network, backed by the Angling Trust and their legal team, 'Fish Legal', who developed a 'Fighting Hydropower' campaign using the Hexham project as an example (Angling Trust, 2020), that led to the demise of the project (Armstrong and Bulkeley, 2014).

The Environment Agency Salmon Stock and Fisheries 2021 report identifies existing and emerging threats affecting salmon populations, such as red vent syndrome and other diseases, poor juvenile recruitment in 2016, pink salmon and escaped farmed salmon (EA, 2022). The report neglects to mention the threat to fisheries from climate change driven ocean warming, particularly to anadromous species such as Atlantic Salmon (Davidson and Hazlewood, 2005, Horreo, Machado-Schiaffino et al., 2011, Jonsson and Jonsson, 2009, Lightfoot, 2008, Nicola, Elvira et al., 2018). Dudgeon et al (2006) identified five key threats to global freshwater biodiversity; overexploitation; water pollution; flow modification; destruction or degradation of habitat; and invasion by exotic species. Environmental changes occurring at the global scale, such as climate change are superimposed on the five key threats (Dudgeon, Arthington et al., 2006). Despite some of the causes of the 1970s major decline, i.e. overfishing and disease, being addressed, there is a continued decline in populations (Nicola, Elvira et al., 2018).

1.3.4 Community energy

Community energy is fundamentally different from large, private energy corporations, with four key principles; community ownership and benefit, renewable energy locally produced and distributed, adaptive and resilient, and prioritising conservation first (Pahl, 2012). Community hydro (run-of-river small HEP) offers opportunities for local renewable energy generation delivered through local investment offering community benefits. Many other countries evolved cooperative energy development models as part of their energy generation model, but these were not a consideration in UK energy policy in the twentieth century (Armstrong and Bulkeley, 2014), as the UK's electricity generation network was designed on a centralised large-scale generation model (Hannah, 1979, Walker, 1997).

Today, Community Energy England, which supports best practise sharing with cooperatives, including EU organisations, states that, whilst community energy organisations need to be financially viable to deliver projects,

> 'By continuing to build strong partnerships with stakeholders and working collaboratively, we will play a key role in responding to the climate crisis whilst creating thriving, fairer and sustainable communities' (Bridge, Proctor et al., 2019 1).

Armstrong & Bulkeley (2014) capture most of the unique challenges of developing small HEP project in the UK, a major factor being the level of complexity and associated expertise required to cope with the Water Framework Directive (WFD) legal frameworks, seeking finance, permits, and planning applications, which is particularly difficult for volunteer led organisations (Bracken, Bulkeley et al., 2014). Also, the financial support for community energy co-operatives continues to change in all aspects, notably grants for feasibility studies, taxation, share ownership rules and renewable energy generation incentives (Armstrong and Bulkeley, 2014).

The consenting process enables the EA to require approved fish passage in HEP developments, to improve specific waterway quality classifications, described as win-win opportunities in the 2010 EA hydropower and sensitivities report (EA, 2010). The costs relating to the water loss and design and build of fish passes, added to the conditions of an EA abstraction licence, have been partially responsible for the failure of Community hydro projects in Hexham (Hexham River Hydro, 2013), Jordan Dam (Sheffield Renewables, 2013) and Ambergate in the Derbyshire Derwent catchment (Transition Belper, 2019) (Section 5.2.3.1).

When the climate change mitigation plans were developed in the UK in 1989, community energy was unknown, but 20 years later there are over 5,000 community energy groups in the UK who have built climate mitigation projects (Lees and Eyre, 2021 17). There are also positive political signals in Scotland, which has set a target of 2 GW of renewable energy capacity in local ownership by 2030 (ibid). One challenge for small HEP developers in England today includes barriers to market entry (Armstrong and Bulkeley, 2014). These prevent the sale of electricity directly to local communities, which would allow the sale of renewable energy above wholesale prices. Restrictive network connections also challenge the viability of potential HEP schemes and require high levels of expertise to manage them. The Local Electricity Bill is a private members bill currently under review by the UK government (March 2021), aimed at overcoming this challenge (Power for People, 2021).

1.4 Research approach and methodology

HEP development is complex, so the research approach requires understanding in a variety of academic disciplines, including geography (human and physical), history and engineering. The overall approach of the research is historicist (Flowerdew and Martin, 2005), aiming to understand the current situation regarding society's use of waterpower (and predict future states), by gaining a detailed knowledge of its history and development.

Research into vulnerabilities, resilience and ability to adapt to future climate change impacts, has been undertaken by geographers and historians in the fields of historical climatology and climate history (Endfield, 2014). Archive collections are being revisited to construct histories of flood/drought and the associated impacts, explore the impact of weather events on communities and understand how weather events were managed (Houghton-Foster, 2021). A collaborative research programme (2013-2016), developed under the Arts and Humanities Research Council's (AHRC) theme 'Care for the future: thinking forward through the past', led to the development of the TEMPEST Database, capturing historic extreme weather events (University of Liverpool, 2017). This approach, 'caring for the future: thinking forward through the past', is used to gain an understanding of the core story of waterpower use through time. Years two to four of this research project were funded by the AHRC, whose priorities include 'Contemporary challenges: analysing the present, and learning the lessons from the past to shape a better future' (UKRI, 2023).

1.4.1 Scope of the research

The Derwent Valley Mills World Heritage Site (DVMWHS), inscribed by UNESCO in 2001 (DVMWHS, 2020), with its waterpower core story, was an obvious research study area option. Whilst the DVMWHS' water powered textile mill sites are a rich source of information, the site only covers a 24 km (15 mile) stretch of the River Derwent, containing a small number of larger industrial textile mills. To fully understand the waterpower opportunities and challenges a broader range of waterways, watermill applications and sizes was required.

The county boundary of Derbyshire was also considered as the potential scope for the research, offering a broad range of watercourses and waterpower applications. Using the county boundary would have the benefit of aligning with the county local authority area and covering the same area as many of the existing industrial archaeological and watermill gazetteers and databases, such as the Derbyshire Industrial Archaeology series '*A gazetteer of sites*' (1984-2011) and the digital Derbyshire Historic Environment Record. Amongst the geographical features of Derbyshire are the Rivers Dove and Erewash that run along the West and East boundaries respectively: including their watermills would mean that tributaries and mill sites may be located, fully or partially, in the adjacent counties of Staffordshire and Nottinghamshire. A 2010 HEP study, focussed on the Peak District National Park (PDNP) land boundary, ran into a similar challenge, where following waterways out of the PDNP led to the inclusion of 42 sites outside the PDNP (Woods, Tickle et al., 2010). A focus on three key rivers would add the complication of engaging with three different river catchment partnerships and county authorities.

It was ultimately decided to focus the research on the hydrological extent of the Derbyshire Derwent catchment (DDC). The catchment has a significant historic use of waterpower, incorporating the whole of the DVMWHS, and encapsulating the River Derwent and tributaries in a single county (Figure 1.10). The DDC is one of eighteen management catchments within the Humber River Basin District (1 of 10 in England) (EA, 2023), and has a stakeholder partnership already in place, hosted by the Derbyshire Wildlife Trust and supported by the Environment Agency. As part of the Trent catchment, the DDC has the additional research benefits of including a national park and a world heritage site, enabling consideration of the constraints that these protected sites pose to HEP development (Scene Connect, 2022). The DDC includes a variety, and achievable volume, of waterpower sites identified within the first year of the PhD, allowing time to research their chronologies in depth, to identify incidents, deviations or step changes in waterpower use, and their causal factors (Kepner and Tregoe, 1981, Suarez-Barraza and Rodriguez-Gonzalez, 2019).

Figure 1.10 The Derbyshire Derwent Catchment Partnership map (Derbyshire Wildlife Trust, 2015)

Recent technological developments, such as the digitisation of historic texts and archives, make available a significant volume of research information. Developing the 'biography' of individual waterpower sites helped to focus the search for information to understand sites' past lives (of the mills and mill owners) and the external factors that have shaped them (Hodder, 2017).

Wherever possible the research focussed on waterpower usage in the DDC but external events and developments that impacted on the usage at regional (local plans), national (government policy and regulation) or international (e.g. Water Framework Directive) level were referenced. Heritage impact statements, required for HEP developments today on heritage sensitive sites, also offer additional sources of information. Examples of the successful use of waterpower through time in regions outside the DDC, such as Scotland or Germany, were also incorporated to identify potential lessons to learn.

1.4.2 Waterpower site identification

With no comprehensive site-by-site list of watermills or HEP generators in the DDC, or indeed Derbyshire, site identification was the first task. Looking for power to drive their new larger textile mills, the early industrialists first considered sites with a history of waterpower. Following a similar principle today, and knowing the rivers were saturated with mills (Cossons and Rees, 1972), historic maps (1880 to 1920 OS maps) of each waterway within the DDC were studied to find evidence of watermills, such as mills, weirs, pumps, and sluices (Section 2.2.3). The resulting list of watermill sites was referenced against existing gazetteers, regional industrial archaeology texts and online resources, initially to confirm name and location, and then to build a timeline for each site, using qualitative historical research to identify and understand changes in waterpower usage.

1.4.3 Identifying the cause(s) of the problem

To gain a deeper understanding of the key themes and issues influencing the use of waterpower in the DDC, identified from the literature review and waterpower site timelines, five in depth case studies were pursued: Ambergate (Alderwasley), the Chatsworth Estate, the Derwent Valley reservoirs, the Derwent Valley Mills World Heritage Site and the Weirs of the River Derwent. These studies covered different aspects, some with large volumes of archive and reference materials available, such as Chatsworth Estate, and others with no previous research and limited primary materials, such as the Derwent weirs.

To understand the historic ‘situations’ and decisions made, primary and secondary materials relevant to the period under consideration were referenced in developing the site timelines and more detailed case studies. This approach gave a virtual version of Genchi Genbutsu (Go and See), a practical problem-solving technique (Liker and Meier, 2006), using the traces left from former lives to reconstruct the relevant histories (Moore, 2010). These materials were used to tease out 'facts' of all sorts - material circumstances, states of mind, motivations, decisions, assumptions and values (Finnegan, Drake et al., 1994 16) - that influenced the use of waterpower. Historic sources published information included directories (e.g. Glover, 1829), travel guidebooks (e.g. *The Compleat Angler* - Walton and Cotton, 1676), engineering reference books (e.g. *Practical essays on Mill Work* - Buchanan, 1823) and newspaper reports (e.g. The Conversazione event organised by the Derby Chamber of Commerce introducing electric lights and motors, *The Derby Mercury* 1882, April 26). Many contemporary 18th century and 19th century books and references have been digitised and are accessible.

The richest source of original research material was to be found within public and private archives, the space in which materials of historic interest or social significance are stored, presented and ordered (Brown and Davis-Brown, 1998). The large volume of archive materials available required a research strategy that evolved over the course of the study. The Derbyshire Record Office (DRO), based in Matlock, Derbyshire holds many archive collections relating to the Derbyshire Derwent catchment, including influential family records (e.g. Strutt family D3772), business records (e.g. English Sewing Cotton Company D3638), legal records (e.g. Hurt versus Strutt, DRO D2535, 1818-44) and maps and plans (e.g. Burdett’s Map, DRO D769/B/13/1/181, 1767). Legal records, including land and property sales and court cases, proved to be important sources of information, sometimes offering different perspectives on a given situation, with the records for the prosecutors and defendants being held in different family or solicitor collections.

Recent article and book references were used to identify original source archive materials but searching the DRO's collections with their online search engine, using generic terms such as weir, watermill alongside the name of a miller, owner or location, proved the most productive in terms of the identification of original, relevant, research materials. Revisiting some of the collections with different lenses and discovering original materials enabled 'the making of modern memories' (Schwartz and Cook, 2002). These materials often led to key finds relating to individual site and waterpower core story timelines. For example, a 'corn mill' search identified papers for the Crich Corn Mill fed by sough water. Further investigation of the 1753 lease found reference to floodgates being required and the species of fish currently found in the River Amber, not to be impacted by the new mill (DRO D2535/M/3/3, 1753). A later walk over survey found the weir to have been removed so it was the 'archival fieldwork' (Harris, 2001) that identified the use of floodgates in 1753. A previously unopened research folder of R S Fitton (DRO D8185, c1950) (co-author of *The Strutts and the Arkwright's*, 1958), was found to include a copy of pages from a PhD thesis on the work of Thomas C Hewes, an important Manchester wheelwright, and led to the discovery of a piece of research generally unknown in the field. A copy of the full (Smith, 1969) thesis was traced to the Ironbridge Library Archives and shared with researchers in the US, also investigating the development of waterpower.

In addition to the specific details and clauses of government acts, such as the Cromford Canal Act 1789, the Parliamentary Archives include evidence given to public enquiries, details of mill developments during the 19th century in the Factory Returns, and debates in the House of Lords and Commons on subjects such as energy security in the 1970s. Other archives accessed during the research project include the Derbyshire Archaeological Society, University of Nottingham Manuscripts and Special Collections (including the River, Drainage and Water records) and School of Geography department (including the complete East Midland Geographer collection), Belper North Mill Trust and the Arkwright Society archives.

Access to newspapers and periodicals, whose digitisation and access have expanded significantly since 2002 (Nicholson, 2013), improved the understanding of specific events and changes. Newspaper archives, usually Derbyshire publications, were searched using dates, location and specific phrases (e.g. turbines), identified from other primary and secondary sources (ibid). The newspaper articles often complemented existing facts with broader reports and descriptions, such as the December 1893 reports of Chatsworth House opening to reporters to see the electric lighting powered by the newly installed hydroelectric turbines (*The Derbyshire Times*, 1893), including the electric light switch by the Duchess's bed. Two national publications were a rich source of information: *The Engineer* (1856-1950) accessed via Grace's Guide, technical perspectives on power developments and the Derwent Valley reservoirs; *The Field* (published since 1853) reported on rural life and included a series of articles on fish passage across the UK in the 1860s.

There are significant gaps in our understanding of the use of waterpower, in particular HEP in the second half of the 21st century (with restricted archives), but the increased interest in industrial archaeology in the 1960s, due to many sites being threatened with demolition (Smith, 1965), led to useful articles and books being produced during that period, including those in the East Midlands Geographer. Several associated research projects looking at the history of industry in the East Midlands, including many watermills, not only included historically useful materials, but also gave rare insights into the status of mills visited in the 1960s (Shaw, 1965, Swindell, 1963), as this current research will offer future researchers a 2023 snapshot.

With over 150 waterpower site timelines and five case studies, covering 270 years, a large volume of qualitative information was collated. Using time as a common x-axis, waterpower sites' activities were compared in a variety of ways and against different attributes, including individual waterways and mill types, to identify potential causes of change in waterpower use (Kepner and Tregoe, 1981). By comparing timeline deviations with information from the broader literature review, waterpower developments were captured along with local (e.g. change of the mill ownership), regional (e.g. reservoirs diverting water for drinking and sanitation), national (e.g. renewable energy support) and global (e.g. wars) contributing factors impacting on waterpower usage.

Identifying underutilised HEP potential as the outcome, the qualitative, systematic, Ishikawa cause-and-effect diagram (CED) tool (Caplen, 1988, Ishikawa and Lu, 1985), also known as the Fishbone diagram (Suarez-Barraza and Rodriguez-Gonzalez, 2019), was used to rationalise and collate the voice of the research. The novel approach of using the CED as the core structure of the research study allowed both major, higher level, and minor causes of the underutilised HEP problem to be identified (Metha, 2014). For this research the six classic 6M aspects of the CED (Measurement, Machine, Man, Methods, Mother Nature and Materials) (George, 2005) were adapted, for the contributing factors impacting on the use of waterpower identified through the literature review and site timeline development. The six factors are: the demand for power and generation technology options (Power: supply and demand); the harnessing and use of waterpower (Waterpower technology); the individuals, families, businesses, communities and authorities influencing the use of waterpower (People); the influence of government policy and regulation (Policy and regulation); the positive and negative impacts of waterpower on the environment (Environmental impacts); and the use, demands and regulation of water and the rivers (Water: supply and demand) (Figure 1.11). The major causes for each contributing factor were addressed in each age of waterpower (Chapters 3 to 5), identifying the specific minor causes that have influenced the use of waterpower over time, to determine options to unlock HEP potential.

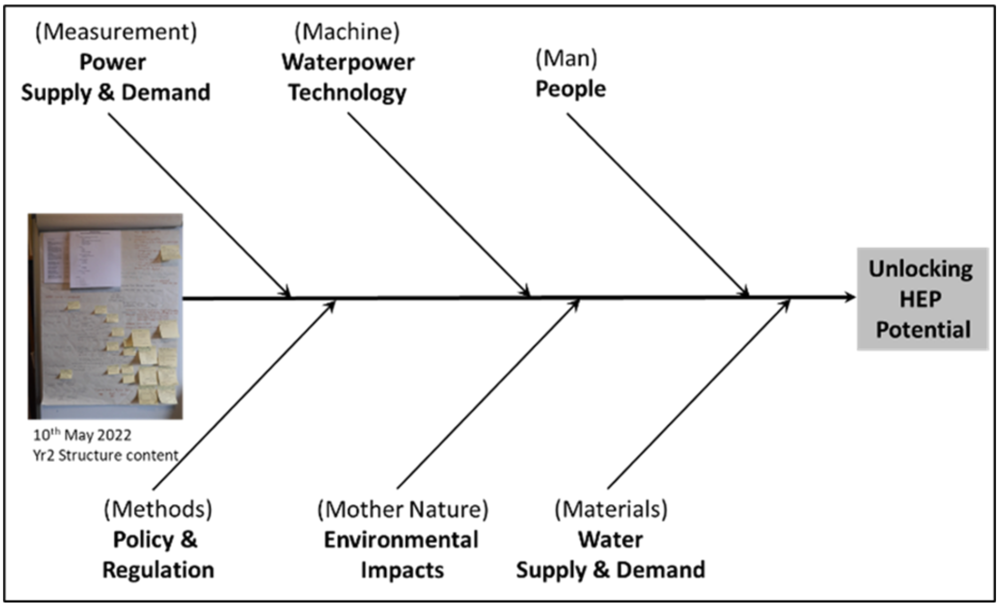


Figure 1.11 The six key contributing factors cause-and-effect diagram

1.4.4 Engaging with stakeholders

Prior to starting the PhD, I was actively engaged as a volunteer in a local sustainability organisation that set up a Community Energy group and investigated potential HEP site opportunities in the DVMWHS. With HEP opportunities located in historic watermills, and limited understanding of historic local waterpower, a new personal interest in researching the mills' use of waterpower led to engagement with heritage groups and a variety of HEP development stakeholders. Membership of related groups and societies, such as The Midland Wind and Water Mills group, has facilitated access to key people, businesses and groups, interested in the 'in-progress' research findings. Nine presentations, to relevant heritage and mill groups, have all led to useful feedback and, on occasion, mill owner vernacular observations on issues, such as the regional nature of the impacts following the introduction of water usage charges in the 1970s. Presentations to wider audiences, such as New Lanark's WHS 20th anniversary conference and the British Hydropower Association annual conferences have also led to new contacts and sources of information.

Throughout the research period, feedback during the walks and talks that I have led, such as the Derbyshire Archaeological Society 'Powering the Derbyshire Derwent Valley' presentation, 4th March 2022, has identified local unpublished information. Many of these talks were open to the public, with attendees interested in the current issues preventing HEP reinstatements at historic watermill sites and sharing their views on conflicting 'good causes', such as historic weir removal for fish passage. I have also been able to share my research findings with key stakeholders in my volunteer roles with the Derwent Valley Mills World Heritage Site (Strategy Board [green energy advisor] and Research Group) and the Derbyshire Derwent Catchment Partnership.

When presenting research findings, the initial slides clarify that the primary purpose of the research is climate change mitigation, aiming to be transparent regarding any bias that may have influenced the research process and findings, recognising the potential conflict with the perceived harm to heritage properties or river ecosystems. This approach was also incorporated during informal, unplanned, discussions with mill owners during the watermill site field surveys. Key stakeholders, such as government ministers, landowners (e.g. Chatsworth Estate Manager) and the local HEP specialists, Derwent Hydro Power Limited (DHPL), were also made aware of the primary purpose of the research during planned interviews. Another ethical consideration was the sharing of information regarding potential HEP sites, that, would have been of interest to potential HEP developers, during the period of Feed-in-Tariff support. The decision taken was to keep site or operator's details confidential, unless they were already in the public domain, but to share any findings regarding the historic use of waterpower at all the sites, to build and convey the most complete, quantitative, picture possible. The aim will be to make this information freely, publicly, available to all interested parties, to encourage and support HEP interest and potential development, ideally by property owners or local communities.

To support the visual storytelling of the research, the findings were mapped using the open-source package QGIS, which allows participants to geographically relate to the findings and, in some cases, identify gaps in the findings, with their local knowledge (Flowerdew and Martin, 2005). An open-source GIS was selected to enable other communities and catchments to repeat this research process and to tell their own waterpower story. Whilst the University's access to Digimap's historic OS maps was an important source of information in the early stage of research, other freely accessible resources, such as the National library of Scotland (historic OS maps) were identified as an alternative source of information. The GIS was used only for visual interpretation of the findings and not quantitative analysis. The large number of c.1890 watermills shown in Figure 2.17 could be misleading if HEP potential was the primary question, as many of the mills on the tributaries would be very small in power availability. The GIS gives a geovisualization (Buckley, Gahegan et al., 2000) of the distribution of communities, mill owners and estates of the DDC. For the purposes of the research, two-dimensional mapping has been used to visualise the use and features of waterpower in the DDC, but this does not clearly show the topography and HEP potential that a more complex three-dimensional map could.

1.4.5 Identifying the HEP potential of the DDC

The Community Hydro project in Ambergate raised the interest of the then Member of Parliament for Mid Derbyshire, P Latham, who, throughout the research period, has facilitated communications with government stakeholders, including renewable energy and rivers ministers. Policy makers at national (Hands, 2022) and regional (Derbyshire County Council, 2012) level are influenced by the overall potential of HEP, in their efforts to decarbonise electricity generation, so a HEP potential assessment was incorporated into the research project, retrospectively.

Current UK government guidance for regional spatial studies references the SQW Energy model (Figure 1.12), to develop a comprehensive evidence base for renewable energy potential (Bronsdon, 2010). The SQW Energy model (not to scale) shows the range of outputs from any opportunities study, based on the level of constraint(s) applied. The application of time specific economic constraints and changing environmental regulation make it impossible to directly compare findings from different HEP studies (Sample, Duncan et al., 2015). The man-made constraints change over time, e.g. the introduction, and removal, of Feed in Tariffs, or additional regulatory constraints, e.g. Water Framework Directive, and will continue to change in the future.

The potential identified in a renewables report for Derbyshire County Council (Scene Connect, 2022) included the man-made constraints (Figure 1.12), such as physical environment constraints of high priority (stage 3), planning and regulatory constraints (stage 4), and economically viable (stage 5), reducing the overall technical HEP potential declared. Every HEP study produced since 1978 has captured the reduced economic, and more recently environmental, constrained potential. For the purposes of the DDC opportunities assessment in this research (Section 2.3.6) the ‘exploitable technical potential’ is used based on current infrastructure, i.e. existing weirs, or stage 2 of the model.

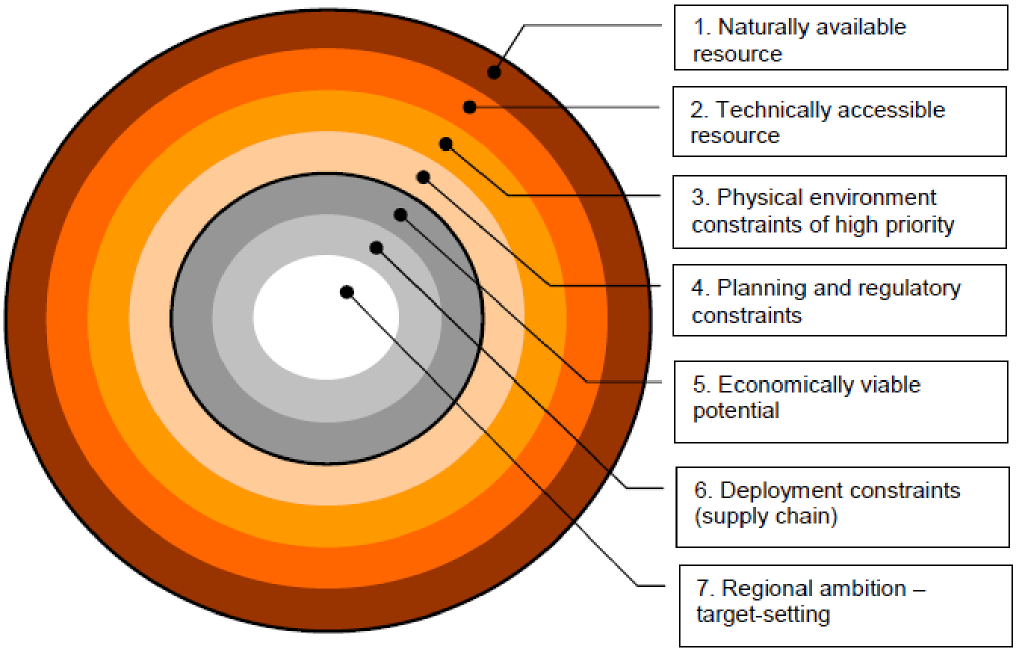


Figure 1.12 The SQW Energy - stages of renewable energy potential (Bronsdon, 2010)

Previous regional and national HEP potential studies were reviewed to identify a methodology for a DDC HEP potential assessment, within the resources and timescale of the research programme. In the first 'comprehensive' HEP study in 1989, commissioned by ETSU for the Department of Energy and completed by Salford University Civil Engineering, run-of-river sites were identified by manually scrutinising Ordnance Survey (OS) maps, looking for close contours on rivers (Duncan, 2012). HEP potential was calculated using catchment characteristics such as soil types, average evapotranspiration and average rainfalls (Sample, Duncan et al., 2015). Despite claiming that the report included 'now disused mills', a minimum 25 kW limit was used due to 'possible developments costs rising exponentially as the power available decreases' (Salford Civil Engineering Limited, 1989 9), thus excluding the majority of historic watermills. Repeatedly, sites larger than 5 MW are ruled out, on the assumption that they would have already been exploited by the public sector (Scene Connect, 2022, Wilson, Day et al., 2022).

Bias can also creep into studies, for example the Atomic Energy Authority's Energy Technology Support Unit, part of the competing Nuclear Power industry, commissioning the UK's 1989 study (Winskel, 2002) and the EA, whose priorities are river ecology improvement through barrier removal of fish passage, completing the 2010 study for the UK Department of Energy and Climate Change.

A new 'automated' method of identifying potential HEP schemes (termed 'Hydrobot') was first employed by Forrest (2006) to identify sites in Scotland in 2008. A GIS, containing flow and elevation data, was used to estimate the hydropower potential at each point along the river network. Flow data for each waterway was supplied by the Scottish Environmental Protection Agency (SEPA) (Sample, Duncan et al., 2015). The automated approach was refined in Duncan's assessment of Scottish Hydropower potential, with site identification automated within the GIS, and Flow Duration Curves for each location generated using the Grid2Grid water balance model (Duncan, 2012, Sample, Duncan et al., 2015). Generating the flows using the model allowed 'what if' scenarios to be run, simulating the possible effects of future climate change (Sample, Duncan et al., 2015). However, both the 2008 and 2012 assessments again incorporated economic discount rate calculations and, despite the total potential HEP capacities being broadly comparable, the detailed findings were very different: Duncan's 2012 study failed to identify any economically viable schemes < 100 kW, whereas Forrest's 2008 study identified 256 MW of potential in that category (ibid). This raises doubt about the value of past HEP studies applying the varying man-made constraints, including the 'automated' GIS assessment-based studies.

Using the findings from the waterpower gazetteer and site timelines, a quantitative analysis was carried out to provide a HEP potential for the Derbyshire Derwent catchment, and an estimated potential for Derbyshire. Using installed HEP kW (current or historic) and typical flow regimes within a given waterway, a HEP potential model was constructed. The relatively low cost, site-by-site, HEP potential method, which could be replicated in other river catchments, is based on the premise that the late 18th century factory masters found suitable waterpower sites, based on existing waterpower sites. With little opportunity for new barriers or weirs being built in the UK waterways in the future, the HEP potential model is based on the existing historic weirs, many originally built when waterpower was the primary power source (1770s-1830s). During this period, optimisation of power generation on 'saturated' rivers was critical, influencing weir locations, weir height, impacts on the river, other river users (including upstream and downstream mill owners) and their local communities, in all conditions, including drought and flood.

Three types of waterpower site were incorporated into the HEP potential model:

1. Any water powered mill site still in operation by the end of the 19th century, and identified on the OS maps from the period, as they are likely to have the structures in place that could be used today to generate HEP (reviewed during walk-over survey).

2. During the 20th century new structures, dams and weirs were built in and around the catchment to capture, store and distribute water. Each of the 20th century barriers, identified on current OS maps and walk-over surveys, may have the potential to generate HEP, as per the turbines installed in the DV reservoirs.

3. A review of current HEP generating sites in the catchment may also identify more original flows of water that have been harnessed for power. Within the DDC, HEP is being generated by the Chatsworth Emperor Fountain water supply, Calver Sough Water and the Longbridge, Derby Canal, weir. In addition to the generating sites identified, these signpost similar opportunities, such as other mining sough water tails.

Carrying out a site-by-site study for each river in the catchment, capturing technically feasible HEP opportunities (with flow available and infrastructure in place), is a replicable methodology that could enable a UK-wide HEP assessment for decision makers, not reduced by timebound, variable, man-made constraints.

1.5 Thesis structure

Following Chapter 1, the introduction, Chapter 2 investigates the use of waterpower in the Derbyshire Derwent catchment (DDC) since the 1750s, identifying the main causes of significant changes in the power harnessed from the River Derwent and its tributaries. Chapter 2 also includes details of the methodology used to build a gazetteer of waterpower sites in the catchment, site timelines and HEP potential for the DDC. The timelines helped identify the key periods, themes and issues relating to waterpower generation.

Three discrete periods of waterpower usage emerged and Chapters 3, 4 and 5 are based on these time periods, capturing the specific DDC related research findings. Six key waterpower themes were identified in the literature review and timeline building exercise: Power (supply and demand), waterpower technology, people, policy and regulation, environmental impacts and water (supply and demand). These form the structure for the period-based Chapters 3, 4 and 5.

Chapter 3 investigates The Age of Mechanisation (1752 to 1878), a period that saw improved scientific understanding and development of power generation to provide the mechanical drive for the new industrial mills producing a range of goods. The chapter looks at the development and use of waterpower, particularly in the DDC, to understand waterpower's influence on the industrial revolution. The 18th and early 19th century uses of water management infrastructure to manage water supplies to match manufacturing operation time, facilitate fish passage, clear silt and manage drought and flood conditions, are poorly understood today, and are explored in this chapter.

Chapter 4, Hydroelectric Power (1878 to 1989), covers a period that saw the repurposing of waterpower and, for the first time in centuries, a decline in its use. The introduction of electric lighting led to water wheels or turbines adding dynamos or generators to produce electricity. Examples, such as Cragside introducing electric lighting are well known, but there is limited understanding of how electricity was introduced across the country for use in country houses and industry. DDC site timelines, compared against turbine sales during the period, help map the deployment of electricity and its use, including the decline in waterpower usage in the second half of the 20th century.

Chapter 5, Renewable Energy (1989 to 2023), captures today's situation, when, faced with the challenge of climate change and the need to decarbonise power systems, renewable energy subsidies were introduced (1990). This led to several HEP reinstatements and new projects across the country, including in the DDC, which in December 2022 had seventeen active HEP generators. Withdrawal of the subsidy in 2019, along with complex planning constraints and environmental regulation, influenced by the Water Framework Directive, effectively halted HEP development across England, including at least three potential opportunities in the DDC.

Chapter 6 synthesises the key learnings from the past, reviewing the achievement of the objectives and overarching aim of the research (Section 1.2), as set out at the commencement of the research project in 2020.

Chapter 2 Waterpower: Investigating the potential and challenges

2.1 Waterpower in the Derbyshire Derwent catchment

This chapter explains the process of developing a waterpower site gazetteer and creating individual timelines for each watermill site in the Derbyshire Derwent catchment (DDC). The aim is to investigate the past and present challenges that waterpower, and its later form, hydroelectric power (HEP), have faced, to unlock the natural renewable energy potential of the River Derwent and its tributaries, and use the gazetteer and timeline findings to assess the DDC HEP potential today.

Following the identification of all the rivers and tributaries of the catchment, waterpower sites were identified using a manual mapping exercise utilising historic (1880s-1920s) Ordnance Survey maps. The mapping exercise and follow-up walk-over surveys also led to the discovery of non-mill sites that have harnessed waterpower for mechanical power (e.g. pumping) in the past and some generating HEP today (e.g. Derby Longbridge 'canal' weir). Non-mill sites were added to the waterpower site gazetteer, along with similar non-mill sites with the potential to generate HEP (e.g. Carsington and Ogston reservoirs).

2.1.1 Waterpower today

In 2010, during my first meeting with the newly formed Transition Belper, a community group focussed on sustainability and resilience, I asked if our local historic textile watermill, part of the Derwent Valley Mills World Heritage Site (DVMWHS), could produce hydroelectric power (HEP) as a practical, local action to support climate change mitigation efforts. With the question unanswered three related research projects followed:

- Determine the quantity of HEP being produced at Belper and the other former textile mills in the DVMWHS.
- If HEP was not being produced on historic watermill sites in the DVMWHS, understand why not.

- Improve our knowledge of the historic use of waterpower in the DVMWHS to understand the opportunity for future local community HEP development, supporting local climate change mitigation efforts.

A supportive coalition government (2010-2015), seeking local renewable energy solutions, introduced fiscal schemes to encourage local communities to identify and develop low carbon projects. The 2011-12 Local Energy Assessment Fund (LEAF) offered grants to support community action on energy efficiency and renewable energy (DECC, 2014b), driving forward 236 community energy projects (DECC, 2014a). Area-wide renewable energy studies were encouraged, incorporating the newly introduced Feed in Tariffs (FiT) (Apr. 2010) mechanism. Transition Belper was one of the successful community groups to receive LEAF funding to support several projects, including a desk top assessment of HEP potential in the DVMWHS. The Transition Belper study identified six locations (five historic watermills and one historic canal weir) currently generating HEP, and six locations with HEP generation potential, including two larger opportunities on the River Derwent at Ambergate and Darley Abbey (Harton, Chandler et al., 2012). The study also referenced two potential constraints to future development of these opportunities: the heritage impact on the listed sites and the Environment Agency seeking opportunities to improve river ecology, through fish passage by weirs (ibid).

Other hydropower assessment studies were completed in Derbyshire, encouraged by the FiT subsidy mechanism. A comprehensive study of waterpower sites in the Peak District National Park (PDNP), carried out by the Friends of the Peak District (Woods, Tickle et al., 2010). This study identified a total of 162 potential sites, 120 in the national park boundary, with 12 sites generating HEP. Of the remaining 150 sites, three schemes were in development, and, from the remaining historic watermill sites, it was estimated that it would be worthwhile carrying out more detailed studies for 80 sites (ibid). Derbyshire County Council (DCC) also prepared a report on hydropower (2012), including case studies on three HEP projects at Longbridge Weir (Derby), Alport Mill on the Haddon Estate and Calver Mill. This report identified 17 water-generated electricity plants in Derbyshire, ranging from 8 kW up to 350 kW, with a total installed capacity of 2.35 MW (Derbyshire County Council, 2012).

Following the Energy Act 2008, which created the FiT scheme (ibid), Severn Trent Water (STW) carried out studies across their assets, including the water storage, treatment and distribution network, leading to HEP upgrades and a new 305 kW HEP project at Howden Reservoir, again benefiting from the FiT scheme. Unfortunately the 2008 STW HEP studies, which had identified other potential opportunities, were unavailable for this research.

In 2022, Derbyshire County Council commissioned a renewable energy study for the county. Regarding hydropower, the study identified 14 HEP installations in Derbyshire with 1.7 MW capacity (Scene Connect, 2022). Both the number of operating sites and installed capacity are incorrect and too low (Section 2.3.6).

2.1.2 Locating historic waterpower sites

To develop a full understanding of the past and present use of waterpower and the potential of the Derbyshire Derwent catchment (DDC), a comprehensive historic waterpower site gazetteer was required. The 1086 Domesday survey identified approximately 98 watermills in Derbyshire, by village locations (Morris, Morgan et al., 1978). Early 19th century Derbyshire County directories, agriculture reports and contemporary history books also reference mills, their activities and approximate locations, but, again, none could claim to be comprehensive records of watermills, with even the most detailed list of manufacturers by Farey (survey 1807-09, published 1811-17) excluding corn mills (Shaw, 1965). Whilst these reference materials do not offer one complete list of water mills, they include important, contemporary, insight into specific topics and issues relating to the historic use of waterpower, by identifying changes in waterpower generation or use relating to specific mill types (e.g. cotton mills or flour mills) or individual mill sites. In his survey of *Agriculture and Minerals of Derbyshire*, Farey identified sites from the following water powered industries in 1807-09 (Table 2.1), many located within the DDC research area.

Table 2.1 Derbyshire watermills 1807-9 (Farey, cited in Gifford, 2003 unpublished)

Animal Based	Vegetable Based	Mineral Industries
Bone Crushing Mills	Turning Mills	Cannon Casting
Fulling Mills	Calico Printing	Grind Mills
Leather Mill	Calico Weaving	Forges, Puddling, Rolling and Slitting Mills
Woollen Cloth Factories	Cambric Weaving	
Silk Spinning Mills	Candlewick, Bump Mills	Foundries
Charcoal Mills	Cotton Spinning Mills	Saw Mills
Shelling, Oatmeal Mills	Flax-spinning Mills	Screws Mill
	Paper Making	Sheet Lead
	Tape Weaving Mills	Colour Grinding Mills
		Flint Grinding Mills
		Malt Mills, Steel Mills
		Scythe - Smiths

Six Derbyshire history and archaeology reference books, some incorporating gazetteers, were used for initial site validation and to help populate the individual site timelines. The books referenced were: *Industrial Archaeology of Derbyshire* (Nixon, 1969); *Industrial Archaeology of The Peak District* (Harris, 1971); *Derbyshire Industrial Archaeology: A gazetteer of sites (part 1 to 7)* (Fowkes, 1984-2011); *Corn Mills of Derbyshire* (Gifford, 1999) and *Mills on the Derbyshire Wye* (Roberts, 2010).

A study of historic (1767-1884) waterpower use in the Derbyshire Derwent Valley was carried out by Shaw (1965) using cartographic evidence, documentary evidence (including contemporary directories) and field surveys. The cartographic evidence included the Burdett map of Derbyshire, surveyed between 1762 and 1767, which was the first large scale county map that showed the distribution of watermills in Derbyshire (Figure 2.1) (Shaw, 1965). Other pre-Ordnance Survey maps referenced by Shaw, included Sorocold’s 1717 map of lead smelting mills (water powered), and the county maps of Greenwood (1825) and Sanderson (1836) (Shaw, 1965). The first Derbyshire County map at a suitable scale with referenceable locations, was the first edition Ordnance Survey map, surveyed between 1880 and 1884. Comparing the Burdett mills against the historic mills identified in this research, using GIS mapping (Figure 2.2), highlights that, whilst Burdett’s map shows the distribution of watermills across the county, he missed a number of watermills on smaller tributaries, and, in locations with a large concentration of watermills such as Derby, many were not recorded.

Figure 2.1 Burdett's map (part) of Derbyshire, 4 watermills on the River Ecclesbourne and 3 watermills on the River Derwent (DRO D769b/13/1, 1767).

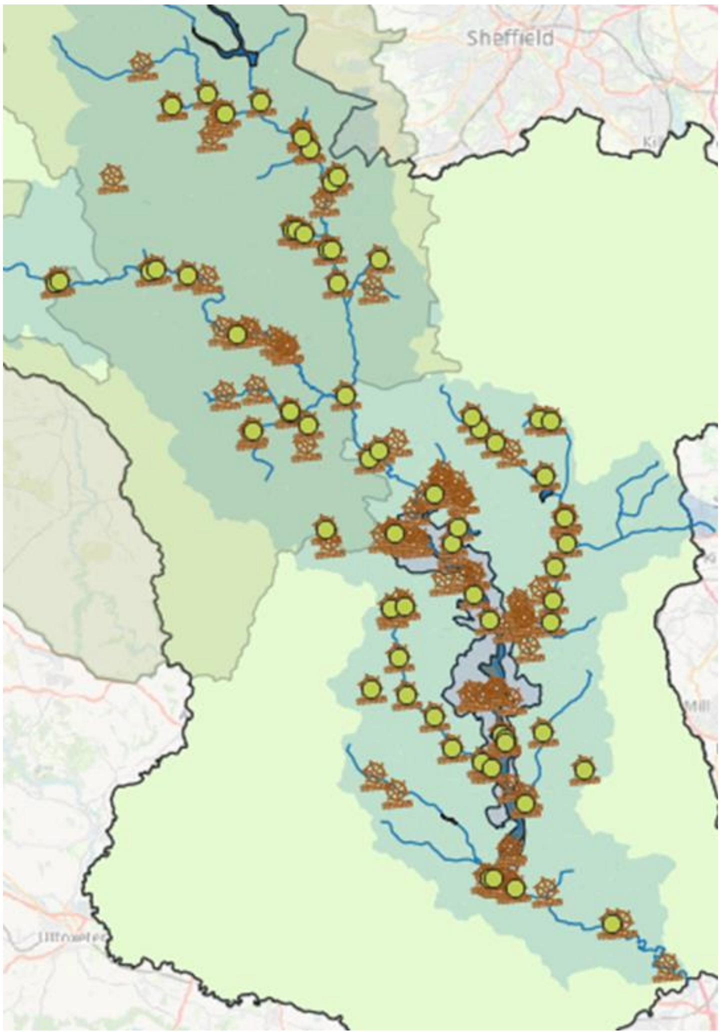


Figure 2.2 Comparison of watermills in the DDC - Burdett's map (1767) (green dots) versus the watermills identified on the early OS maps (brown waterwheels).

In the search for an existing historic watermill gazetteer or database for the DDC, three possible online sources were identified, the Derbyshire Historic Environment Record (HER), maintained by Derbyshire County Council, the national Mills Archive, and a "Mills in Derbyshire and Peak District" list on a privately maintained website (Derbyshire Heritage, 2024). None of these sources facilitated a search by the specific river catchment. The Derbyshire HER identifies 215 records from a watermill search for the County of Derbyshire. A search for mills in Derbyshire on the national Mills Archives identifies 151 mills for the whole of Derbyshire, including windmills. The Mills in Derbyshire and Peak District site lists 170 mills, including windmills. The existing online mill databases proved to be a valuable source of information to validate locations, names and known references materials (listed on the HER) but were not comprehensive. With no specific search option by Derbyshire Derwent catchment (DDC), and for thoroughness, the decision to manually search for watermills using historic (c.1900) maps, gave the additional benefit of ruling out ancient watermills with no infrastructure in place by c.1900, and therefore unavailable to generate HEP. The waterpower site gazetteer process, described below, identified 164 historic watermill sites in the DDC. The Derbyshire HER included approximately 140 of these, the national Mills Archive lists 59 and the Derbyshire Heritage site lists 68.

2.1.3 Waterpower in the past

To gain an understanding of waterpower use, biographies were developed in the form of individual timelines for each watermill in the DDC gazetteer. An important contemporary source, recording developments of waterpower in the textile industry, is *Rees's Cyclopaedia*, 1819, which incorporated reports produced by John Farey jnr. on the Belper Mills complex in Derbyshire (Gifford, 1994, Hills, 1970, Johnson and Skempton, 1956, Reynolds, 1983). Visitor reports from the period also help develop the waterpower story of Belper, and other significant sites, e.g. Glover (1833) described Belper as having eleven iron waterwheels. Some caution needs to be taken with contemporary visit reports, with Daniel Defoe's (1724) *A tour thro' Great Britain's* description of Derby's silk mill, challenged by a former 'unhappy' apprentice, who raised concerns about the quality of the machine descriptions ‘by an author who does not understand it himself’ (Hutton, 1817 168).

Compared to the ‘industrial revolution’ period, there is very limited published material relating to waterpower usage in the DDC during the transition from waterpower providing mechanical drive to waterpower generating HEP c.1900. As indicated in Chapter 1, many national policies impacted the use of run-of-river HEP during the 20^{th} century, but the impacts on HEP generation have never been quantified for the DDC, or indeed, for the whole of the UK.

Sales information relating to the water turbine manufacturers and installers in the UK helped identify key changes in a number of DDC waterpower sites. Gilbert Gilkes & Co, the largest UK manufacturer of water turbines, have operated since 1853 and kindly shared their historic UK turbine sales volume data, identifying many Derbyshire sites previously unknown as self-generators of HEP. The main sales list includes all turbines supplied since 1900 to sites across the UK (Gilkes UK, 1900-2022), but a copy of the Derbyshire turbine hand ledger dates back to the earlier 1890s turbines (Gilkes Derbyshire, 1890-1920). An article discussing John Turnbull (Hercules Turbines), whose business supplied water turbines between 1881-1913, highlights some of their larger projects, including the English Sewing Cotton Company’s mills at Belper (600 HP [450 kW], 1901). Interestingly, among the ‘other’ installations mentioned in the Turnbull article, several DDC site owners and locations are included (F.C. Arkwright - Cromford; Biddulph Bros. - Cromford; S. Evans & Co. - Derby; and J. Towle & Son – Derby) (Ritchie, 1980).

Researchers’ visits to sites in the 1960s were particularly valuable in the development of the watermill timelines (Shaw, 1965, Swindell, 1963). The status of a mill’s water wheel(s), turbine(s) and HEP generation in the 1960s were sometimes captured, for example Figure 2.3, from Swindell’s thesis, showing distribution of mills with or without turbines, that he visited during his 1961-3 research. Similarly, closures of mills such as Cressbrook (River Wye) and Bamford (River Derwent), and the demolition of mills, were recorded in the East Midland Geographer (1963-5), a six-monthly journal. Industrial archaeologists, compiling lists of important assets in Derbyshire and historic building reports in the 1960s-1990s, recorded the status of sites, including watermills, occasionally capturing valuable insight from mill owners' use of waterpower for a specific period of time.

In addition to the heritage and archaeological articles and publications mentioned earlier, more recent 'official' reports, produced by developers as a condition of planning applications or commissioned by Historic England (formerly English Heritage), provided valuable waterpower related information. For example, the Darley Abbey study, recording that the use of HEP turbines ceased in 1969 as a result of road and sewage works, requiring the site to derive its power entirely from the National Grid (Menuge, 2006).

Redacted: Unable to trace author.
Available in the University of Nottingham library.

Figure 2.3 Waterpower status in the Lower Derwent Valley (Swindell, 1963 V.2 Fig. 13)

2.2 Methods

The following methodology and assumptions were used to identify the waterways of a suitable study area, build a comprehensive gazetteer of waterpower sites and develop the waterpower story for each of the identified watermill sites.

2.2.1 Identifying the study area

The first element was the identification of the administrative boundary or geographical study area, that would provide a good sample of watermill sites (run-of-river small HEP sites or opportunities). The study gazetteer needed a broad range of watermills (size and activity) powered by a wide range of waterways (rivers, brooks, streams and manmade), from a flow and fall aspect. The scope needed to be broad enough to also capture non-mill waterpower opportunities, such as a weir or dam built for water storage (Punys, Kvaraciejus et al., 2019).

Whilst other study areas were considered (Section 1.4.1), the Derbyshire Derwent catchment (DDC) was selected, with its broad range of mills and waterways. In addition to the wide range of watercourses and watermills, the DDC also incorporates the Severn Trent Water reservoirs and their distribution and treatment network. The DDC includes the industrial mills of the Derwent Valley Mills World Heritage Site (DVMWHS), 'that led to immense and lasting technological and cultural changes which resonated around the planet' (Fitton and Wadsworth, 2012 x). Some of these industrial mills have continued to harness the power of the Derwent for over 240 years, but many historic mill sites with weirs still in place have not. In addition to the DVMWHS (including buffer zone), the DDC incorporates part of the Peak District National Park (PDNP), flows through the city of Derby, includes many rural communities, and is located wholly within Derbyshire (Figure 2.4).

The DDC is one of the UK catchment-based water management systems in place (Collins, Johnson et al., 2020, DEFRA, 2013), with an active Derbyshire Derwent Catchment Partnership, a group of key waterway stakeholders. Many organisations that are likely to have interests and issues with future HEP reinstatement and development, such as Rivers Trusts, are represented in this partnership, offering an opportunity to understand a wide range of issues and identify mutually beneficial solutions to unlocking the HEP potential of the DDC.

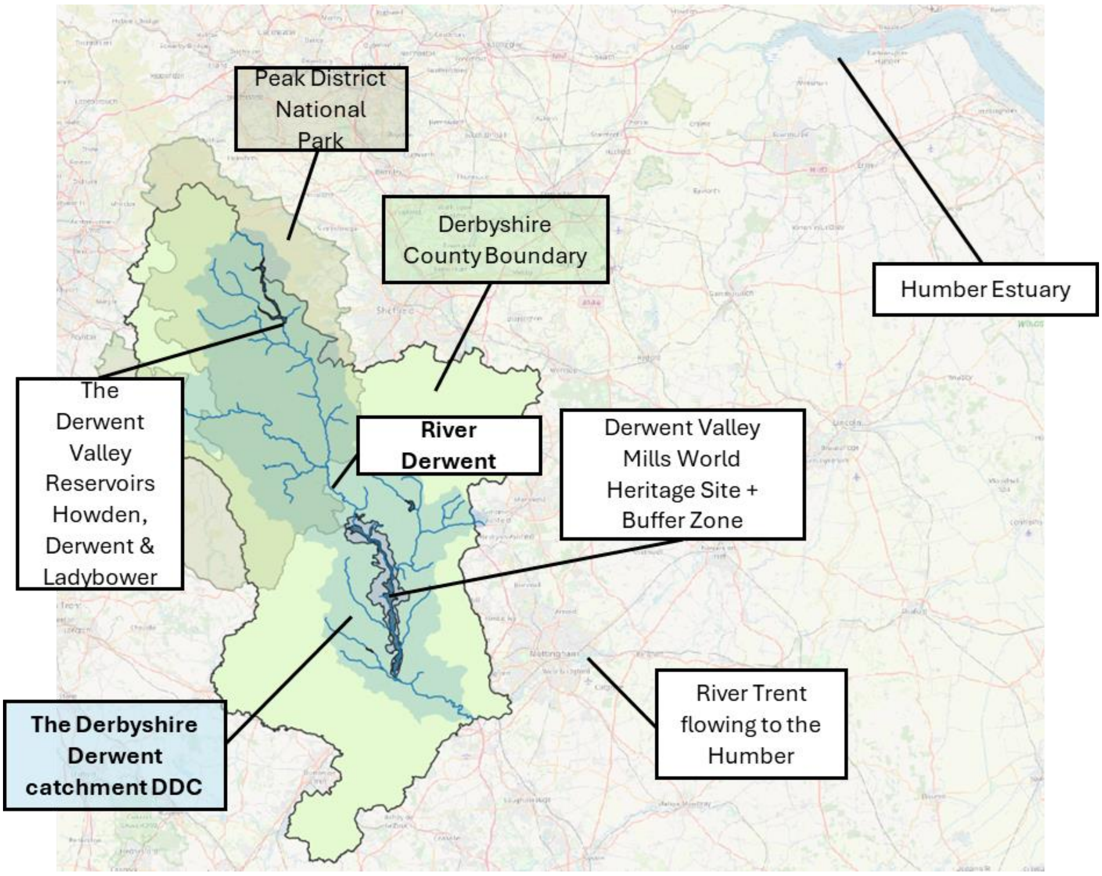


Figure 2.4 GIS map identifying the key aspects and constraints within the research area

2.2.2 Waterways: The Derbyshire Derwent catchment (DDC)

The first task was to identify the DDC watercourses that might have powered a watermill. A mill with infrastructure, identified on the c.1900 OS map, would have had the potential to self-generate HEP, for electric lighting and power introduced between the 1890s and 1930s. It is possible that any site that had the ability to generate HEP 100 years ago could have infrastructure in place today, such as a weir, offering future HEP potential, if not already generating. Unfortunately, some useful detail was omitted from later OS maps, with instructions for the 1937 revision to exclude many specific details, including aqueducts and weirs, and from 1957 aqueducts were hidden and reservoirs not named for security reasons (Oliver, 2005).

Therefore, one of the most useful OS maps, and the only one showing the route of the Derwent Valley Aqueduct, is the second revision 1912-21 County Series map.

A pdf version (740 sheets) of the ‘combined index’ black and white Ordnance Survey (1:2500) Derbyshire 2nd edition, surveyed 1872-83 and revised 1912-21 (DRO Digital Archive Ass, 2008), was the first map used to identify the watercourses and watermills. Where necessary individual sheets of the map were printed and waterways hand coloured, as per some of the early OS maps (Oliver, 2005), to identify all of the main rivers and the tributaries, brooks and streams feeding them. This process also captured river diversions, mill races and mill streams. Some of the early OS maps, accessible via the National Library of Scotland show the blue coloured waterways, highlighting mill ponds and dams (Figure 2.5).

Figure 2.5 A ‘coloured’ section of the OS map showing the Derwent through Matlock and Bonsall Brook through Lumsdale (Reproduced with the permission of the National Library of Scotland).

The watercourses were traced from the River Derwent and River Trent confluence near Shardlow in the south to its source in the north, identifying all of the tributaries entering the Derwent, capturing the names, if available on the 2nd edition map, and the location of the confluence of each tributary with the Derwent. An approximate location was captured from the early map and geo-referenced using the current OS digital mapping, recording the 12 figure OS coordinates. The process was repeated for each tributary, capturing the names and locations of the streams and brooks feeding each tributary river. An initial assessment of watercourse size could be made, with waterways over 5 m wide being identified by a double, rather than a single, line on the county Series OS maps. The waterway mapping findings were captured in the format shown and below used during the research project to log survey progress (Figure 2.6).

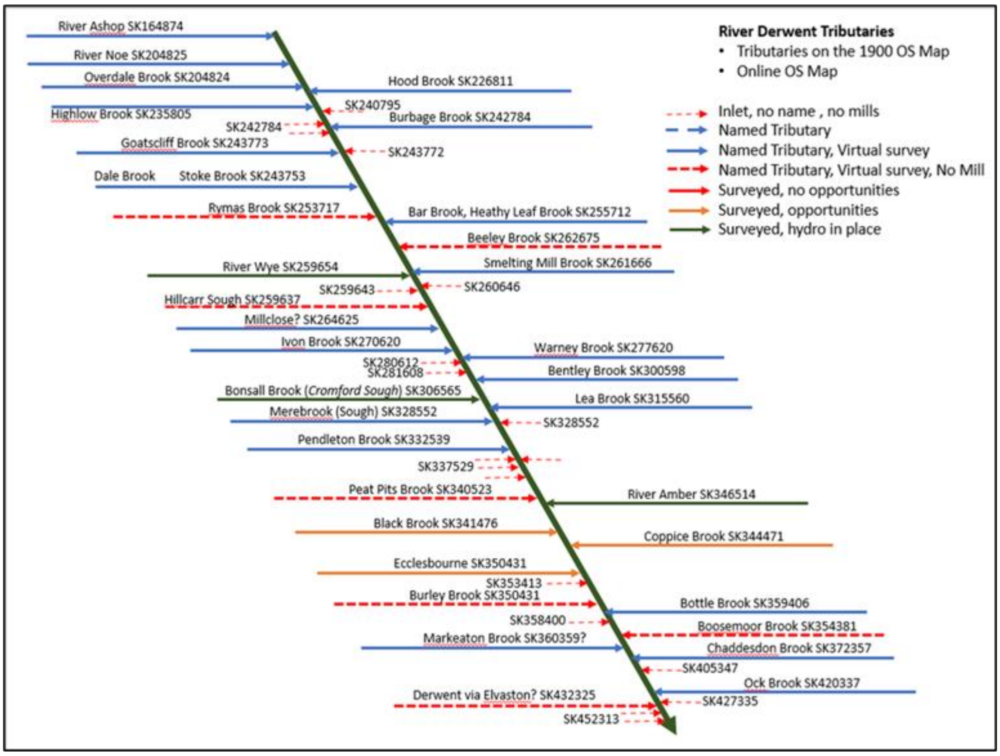


Figure 2.6 October 2020, waterway and mill virtual and physical survey log report.

Details of the waterways, including current names, and status, are maintained by the Environment Agency for each catchment in England in the catchment data explorer database (https://environment.data.gov.uk , The Humber River Basin, Derwent Derbyshire Management Catchment), which was used for cross referencing, although some of the smaller streams and brooks identified from the map search are not included in the EA database. Throughout the research project, the QGIS, an open-source geographic information system, was used to confirm locations and visualise the findings of the research.

2.2.3 Watermills: the DDC waterpower gazetteer

The premise of this research is that many of the available waterways were fully utilised by the industrial mills by the early 19th century, so potential HEP sites would be based on those existing, historic weirs, or similar infrastructures. Therefore, site identification and location for the gazetteer was based on a weir or mill site being evident on an Ordnance Survey map of the Derbyshire County Series Map, 2nd edition.

Once all watercourses were identified, each waterway was retraced looking for watermills or associated waterpower assets, such as mill ponds, weirs, waterfalls (natural feature) and sluices. OS maps used the basic descriptor Mill for both water and steam mills, with the County Series maps sometimes also noting the application e.g. Matlock Mill (Corn). Standard OS terminology describes water leading to a watermill as “mill-race” and water leaving the mill as “mill-stream” (Oliver, 2005). The 1:2500 OS scale offered a 2 m threshold on buildings, allowing an estimate of waterwheel location, mill building, mill pond or weir, and the 12 figure OS coordinates location, geo-referenced with the current OS digital mapping system.

For each location the name of the mill, often including purpose of the mill at the time (map range 1872 to 1921) (Figure 2.7), was recorded. A spreadsheet was developed using the initial location, mill name, waterway and purpose/product. Confirmation of the locations, name(s) and purposes was carried out as a desk-top exercise during the covid pandemic, using online resources, existing gazetteers and more recent HEP assessment studies in Derbyshire. A more comprehensive site report was then developed for each watermill listed on the gazetteer (Table 2.2).

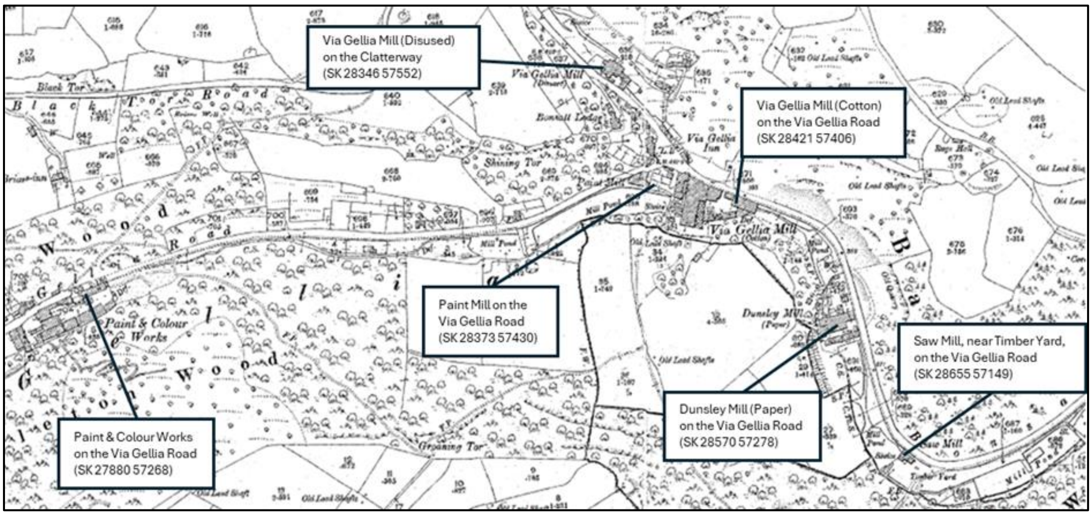


Figure 2.7 An example from a tile of the Derbyshire Sheet XXXIV-6 (SECOND EDITION 1899), part of the Bonsall Brook in Via Gellia near Bonsall and Cromford (Reproduced with the permission of the National Library of Scotland).

Table 2.2 The generic waterpower site timeline report

<table>
<tr><td colspan="2">Location (SK ---- ----)</td><td colspan="2">Name, activity and village, town, city</td></tr>
<tr><td colspan="2">Waterway</td><td colspan="2">River Derwent or tributary</td></tr>
<tr><td colspan="2">Status (if known)</td><td colspan="2">Generating HEP, Weir in place, No Infrastructure, Not accessible (private)</td></tr>
<tr><td colspan="2">Derbyshire Historic Environment Record (s)</td><td colspan="2">MDR ----</td></tr>
<tr><td colspan="2">Key Reference Books List</td><td colspan="2">Entry (Yes or No) - page number</td></tr>
<tr><td colspan="2">Mills Archive</td><td colspan="2">Entry (Yes or No) – mill reference number (Mills in historic county – The Mills Archive)</td></tr>
<tr><td colspan="2">Derbyshire HER</td><td colspan="2">Full description</td></tr>
<tr><td colspan="2">Derbyshire HER</td><td colspan="2">Sources and archives</td></tr>
<tr><td colspan="2">Additional references</td><td colspan="2">Articles, reports, publication, archival documents</td></tr>
<tr><td colspan="4">Historic OS maps for each time period available (e.g.)</td></tr>
<tr><td colspan="2">1880s</td><td colspan="2">1900s</td></tr>
<tr><td colspan="2">1920s</td><td colspan="2">1960s</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="2">Timeline</td><td colspan="2">Location and Name</td></tr>
<tr><td>Year</td><td colspan="2">Activity (e.g. Mill built, change of owner, operation, change in power supply, site development, details of waterpower (wheel size, turbine output))</td><td>Reference</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="2">Key Points</td><td colspan="2">Waterpower development, Challenges to waterpower</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="2">Site Visit</td><td colspan="2">Location and Name, contact details</td></tr>
<tr><td colspan="2">Status</td><td colspan="2">Date and current condition and operation</td></tr>
<tr><td colspan="2">Visit photographs</td><td colspan="2"></td></tr>
</table>

2.2.4 Watermill timelines

With the historic OS map references used as stages of the chronological development, the site timeline was started using the references mentioned above. All relevant and dated references from the historical OS maps, the Derbyshire HER description (and related references), and any additional information from the local reference books, were used to develop the timelines. This information included the findings of researchers and authors who visited watermills in the DDC during the 20th century, who often recorded the mill and waterpower status between the 1960s and 1990s. For any site that had any evidence of waterpower being harnessed to generate hydroelectric power (HEP) in its history (post 1880), a more in-depth study was carried out to fully understand the size, use and challenges it faced, where possible. This included the site's current HEP generation status, size and any feasibility study information publicly available.

2.2.4.1 Mapping through the decades

The Historic Digimap system allows online access to a series of historical Ordnance Survey maps of Great Britain (Crown copyright and Landmark Information Group Limited (2023). All rights reserved (1880s-1960s)). The most useful Derbyshire maps available were the County Series, originally surveyed 1875-82, with the first revision 1896-1900, second revision 1912-21 and the third revision (incomplete) 1937-8 (Oliver, 2005). The digital historic mapping facility supported the confirmation of site locations, searching by OS coordinate, and included mill names by decade. These formed the basis of each mill timeline, with changes of name often due to change of ownership or change of mill activity, including 'disused'. Figure 2.8, shows the Chaddesden Mill (flour) in the 1880s becoming a housing estate by the 1960s. The images are largely captured from the County Series Maps and the British National Grid maps (1943 to 1996). The maps are accessed by decade, with the zoom facility giving maps of different scales, i.e. 1:1,250, 1:2,500, 1:10,000, or 1:10,560, dependant on the availability of maps for a particular location.

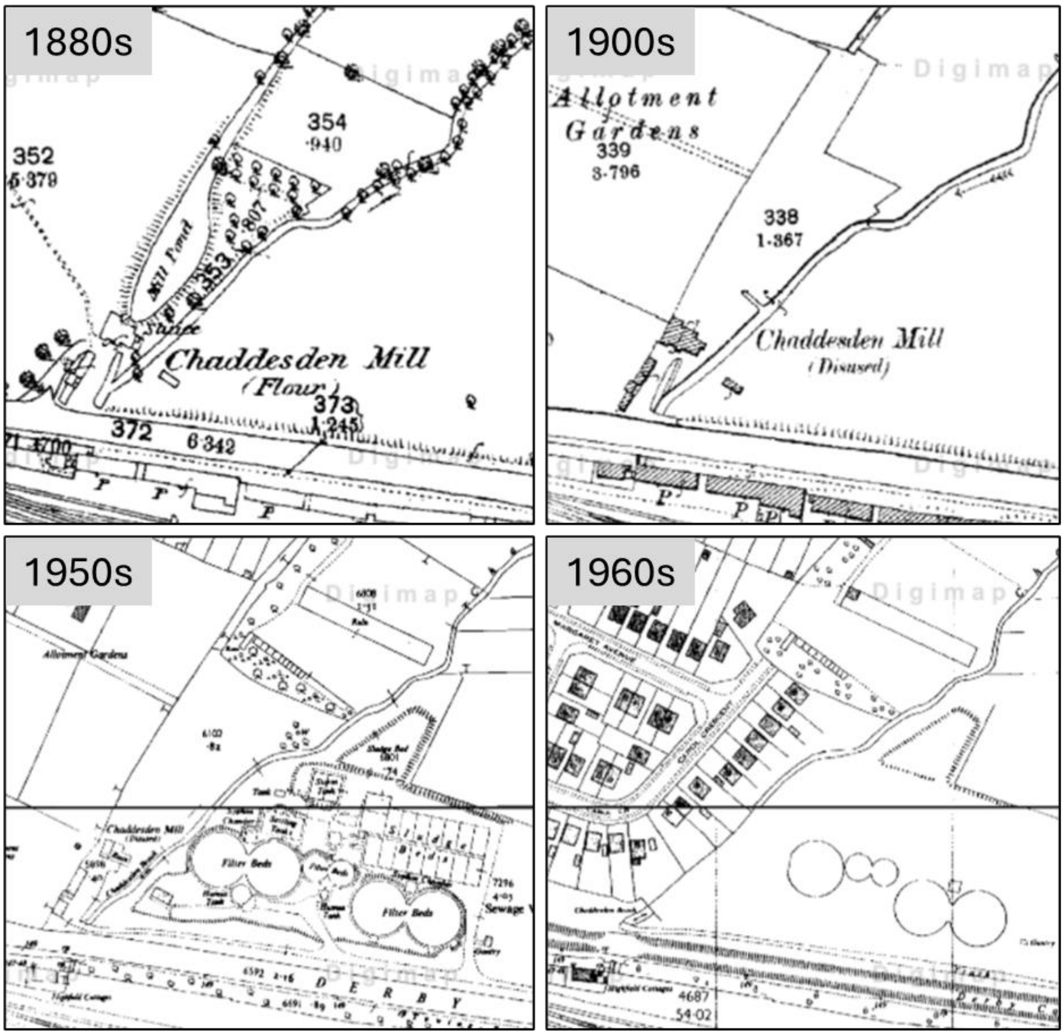


Figure 2.8 Chaddesden Mill site, 1880s, 1900s, 1950s and 1960s, using the Digimap system.

2.2.5 Walk-over survey

Whilst the waterpower site by watercourse list was being developed, walk-over surveys were carried out to confirm site locations and assess the current status of infrastructure. To prepare for a walk-over survey, the online Explore Ordnance Survey mapping system was used, with the topographic 1:25k scale enabling routes to be planned adjacent to watercourses and mill sites. With over 150 mill site locations to review, the research time period available and the first two years being impacted by the covid pandemic, this work was based on access using adjacent public rights of way. Landowners were not directly contacted but, on occasions, site owners were available and did allow access to their land, enabling a more accurate condition assessment. Mobile digital maps helped to locate weirs previously identified through the desktop mapping exercise. Two additional physical attributes also helped confirm locations and, importantly, identify previously unidentified weirs: the 'stilling' of the river when approaching a weir becomes visibly obvious and the sound of the water over a weir helped to pinpoint several weirs, including ones hidden behind trees and under bridges. The sound of waterwheels and turbines also assisted in confirming the location of HEP generation at sites, including the Calver Corn Mill, powered by sough water.

Each site's restorable condition was recorded in a simple classification (Table 2.3). A similar study of European watermill sites, the EU RESTOR project, used the site condition categories below (Table 2.3). For each site, photographs of the waterways, weirs and sluices, mill races and streams, mill buildings, waterwheel houses and wheels were taken, where possible. One additional, and unplanned, benefit of the physical surveys was the occasional informal interview with current mill owners, who were willing to share their knowledge and understanding of historic use of their property and the status regarding HEP generation.

Table 2.3 The restorable condition of HEP sites, classified during the walk-over surveys.

EU-RESTOR restorable condition categories (Punys, Kvaraciejus et al., 2019)		
D	A degraded condition	The waterway is flowing with few or no visible remnants.
M	A moderate condition	Visible remnants and may function with restoration.
A	An advanced condition	The site is complete and likely to be generating HEP
For this research project		
R	No infrastructure	
A	Weir or other infrastructure, creating head, with flowing watercourse.	
G	Site generating HEP.	
	Not accessible (private)	

2.2.6 Non-Mill waterpower sites

During the walk-over surveys it became apparent that there were non-mill sites generating HEP, or with HEP potential, that had not been captured through the watermill OS desktop identification process (e.g. sough water tailraces; 20th century weirs built for river management; 20th century reservoirs). These non-mill sites with HEP potential were captured in the EU RESTOR project as separate entities from the watermills, so for the purposes of this research project the waterpower site gazetteer was extended to include three categories:

- **Waterpower Mill sites**
- **Waterpower Non-Mill sites generating HEP** (e.g. Longbridge Weir, Derby – repurposed Canal weir; Chatsworth Emperor Fountain HEP; Calver Flour Mill - Sough tailrace HEP)
- **Waterpower Non-Mill sites with HEP generating potential** (Opportunities)

The EU RESTOR project also included an ‘Unknown’ category, but for this research it was not required as, by limiting the initial search to active mill sites c.1900 (from the 2nd edition Derbyshire OS Map), ancient mills and weirs no longer recorded on the OS map with no HEP generation capability, were filtered out.

2.2.7 HEP generation – calculating the potential

The HEP potential of any individual site is dependent on the height that the water falls (known as the head) and the available flow of water in the river, stream or channel. The head is usually created by a weir, sometimes associated with natural river features such as waterfalls, cascades, knickpoints or meanders. The individuality and complexity of developing small HEP schemes means that individual site assessment of HEP potential is relatively expensive. Based on 2010 costings, following an initial ‘show-stopper’ site assessment and pre-feasibility study (£500-£1,000), a detailed feasibility would cost in the range of £3,000 to £10,000 (Woods, Tickle et al., 2010). It was therefore not possible, from a time or cost point of view, for a site-by-site HEP potential of the complete DDC gazetteer to be included in this research project.

In order to estimate the HEP potential for the DDC the following, four level, process was followed for each waterway (Table 2.4) (Section 1.4.5), using existing operational HEP installed capacity (kW) information as the key foundation of the model (Level 1, most confidence), and then estimating for sites on the same waterways but with limited information available (e.g. Level 2, a feasibility study). In addition to the known HEP generators listed on national renewable energy registers, two community led renewable energy studies provided the majority of Level 2 sites, those with 'feasibility assessment' data, the Friends of the Peak District (2010) *Peak Power: Developing micro hydro power in the Peak District* report (Woods, Tickle et al., 2010) and the *Estimate of hydro resource in the Derwent Valley* commissioned by Transition Belper (Harton, Chandler et al., 2012).

Table 2.4 The four levels of HEP potential assessment

Level 1	For HEP generating sites, use installed capacity	Installed capacity kW
Level 2	For sites with a completed feasibility study, use potential capacity	Assessed potential kW
Level 3	For sites with known HEP removed, use historic use (kW)	Historic use kW
Level 4 – Calculated for each waterway		
Step 1 Number of Mill and Non-Mill sites remaining	Step 2 Typical HEP size (kW) on the waterway (Average calc. from Level 1 or Level 2)	Step 3 Waterway HEP potential (No. of Sites x Average kW)

2.3 Results

2.3.1 The Derbyshire Derwent catchment (DDC) waterways

The tracing of waterways and mill sites in the DDC identified 46 different rivers, brooks and streams that powered watermills of varying power capabilities. The primary rivers and brooks (including their tributaries), powering at least five watermill sites, are the River Derwent, River Noe, River Wye, Bentley Brook, Bonsall Brook, River Amber, River Ecclesbourne and Markeaton Brook (Figure 2.9).

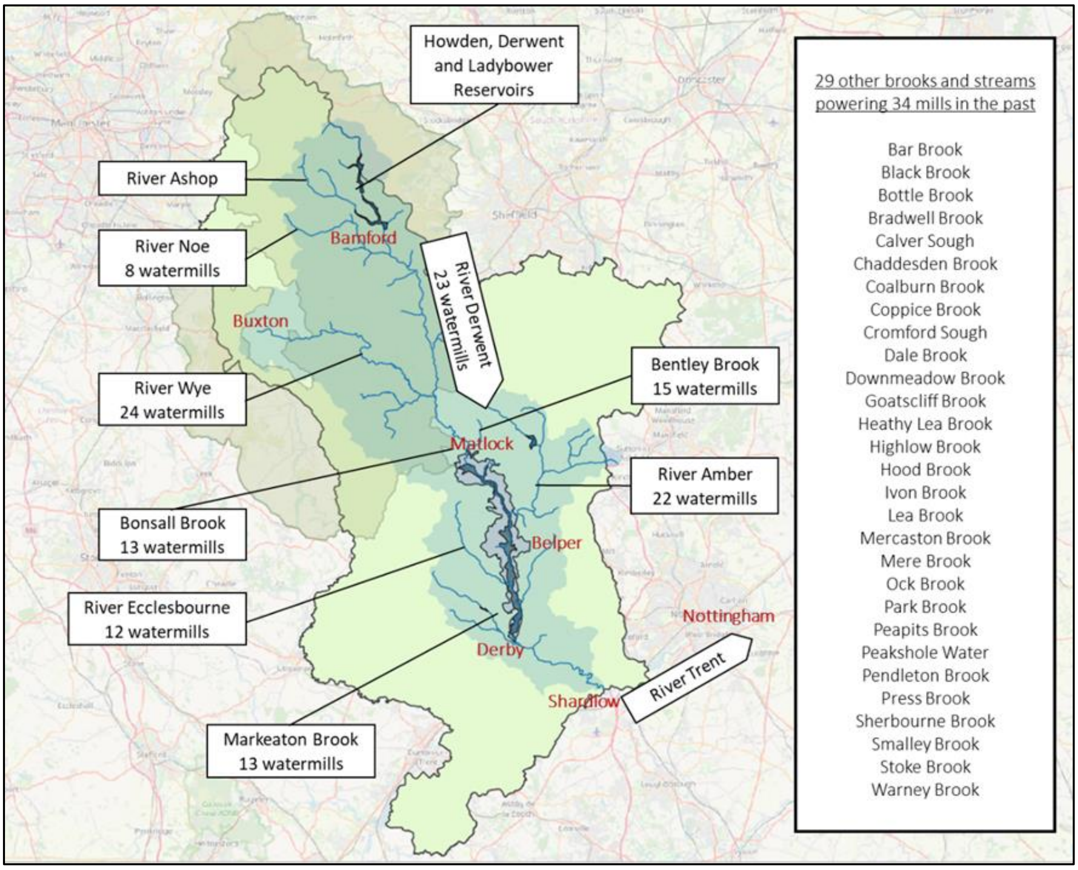


Figure 2.9 Showing the waterways and watermill distribution across the DDC.

In addition to waterpower driven by natural waterways, the DDC has a long history of harnessing the power of man-made waterways in the form of soughs (mine drainage channels) (Section 3.4.1.1). Richard Arkwright's first cotton spinning mill, 1771, was famously powered by the Cromford Sough flow (Trinder, 2013 49). The walk over survey led to the discovery of a former corn mill in Calver, using sough water to drive a wheel and generate HEP (10kW) for the now private residence

(Figure 2.10). A more novel, historic, man-made source of waterpower is the diverted Emperor Fountain water feed at Chatsworth House, Derbyshire, first installed to provide electric lighting in 1893, which despite being shut down in the mid-20th century, is again producing HEP for Chatsworth House, with any surplus HEP exported to the national grid (Section 4.2.1.1).

Figure 2.10 Private house (former Calver corn mill), powered by the Calver Sough, 10 kW installed in 2010 (Photograph: Author, 2021)

During the 20th century the River Derwent had significant river management changes, including the building of five reservoirs, the straightening of the river south of Derby and the addition of flood and river gauging weirs . The three Derwent Valley reservoirs at the head of the River Derwent (Figure 2.11), diverted water for drinking water supplies, but the Derwent Valley Act required a steady and regular minimum compensation flow for the scheduled industrial mill owners, who depended on the water to power their industrial sites (Section 4.4.1.1).

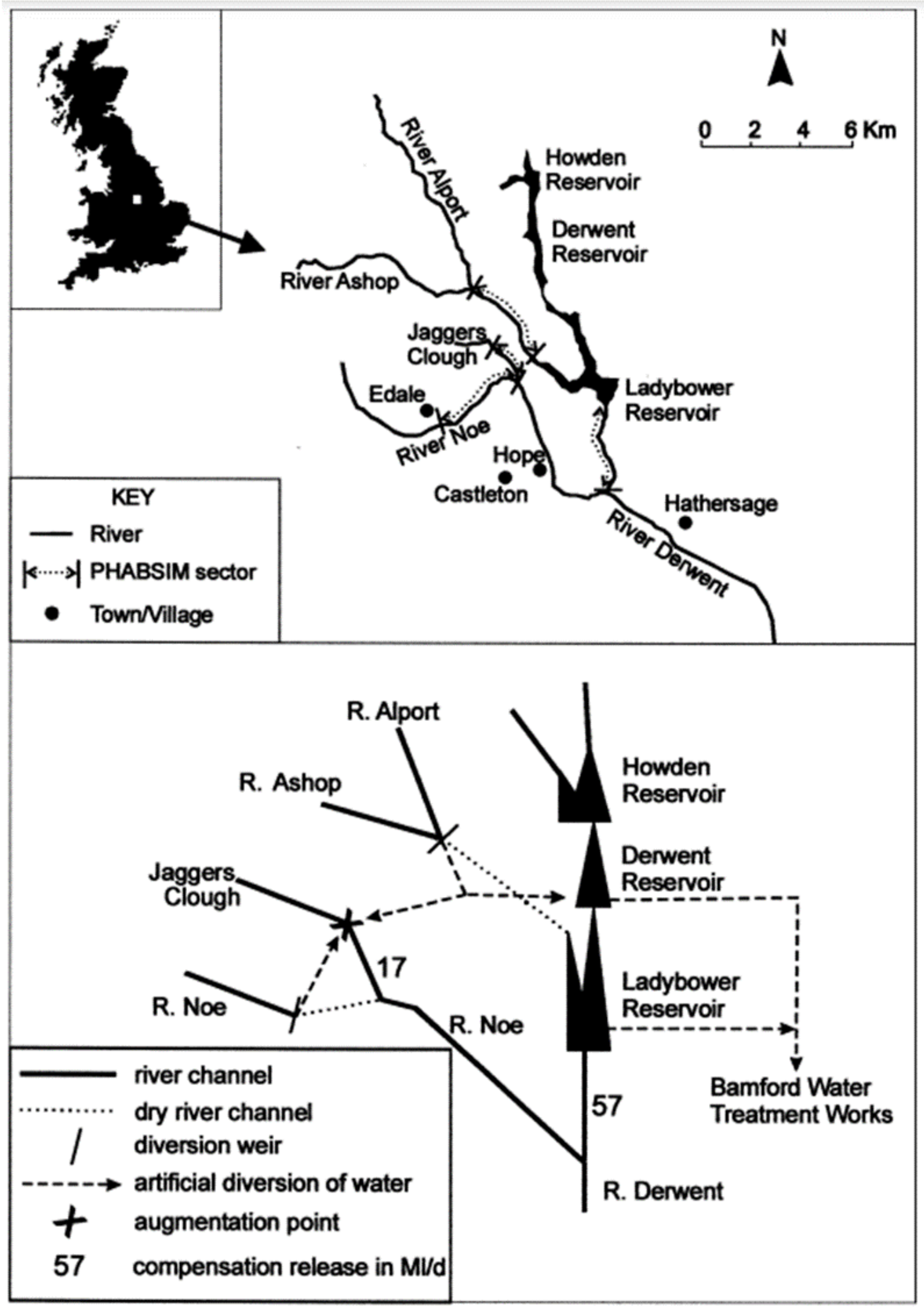


Figure 2.11 The Derwent Valley Reservoir network (Maddock, Bickerton et al., 2001 148)

2.3.2 River Derwent weirs

A critical element of run-of-river HEP sites in the DDC is the weir. Considering their past and present role in waterpower, impact on floods (including flood control) and impact on river ecology, there is very limited information or understanding about weir design, construction, historic use and current ownership. During the walk-over survey, the location, status and whether or not a fish pass was installed, was recorded. Including the Derwent Valley reservoirs there were 30 weirs or barriers on the River Derwent, including one natural fall at Yorkshire Bridge and two partially removed (Figure 2.12). Several other historic industrial weirs identified on historic maps had been removed in the 20th century.

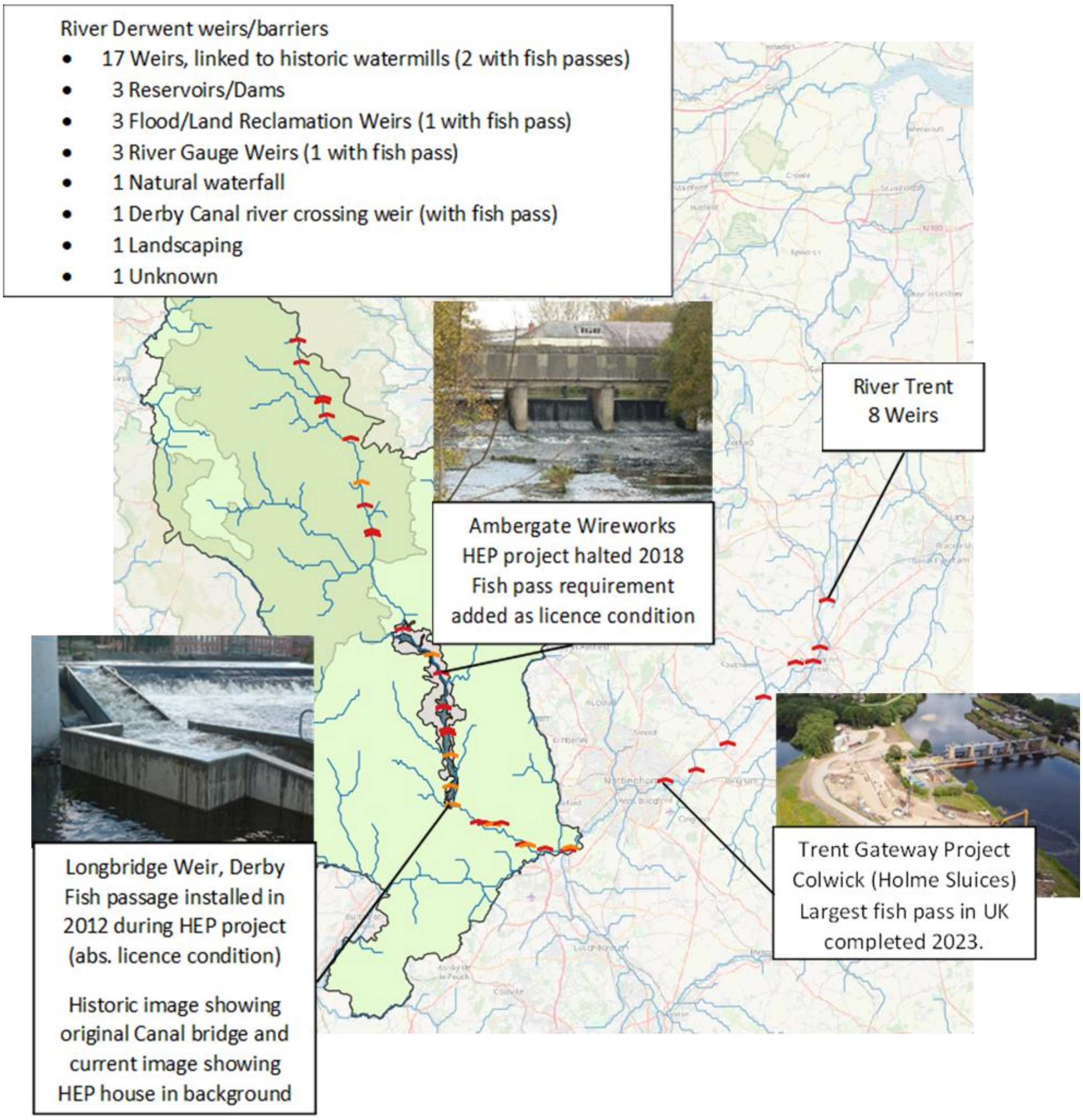


Figure 2.12 Weirs along the Rivers Derwent and Trent, flowing to the Humber Estuary. The orange weirs have some form of fish passage.

2.3.3 Natural and managed flows in the Derbyshire Derwent catchment

Waterpower potential is dependent on river flow so an understanding of river flows across the catchment helps establish the distribution of mills with different power capabilities. River flow data (mean flow) was captured using publicly accessible river gauge data and mapped onto the DDC map (Figure 2.13). This data shows how the river develops, with a River Derwent managed mean flow at the source (Yorkshire Bridge [Ladybower compensation flow plus overspill]) of 2.1 m^3/s growing to a mean flow of 18.9 m^3/s at the Church Wilne gauge, the final measurement before the River Trent confluence. Whilst waterpower potential of the DDC should not have changed dramatically over time, human interventions to the watercourse have impacted flows and resultant HEP generation. The greatest man-made change was the early 20th century Derwent Valley Reservoirs project, built for public water supply abstractions, supplying municipal water to four counties. Water was diverted from the Rivers Ashop, Noe and Bradwell Brook to feed the reservoirs and the restricted, but steady, compensation flow from Ladybower reservoir, which commenced in 1943, reduced the flow available to all HEP on the river Derwent, and continues today (Section 4.4.1.1) (Figure 2.14).

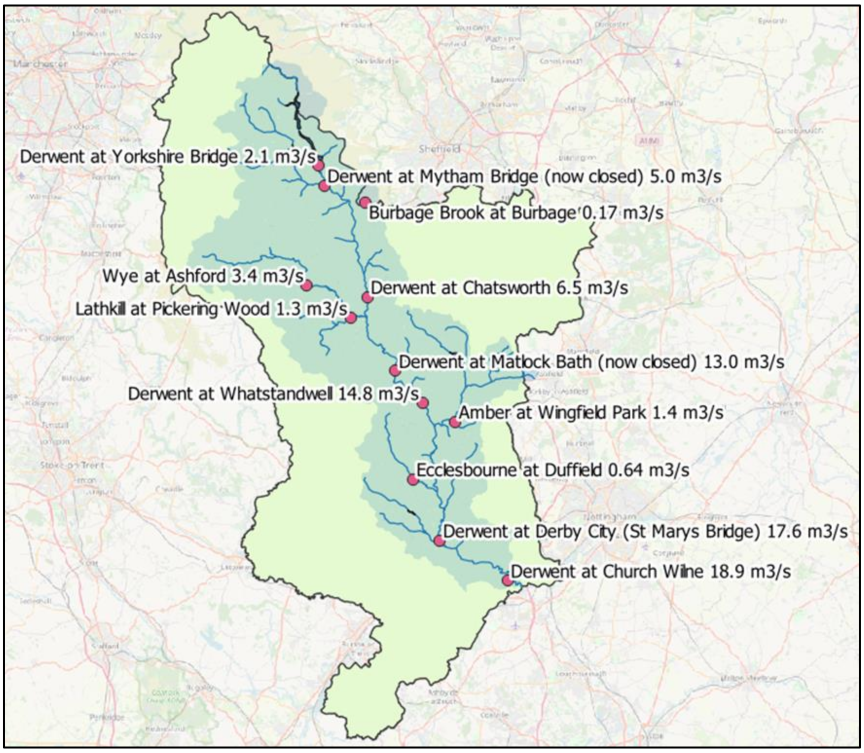


Figure 2.13 DDC mean river flows (National River Flow Archive, 2024).

Plotting the daily flows at the Yorkshire Bridge flow gauge, immediately downstream of the Ladybower Reservoir outlet, from 1933 to 2020, shows the changes in flow feeding the River Derwent and impacting on HEP generation down the Derwent Valley. It is clear when the steady compensation flow started in 1943 (Figure 2.15), following a reduction in flow, possibly related to the completion of the Ladybower Reservoir. Figure 2.15 shows that from 1944 to 1973 there appears to be a steady flow of c.0.9 m^3/s with one significant drop in 1959, probably as a result of the ‘great drought’ across Europe (Derby Evening Telegraph, 1959 10). Between 1976, another drought event, and 1998 the base flow varies between 0.9 down to 0.7 m^3/s. From 1998 the flow appears to be steady again, although slightly lower than the original compensation flow, now averaging 0.8 m^3/s.

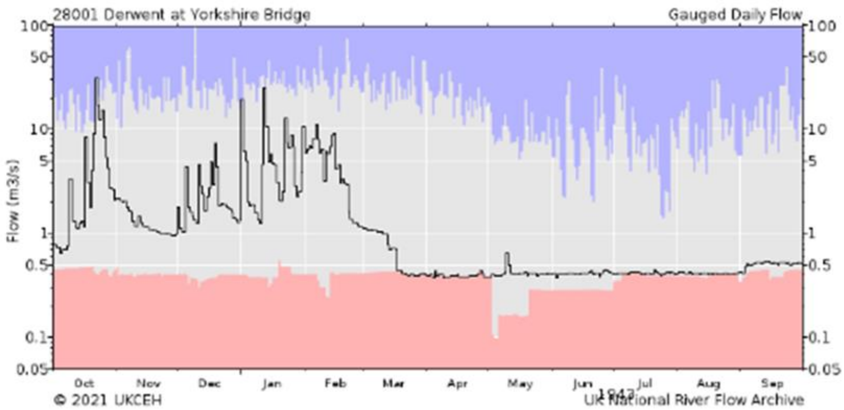


Figure 2.14 The Yorkshire Bridge gauge for 1943, start of compensation flow (National River Flow Archive, http://nrfa.ceh.ac.uk/data/station/info/28001, 22 November 2021)

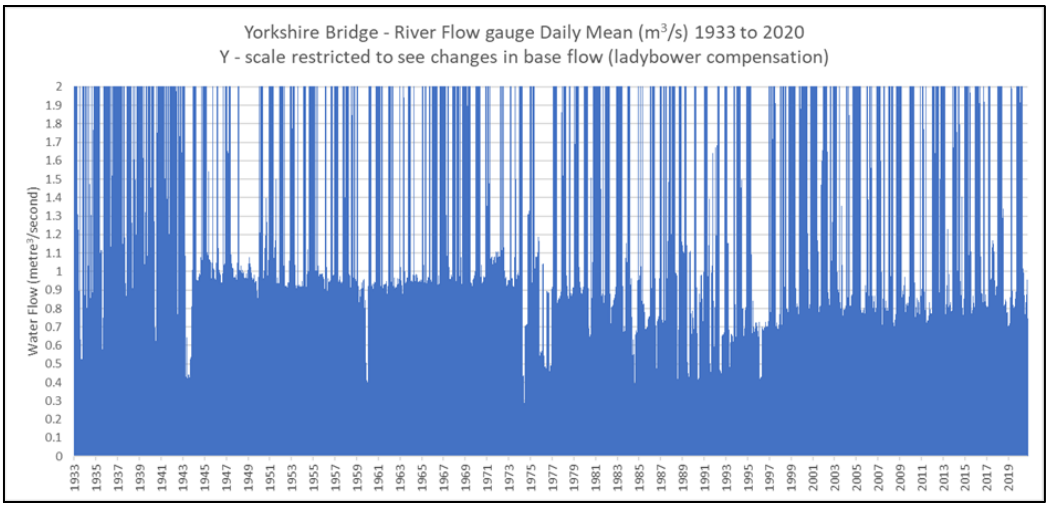


Figure 2.15 The Yorkshire Bridge daily gauge flows, 1933 to 2020 (www.nrfa.ceh.ac.uk Accessed 22nd November 2021).

2.3.4 The Derbyshire Derwent catchment waterpower site gazetteer

The gazetteer (as of December 2022) has a total number of 197 waterpower sites (http://doi.org/10.17639/nott.7459). It includes 164 historic watermill sites identified on 1880s to 1920s OS Maps, 18 non-mill sites that have harnessed waterpower (mechanical and electric) (e.g. water pumps on the Wye or HEP generation on the former Derby canal Longbridge weir), and 15 other non-mill sites that have the potential to generate HEP using existing flows and infrastructure (e.g. Carsington Reservoir or Derby flood management weirs). There are a wide variety of watermill and non-mill applications (Figure 2.16).

The quantity of specific mill types is approximate due to occasional changes in use of some waterpower sites over their lifetime. Once waterpower was harnessed, weirs constructed and water channels dug (leat, goyt, race), any site could have a range of potential uses. In some cases, the use of a site varied seasonally (e.g. corn mill following harvest and paper mill the rest of the year) (Section 1.3.1.1). Many of the larger 'industrial revolution' textile mills were built on historic mill sites, benefiting from the natural geology (e.g. meanders, waterfalls, knickpoints or cascades) or on wooden weirs that would have powered the original corn or smelting mills (Section 1.3.1.2).

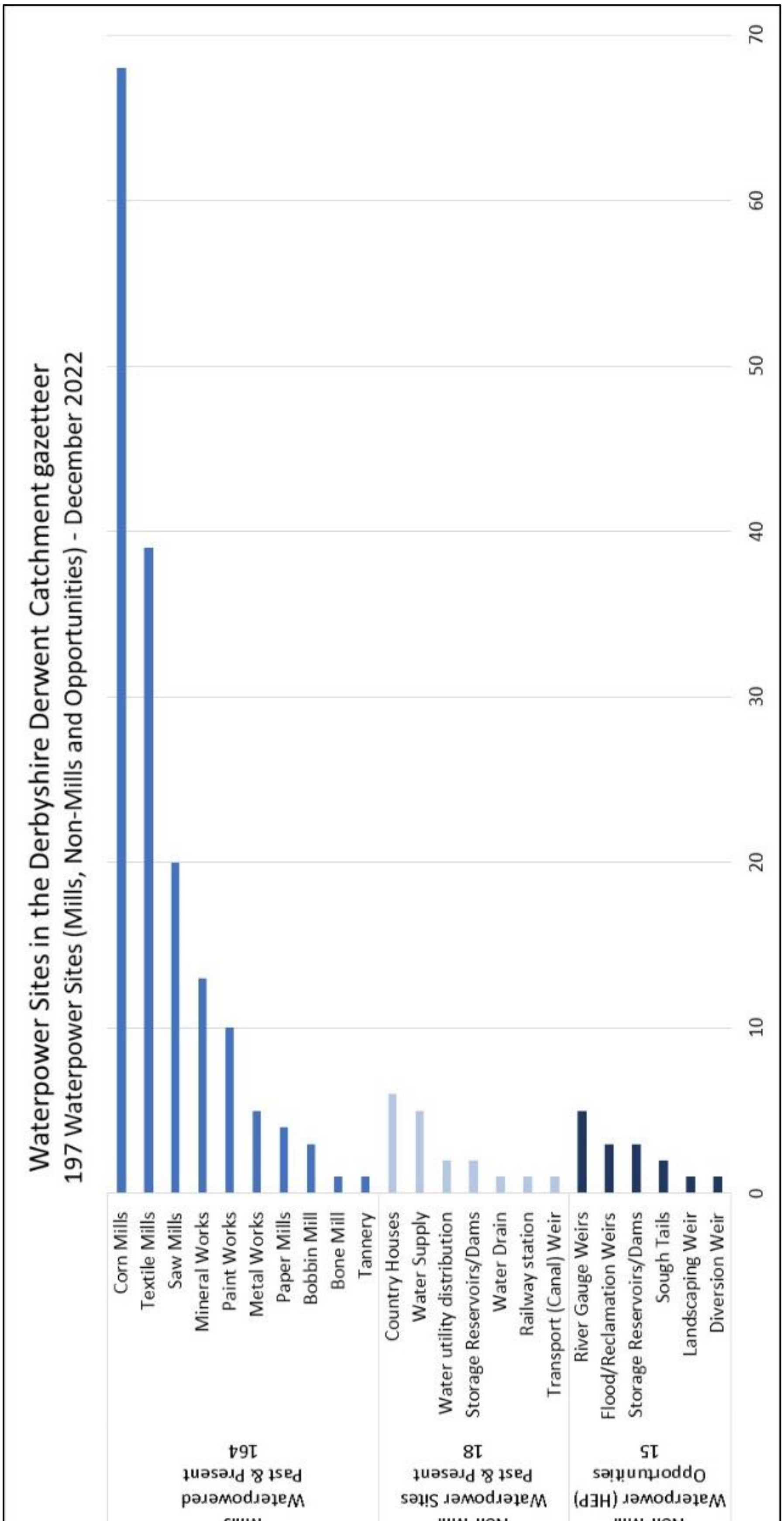
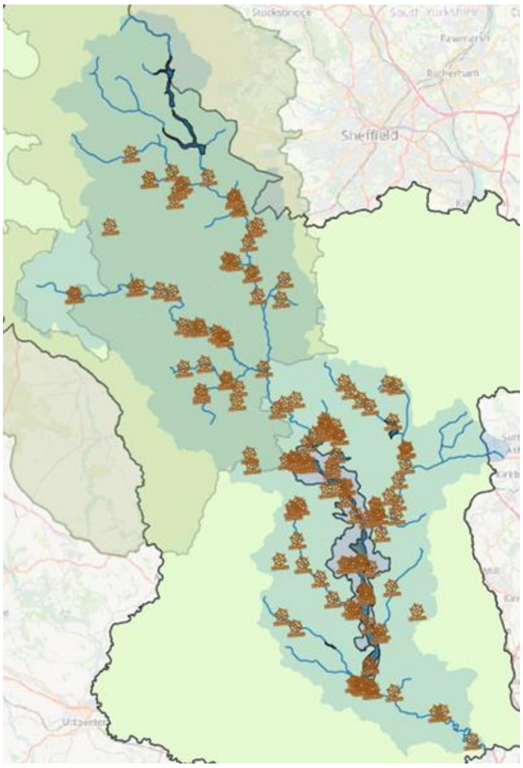


Figure 2.16 The quantity of Mill and Non-Mill types in the DDC gazetteer

The DDC watermills range in size, dependant on the power available in the waterway and the technology of the day. Figure 2.17 shows the distribution of the 164 watermills and Figure 2.18 the 18 non-mill historic waterpower sites (○) and 15 other non-mill HEP opportunity sites (○), showing how the available power within any given waterway was utilised.

Figure 2.19 shows the wide distribution of corn mills within the DDC, with the smaller brooks and streams being used, often with mill ponds ‘storing’ the energy. Whilst some corn mills, such as Caudwell’s Mill on the River Wye, had the power to drive eight pairs of stones for flour production, mills on smaller tributaries such as the Brook, an Amber tributary, could only drive three pairs of stones as at Brook Mill, Crich (Gifford, 1999). With one pair of stones requiring 1.5 to 3.7 kW of power to work, depending on stone size, (Vince, 1993), an estimate of the power available in the smaller tributaries can be made, e.g. the Brook, Crich with three pairs of stones had between 4.5 to 11.1 kW available, possibly supplemented by storage in a mill pond. Figure 2.20 shows the larger ‘industrial’ textile mills, clustered around the larger Wye and Derwent rivers. There are some textile mills on smaller tributaries but with larger, natural fall heads, utilised to power their mills, such as Two Dales Flax Mill on Sydnope Brook and Tansley Wood Mill (cotton) on Bentley Brook. Figure 2.18, non-mill sites, shows a similar distribution to the larger textile mills, with the potential to harness the highest levels of HEP (e.g. Wye and Derwent), with the addition of Howden and Ladybower reservoirs generating HEP and the Derwent, Carsington and Ogston reservoirs listed as potential HEP generating sites.



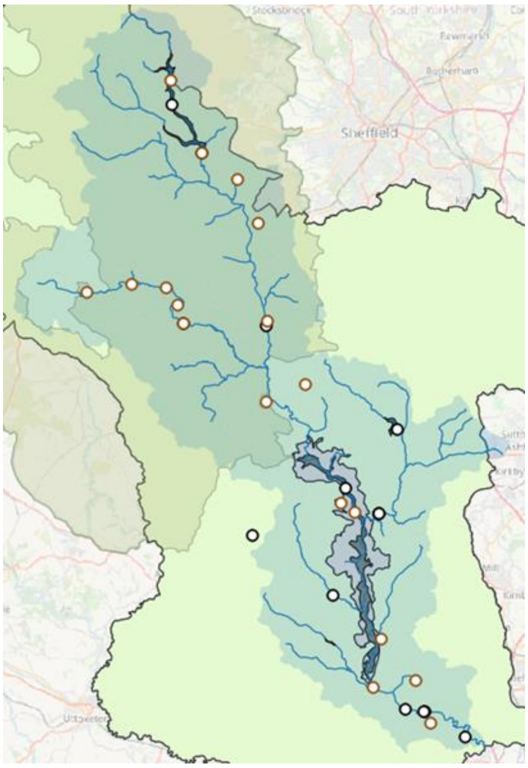
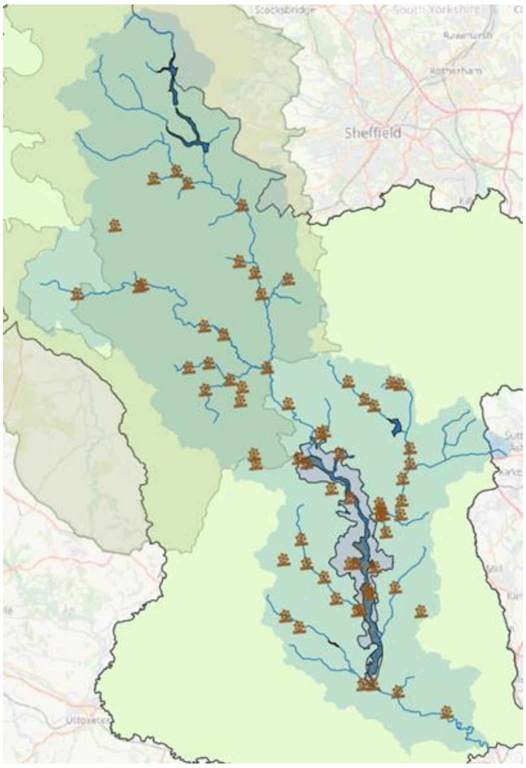


Figure 2.17 Watermill sites in the DDC

Figure 2.18 Non-Mill waterpower



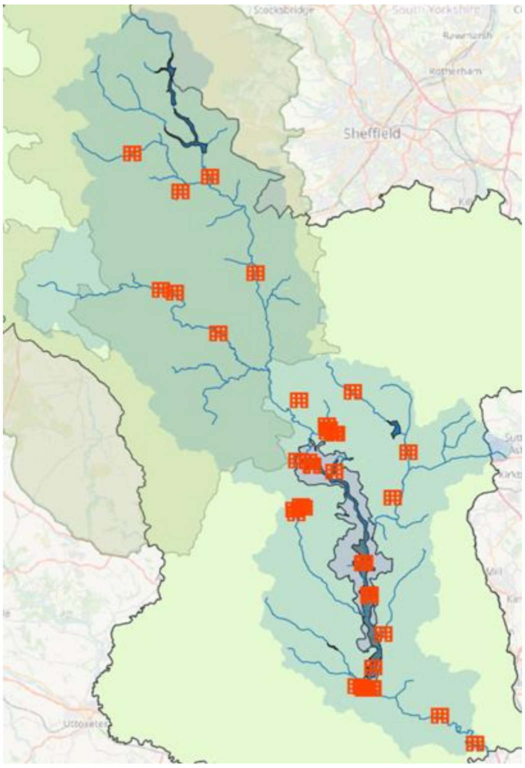


Figure 2.19 Corn or Flour watermills across the DDC.

Figure 2.20 Textile watermills across the DDC

2.3.4.1 Non-mill sites

The walk-over survey and research materials, including water turbine installations in Derbyshire, identified several sites that are either generating HEP today, have generated HEP in the past or are 'technically' capable of generating HEP in the future. All photographs below were taken during the walk-over surveys.

Country Houses - example

Chatsworth House was an early adopter of HEP, with electric lighting introduced in 1893 (disconnected in 1936). The Emperor Lake was reused in 1987 to produce HEP and continues today. The Gilkes UK sales and Turnbull – Hercules Turbines article identified a number of DDC houses that also introduced HEP early to generate lighting.

Figure 2.21 Chatsworth Emperor Fountain HEP

Sough Water – example

The original Richard Arkwright water powered cotton thread mill (1771) in Cromford was famously powered by the drainage waters from local lead mines, captured in dug tunnels, called soughs. The Cromford site closed following a deeper sough being dug, which drained the water. This sough, Meerbrook, has continued to flow since the 1830s, along with other sough tails in the DDC.

Figure 2.22 Meerbrook Sough tail

Water Pumps - example

Along the River Wye there is evidence of small weirs with waterwheels and hydraulic rams abstracting and pumping water to local villages, and potentially railway sidings for the steam trains. Five of these pumps, sometimes notated on the OS map as Hydraulic Pumps, are recorded in the *Water Mills on the Derbyshire Wye* (Roberts, 2010).

Figure 2.23 Cressbrook Water Pump (Wye)

Reservoirs – example

Two of the larger HEP generating sites in the DDC are the Ladybower Reservoir, recovering electricity since 1945 and generating and exporting today, and the 2017 HEP turbine added to the Howden to Derwent levelling flow pipeline. There are additional reservoirs in the DDC with HEP potential.

Figure 2.24 Ladybower Reservoir

Weirs (non-watermill) – example

Out of a total of 30 weirs on the River Derwent 13 were built for purposes other than waterpower. The Longbridge, former canal weir, had HEP installed by Derby City Council in 2012. Other flood, land reclamation, diversion, landscaping and storage weirs or dams may have HEP potential.

Figure 2.25 Longbridge Weir (former Derby Canal) HEP installed.

Water Storage, Distribution and Treatment – example

Globally, water utilities are installing HEP generating plant in their service reservoirs, treatment works and distribution networks. Whilst Severn Trent Water have no HEP installed in their distribution and treatment assets, the historic turbine sales data include sales to the Water Board in the 1920s, 1940s and 1950s.

Figure 2.26 Belper Treatment Works

2.3.5 The waterpower timelines

Whilst the literature review identified some events and key challenges that impacted the development and use of waterpower, the individual site timelines helped to identify the specific challenges (local, national and global), affecting waterpower users in the DDC. Some of the 164 watermill sites timelines are more comprehensive than others, based on available material. The individual site timelines typically capture changes of ownership, application, growth and sometimes closure, all aspects affecting the use of waterpower. The timeline findings highlighted several key themes that led to five, more in depth, case studies, to develop a more comprehensive understanding. The five case studies: Ambergate (Alderwasley), the Chatsworth Estate, the Derwent Valley reservoirs, the Derwent Valley Mills World Heritage Site and the Weirs of the river Derwent identified new key issues, such as the impact of the Derwent Valley Water Act (1899-1944) on the industrial watermills and the 1930s Derby land reclamation and flood protection Riverlands project's impact on the River Derwent.

Figure 2.27 presents the timeline of the most significant location of waterpower usage in the DDC, the Belper mill complex site, located in the centre of the DVMWHS. Belper Mills has had an almost continuous use of waterpower, since 1776 (green). The 1980s HEP stoppage period (red), relates to the closure of the site by the English Sewing Cotton Company and the HEP generation facility being reinstated and operated by a third party (Section 5.2.2). The Belper Mills timeline captures the site's chronological development and related, impacting, events. Some of the external events potentially impacting the textile industry, identified during the literature review process, were included to the Belper Mills timeline. Raw materials and markets were impacted by wars around the world, including the Seven years' war (1756-1763) (Anderson, 2000), American revolutionary war (1775-1783) (Mokyr, 2009), Revolutionary and Napoleonic wars (including restrictions on British exports) (1803-1815) (Juhasz, 2015, Mokyr, 2009), the Crimean war (1853-1856), the American civil war (Lancashire cotton famine) (1861-1864) (Aspin, 2004) and the Franco-Prussian war (1870-1871) (ibid). The Belper site continues to generate HEP today, supplying the wholesale market (national grid) with renewable energy.

BELPER MILLS – POWER TIMELINE		EXTERNAL EVENTS AFFECTING WATERPOWER
1759, Jedediah Strutt – Derby Rib patent	1750	1759, Smeaton's enquiry, natural powers of water & wind to turn mills published.
	1760	1769, R Arkwright + J Strutt partners Richard Arkwright patent Spinning Frame
WEIR 1776, J Strutt – Builds Burton Weir (6ft 2")	1770	1771, R Arkwright & Co. move to Cromford Mill powered by Cromford Sough Water 1775, R Arkwright - Carding M/C patent R A & Co. Ltd build 'Arkwright' type mills
WATER WHEELS – WOODEN (12ft dia.) 1778, South Mill 2 wheels 1784, North Mill 1 wheel 1795, West Mill 1 wheel (48ft x 12ft)	1780	1789, River Derwent Mill owners petition against Cromford Canal abstraction.
CIRCULAR WEIR (+ 4 floodgates & fish pass) 1796, WG&J Strutt – 350ft x 9ft 2"	1790	1792, River Derwent Mill owners v Duchy of Lancaster fish and water rights 1795, Major flood, destroy Belper bridge
WATER WHEELS – HYBRID (18ft dia.) 1797, West Mill 2nd wheel (40ftx18ft) 1804, North Mill (rebuilt) 1 x (23ft x 18ft)	1800	1803, Cotton, Britain's biggest export
WATER WHEELS – IRON (21 ½ ft dia.) c. 1805 First pair of Iron Suspension Wheel installed. TC Hewes build, W Strutt design (possibly for 1808 Reeling Mill) 1805-33 Wooden wheels replaced by Iron 5 Wheels (normal river flow) 6 Flood Wheels (high river flow)	1810	1807-11, Napoleonic War, export blockade 1808, Ward v Strutt – Flooding case
	1820	1818, Hurt v Strutt – Raised weir, stopping upstream Iron Forge 1844, Hurt v Strutt - Agreements
	1830	1833, First Factories Act – Hours restricted
WEIR (more storage & power) 1818, Raised 3ft 1844, Raised 8"	1840	
STEAM (back up, additional power) 1854, Steam engine installed + Chimney Possible B&W engine from Derby Mill fire.	1850	
WATER WHEELS – IRON 1858, Last Waterwheel, South Mill 200 HP Flood Wheel	1860	1861-4, American Civil War, Cotton famine
	1870	1870-1, Franco-Prussian War Germany & Russia raised tariffs against British manufactured goods. The Strutts lost 75% of their market. 1885 – Milford spinning operation closed
STEAM (back up, additional power) 1882, Additional steam engine to be used when river falls.	1880	1886, World's first Electric Lighting water powered at Cragside by Lord Armstrong

BELPER MILLS – POWER TIMELINE		EXTERNAL EVENTS AFFECTING WATERPOWER
1897, 14 Cotton manufacturers combine to form English Sewing Cotton Company. Site owned & leased by GH Strutt until 1907	1890	1896, GH Strutt installs Electric Lighting in Makeney House, Turbine installed in forge.
	1900	
WATER TURBINES 1901-6, 4 Turbines installed in South Mill 1911, 3 Pairs Turbines installed West Mill Total HEP Power 1,000 HP	1910	1908, GH Strutt installs Turbines in Milford Mills to show ESCC HEP potential.
+ STEAM 1912, East Mill built, Additional Steam Turbines, 1,000 kW. Electric Power on site. 30 motors (1/2 HP to 275 HP)	1920	1922, Derbys. and Notts. Electric Power Co. introduces Electric Power to Belper
WATER TURBINE 1936, Gilkes turbine added, weekend use	1930	Derwent Valley Water Acts 1899 to 1944 Howden, Derwent & Ladybower built. Noe diverted, reducing flows in Derwent. 1944 Parliament petition led by ESCC. Compensation flows & penalties agreed
1940s Power from West Mill turbines reduced from 400 kW to 200-250 kW due to fall in river volumes. 2 HEP + 1 Steam synchronised manually 7am (6 days per week) to start electricity generation and mill operations.	1940	1939-45 Sale of embroidery thread banned Exports impacted during & post war
	1950	1948, Electric Supply nationalised
WATER TURBINES 1958, 2 x 175 kW Gilkes turbines installed in the South Mill. Still operating 2023.	1960	1958, Britain becomes Cotton importer 1959, Cotton Industry Act – funds for streamlining, modernising, diversification
1960s, West Mill site redeveloped, new hosiery factory (1911 turbines removed)	1970	1963, Water Act – New Water Authorities, abstraction licencing & HEP water charges
1966 National Heritage listing Grade I Belper North Mill Grade II* Belper Weirs, Walls and Sluices Grade II Mill Chimney & East Mill (1979)	1980	1974, Water Power Users petition parliament to reduce/stop water charges. 1981, Energy Conservation Act stops HEP water charges. 1983, Energy Act – allows grid connections
1986 ESCC close Belper Mill. HEP stopped		
1989 HEP restarted, exporting to grid. 1990, Operators Derwent Hydro Power Ltd Sluice gates automated	1990	1989, ETSU produce first report on climate change mitigation for UK gov. In 1988 only HEP made a significant contribution to renewable electricity (4.8 TWh).
2001, Derwent Valley Mills World Heritage Site inscription by UNESCO	2000	1989, National Rivers Authority formed. 1995, NRA included in new Environment Agency, inc. Abstraction licencing 2000, Water Framework Directive (WFD)
2013, Fish Pass working party study	2010	
2015, New 'self-cleaning' screens installed	2020	1990, UK Gov. Renewable subsidies NFFO 2002, Renewables Obligation (RO) 2010-2019 Feed in Tariffs (FiT)
		2023, Dept. of Energy Security & Net Zero

Figure 2.27 Belper Mills timeline

2.3.5.1 HEP generation timelines

One of the most surprising findings in the DDC timelines, is the high number of sites with references to water turbines being installed in the late 19th or early 20th century, most of which no longer have turbines or any facility to generate their own electricity. This new finding, from individual timelines and historic water turbine sales data, was potentially critical to the overall aim of understanding the challenges faced today, so a deeper study was made of any site in the DDC that may have installed a water turbine, potentially to generate electricity. Turbines were also introduced in the early 20th century at non-mill sites, to produce electric lighting and power for local use, particularly in country houses, and to 'recover' energy in new water storage, transfer and treatment plants operated by the Derwent Valley Water Board. A grouped timeline (1890 to 2020) was produced for the 59 sites that have introduced a water turbine and/or HEP at some point since 1890, highlighting significant periods of change (Figure 2.28). Following the transition from wholly mechanical power (yellow) to the development of local HEP generation (green), over 35 sites stopped generating HEP between the 1930s to 1970s, instead choosing to purchase electricity, initially from the Derbyshire and Nottinghamshire Electric Power Company and later from the nationalised coal-powered national grid. The timelines also show new HEP projects and reinstatements taking place from the late 1980s.

The overall picture is clear (Figure 2.28), with watermills in the early 20th century harnessing the power of water to produce electricity, initially for electric lighting and then electric power. The subsequent decline in HEP usage during the 20th century was highlighted in the Department of Energy report in 1978 (Francis, 1978). There is also a 'revival' in HEP developments from the 1980s with both reinstatements, e.g. Chatsworth, and new projects, e.g. Howden Reservoir.

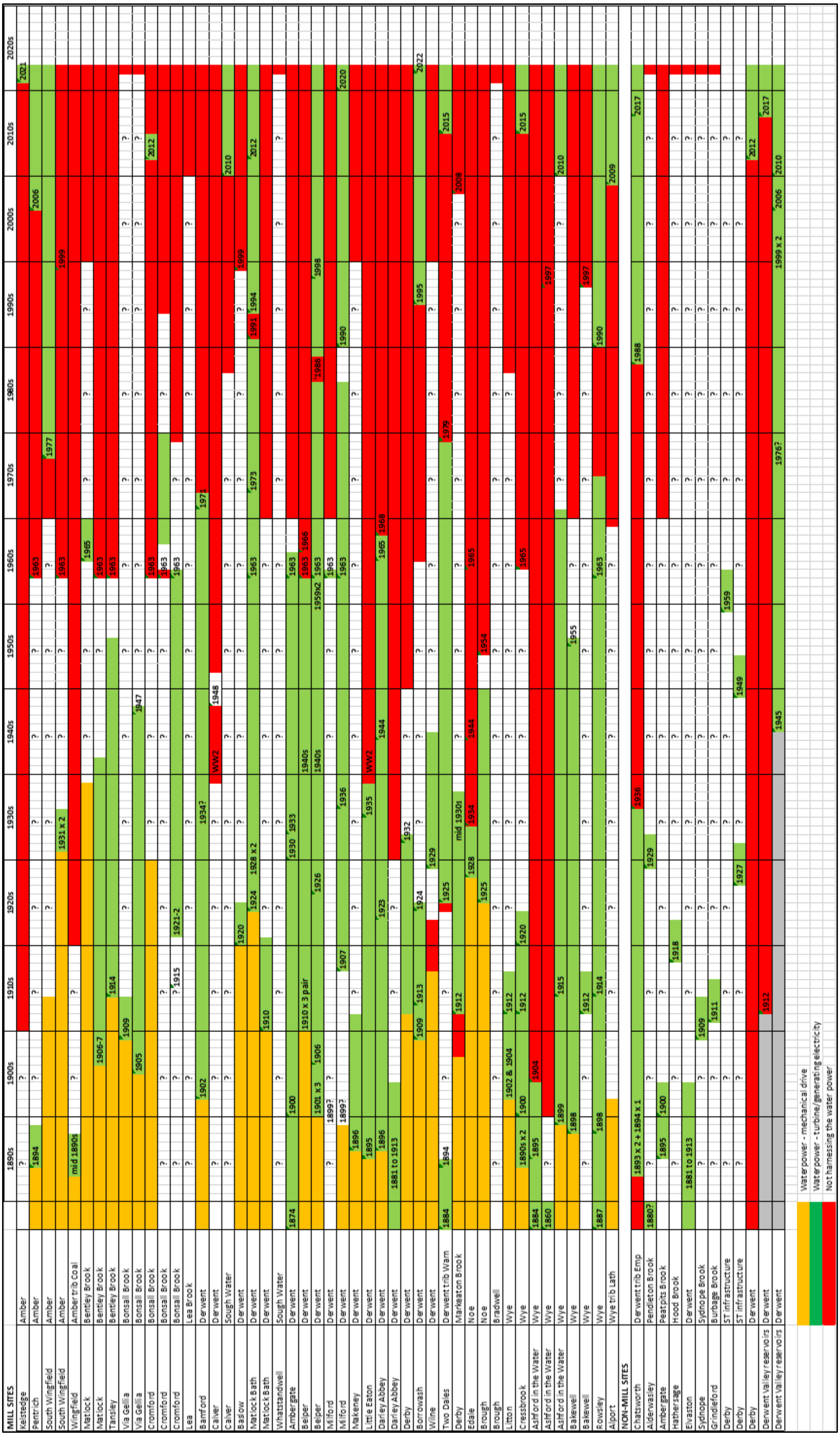


Figure 2.28 Waterpower timelines in the DDC for sites installing turbines since 1880

2.3.6 HEP potential in the Derbyshire Derwent catchment

With information captured relating to current and past HEP generation, plus recent HEP assessments (http://doi.org/10.17639/nott.7459), it was possible to build a HEP potential model for the DCC (Table 2.5) based on actual installations, assessments and past use, rather than theoretical modelling. The HEP potential is approximate and intends to identify a scale of opportunity (number of sites and overall capacity) for the DDC, to understand the value in unlocking its potential and provide a justification for making possible changes to policy and regulation.

Level 4 (least confidence) was a calculation, based on the average potential for a given waterway (based on actual installations or feasibility studies from the waterway) and the number of sites confirmed with some infrastructure in place during the walk-over survey: the HEP assessment, therefore, does not include sites that could not be viewed during the walk-over survey. One, potentially significant, omission are the HEP opportunities within the Severn Trent Water (STW) network in the DDC, presented to the British Hydropower Association by STW in 2008 (Dent, 2008), but unavailable for this study.

Based on the information assembled in the waterpower gazetteer, the results indicate that the DDC HEP potential is significantly higher (5.5 MW from 152 sites Table 2.5) than the recently published report investigating renewable energy potential across Derbyshire, commissioned by Derbyshire County Council (Scene Connect, 2022). The December 2022 report states there is limited opportunity for any further development on top of the existing 1.7 MW (14 HEP installations in all Derbyshire) (ibid). This data is incorrect, as there is currently installed 2.2 MW (capacity) at 17 HEP installations in the DDC (http://doi.org/10.17639/nott.7459), and an additional 7 HEP sites with approximately 1MW of capacity elsewhere in Derbyshire; a total of 3.2 MW at 24 sites, (http://doi.org/10.17639/nott.7459).

Table 2.5 The HEP potential for the Derbyshire Derwent catchment

DDC Gazetteer December 2022		Level 1 Installed HEP	Level 2 HEP study (potential)	Level 3 Historic HEP (no study)	Level 4 Others (calc.) No. Sites x av. HEP	**Total kW**
			MILLS			
Amber	Total kW	3 HEP 27		2 ex-HEP 18	6 x 10 60	105
Amber tributaries	Total kW				7 x 5 35	35
Derwent	Total kW	4 HEP 820	6 Studies 484	2 ex-HEP 436	3 x 50 150	1,890
Derwent Small tribs.	Total kW	2 HEP 25	7 Studies 240	1 ex-HEP 8	21 x 10 210	483
Ecclesbourne	Total kW				7 x 10 70	70
Noe	Total kW		2 Studies 24		5 x 10 50	74
Wye	Total kW	3 HEP 160	4 Studies 210	1 ex-HEP 19	7 x 25 175	564
Wye tributaries	Total kW	1 HEP 30			6 x 10 60	90
Bentley Brook	Total kW		1 Study * 75	2 ex-HEP 52	2 x 25 50	177
Markeaton Brook	Total kW				6 x 10 60	60
Number of Mill sites	***111***	*13*	*20*	*8*	*70*	
			NON-MILLS			
Derwent	Total kW	1 HEP 230	1 Study 43		9 x 50 450	723
Derwent Small tribs.	Total kW			5 ex-HEP 72	4 x 10 40	112
Ecclesbourne	Total kW				1 x 10 10	10
Wye	Total kW				2 x 25 50	50
Wye tributaries	Total kW				5 x 10 50	50
Chatsworth Fountain	Total kW	1 HEP 100				100
Water utilities	Total kW	2 HEP 805		2 ex-HEP 118	1 x 10 10	933
Number of Non-Mill sites	***42***	4	1	15	22	
		Installed	**Studies**	**Historic**	**Others (calc.)**	
Number of sites		**17**	**21**	**23**	**92**	
Level Total kW		**2,197 kW**	**1,076 kW**	**723 kW**	**1,530 kW**	
Level Total MW		**2.2 MW**	**1.1 MW**	**0.7 MW**	**1.5 MW**	
Cumulative Total MW		**2.2 MW**	**3.3 MW**	**4.0 MW**	**5.5 MW**	**5.5MW**

* The study for Bentley Brook includes all of the Lumsdale head and flow in its calculation.

Figure 2.29 shows the location of sites for Levels 1, 2 and 3 of the HEP potential calculation. The large cluster of HEP assessment studies in the Peak District (Level 2) come from the Friends of the Peak District 2010 *Peak Power: Developing micro hydro power in the Peak District* report (Woods, Tickle et al., 2010). The second cluster of studies cover the DVMWHS area, uses information from the study *Estimate of hydro resource in the Derwent Valley* (Harton, Chandler et al., 2012). A similar, in depth, site-by-site study across the DDC or Derbyshire would quantify the total HEP potential more accurately.

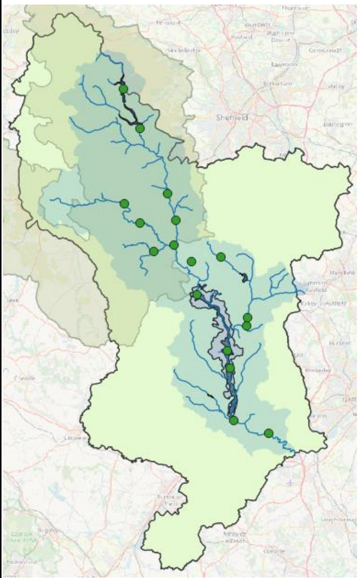
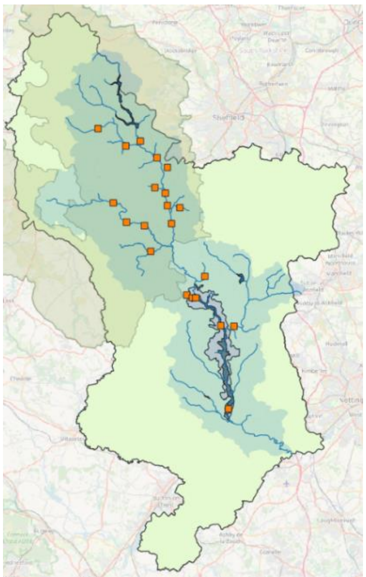
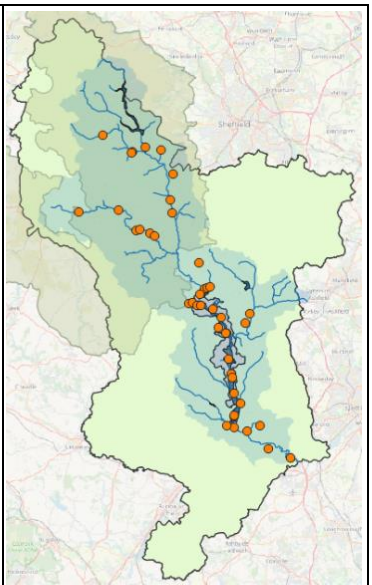
		
Level 1 – HEP generation (Dec. 22)	Level 2 - 21st Century HEP feasibility assessment	Level 3 - Historic HEP generation

Figure 2.29 Levels 1, 2 and 3 site distribution across the DDC.

2.4 Discussion

The Derbyshire Derwent catchment (DDC) waterways and gazetteer

Identifying 164 watermills on 46 different waterways within the DDC confirms the contemporary reports of Britain's waterways being 'saturated' with mills c.1800. The watermills were identified using the 1880 to 1920 OS maps, showing the mills and their weirs were still in situ and potentially producing power, despite the 19th century growth in steam power usage. The different flows and falls of the main rivers and tributaries offered the opportunity to harness different quantities of power for many different applications, with the main rivers (Derwent, Wye, Bentley Brook, Bonsall Brook, Amber, Ecclesbourne and Markeaton Brook) powering the larger industrial watermills and offering larger HEP opportunities in the DDC.

The site timelines and walk-over survey identified catchment developments that impacted on the water available to the watermills over time, such as the lead mining drainage channels (soughs) and water abstraction for canals in the 18th century, and the 20th century Derwent Valley reservoirs. Water abstraction impacting on waterpower will be reviewed in Chapters 3, 4 and 5.

Site biographies

Developing the timelines for watermills across the catchment captured the development of waterpower, including game-changing innovations. Mill ponds were developed to store water (power) and Richard Arkwright was an early adopter of using a steam pump to recirculate water from the tailrace back to the mill pond at his Haarlem textile mill, Wirksworth (Menuge, 1993). The most detailed timeline, the Belper mills complex from 1776 to 2013, evidences the generic development of waterpower in Britain. Industrial watermills strived to improve the traditional overshot or undershot wooden waterwheel, to increase power output but it was the introduction of iron, initially to build hybrid wood/iron wheels, that led to a step change. Along with improvements in river and waterwheel control, the iron suspension wheel (Belper c.1808) led to a potential fivefold increase in power harnessed by one waterwheel, changing the constraint from the wooden waterwheel to the waterway.

By the end of the 19th century water turbines for mechanical power, common in countries more dependent on waterpower, were introduced to Britain, with the new wireworks in Ambergate installing the largest turbines in England in 1874 (Bulmer, 1895). The end of the 19th century saw waterwheels and turbines being used to self-generate electricity, initially for lighting (such as Oakhurst House, Ambergate [Jewell, 1995]) and later for power.

The site timelines also captured new water-powered applications being patented within the DDC, in addition to Arkwright's famous cotton spinning developments. In 1751 Henry Watson patented his water powered machine 'for cutting or sawing marble, or any other stone, for sweeping for facing and also polishing the same' (Brighton, 1997 48). This invention led to Ashford in the Water, River Wye, marble works becoming the centre of excellence with floors and vases still viewable at Chatsworth House (ibid). In 1789 Pilkington wrote 'At Higham [River Amber] has been invented a machine for carding and spinning hurds (i.e. coarse flax) for candle wicks, for which the proprietor is said to have obtained a patent' (Pilkington, 1789 Vol II 323).

Reviewing sites by decade, where available, using the OS maps, identified patterns and step changes specific to waterways or industries. Caudwell Flour Mill's, Rowsley, and Warney Mill's, Darley Dale, early adoption of roller milling technology in 1881, required them to introduce the more efficient water turbine technology. The improved efficiencies and volumes impacted, negatively, on many local smaller traditional stone grinding flour mills (Walker, 2000). Many of the smaller flour mills on the DDC tributaries become 'disused' on the OS maps by the 1910s, see a sample of mills on the river Amber, Figure 2.30.

Master Ref (SK)	Common Name	Waterway	1870's	1880's	1890's	1900's	1910's	1920's
SK 33513 63699	Kelstedge Mill	Amber	Kelstedge Mill (Thread)	Kelstedge Mill (Thread)	no name			no name
SK 34540 62860	Ashover Mill	Amber	Ashover Mill (Corn)	Ashover Mill (Corn)	Ashover Mill (Disused)		Ashover Mill (Disused)	Ashover Mill (Disused)
SK 35147 51835	Saw Mill, Sawmills	Amber		Saw Mill		Saw Mill	Saw Mill	Saw Mill
SK 35406 62283	Fall Mill, Ashover (Corn)	Amber		Fall Mill (Corn)	Fall Mill (Corn)		Fall Mill (Disused)	
SK 35888 52218	Bullbridge Mill (Corn)	Amber		Bullbridge Mill (Corn)	Bullbridge Mill (Corn)		Corn Mill	
SK 37817 52234	Pentrich Mill	Amber		Pentrich Mill (Flour)		Pentrich Mill (Corn)	Pentrich Mill (Corn)	
SK 37944 53516	Weir Mill Farm, South Wingf	Amber		Wire Mill (Corn)		Wire Mill (Corn)	Wire Mill (Corn)	
SK 38031 55531	South Wingfield Corn Mill	Amber		Corn Mill	Corn Mill	Corn Mill	Corn Mill	
SK 38680 56917	Amber Mill	Amber		Amber Mill (Flour)	Amber Mill (Disused)		Amber Mill (Furniture Works)	
SK 38657 58203	Bumpmill	Amber	Bumpmill	Bumpmill	Bumpmill		Bumpmill	
SK 38674 58388	Higham Mill (Flour)	Amber	Higham Mill (Flour)	Higham Mill (Flour)	Higham Mill (Flour)		Higham Mill (Flour)	
SK 38701 58387	Saw Mill, Higham Dairy	Amber		no name	no name		Saw Mill	
SK 37465 60860	Woolley Mill (Stone Sawing	Amber (under Ogston)	Woolley Mill (Disused)	Woolley Mill (Disused)	Woolley Mill (Stone Sawing)		Woolley Mill (Disused)	
SK 35870 53315	Corn Mill, Crich?	Amber trib		Corn Mill	Corn Mill	Corn Mill	Corn Mill (Disused)	
SK 35924 53163	Bobbin Mill, Fritchley	Amber trib		Bobbin Mill	Bobbin Mill (Disused)	Bobbin Mill (Disused)	Bobbin Mill (Disused)	
SK 36100 52756	Corn (Brook) Mill, Fritchley	Amber trib		Corn Mill		Corn Mill (Disused)	Corn Mill (Disused)	
SK 37208 54038	Park Mill (Doubling)	Amber trib Coal		Park Mill (Doubling)		Park Mill (Doubling)	Park Mill (Disused)	
SK 36458 50612	Shore's Flour Mill, Heage	Amber trib Down		Flour Mill		Flour Mill	Old Mill	
SK 37033 64353	Press Mill (Corn), Alton	Amber trib Pres		Press Mill (Corn)	Press Mill (Corn)		Millhouse Farm	
SK 37795 64161	Woodthorpe Mill (Flour) N V	Amber trib Pres		Woodthorpe Mill (Flour)	Woodthorpe Mill (Flour)		Woodthorpe Mill (Flour)	
SK 33064 64480	Brockhurst Mill, Ashover	Amber trib Smal		Brockhurst Mill (Corn)	Brockhurst Mill (Corn)			Brockhourst Mill (Disused)

Figure 2.30 River Amber sites (OS maps, by decade, 1870 to 1920 (full model to 1980). Green showing latest active decade, Red highlighting the site classified as 'disused'.

With no national electricity grid available at the start of the 20th century, the DDC timelines identified 59 sites that installed water turbines in the last 120 years, probably to generate electricity for themselves. One of the key findings of the timeline was the fact that, by the 1980s, only five sites in the DDC continued to harness river power to generate electricity, including the three English Sewing Cotton Company sites at Matlock Bath (Masson Mills), Belper and Milford. From the 1980s the DDC has seen a mini revival in HEP reinstatements, and new projects, with sites such as Borrowash Mill exporting and selling surplus electricity, upgrading their turbines and control systems with the support of UK government subsidies, such as the Feed in Tariffs. From a situation of five turbines generating HEP in the DDC in the 1980s, by the end of 2022, 17 sites were generating.

Walk-over survey

The original scope of the research project focussed on run-of-river waterpower opportunities associated with historic watermill sites and weirs. The physical survey broadened the waterpower opportunities, identifying hydroelectric power (HEP) generation at locations using man-made water flows (e.g. Calver Corn Mill (former) powered by sough water and Chatsworth House, powered by the Emperor Fountain feed). Additionally, sites generating HEP using weirs built for alternative purposes (other than watermills) were discovered (e.g. Ladybower reservoir and Longbridge Weir [former Derby Canal], Derby). Considering HEP generation using man-made flows and structures opens the possibility for more HEP sites, with the water utility assets, currently operated by Severn Trent Water, potentially offering significant generation and energy storge opportunities.

Bodies such as the Environment Agency, working to improve the fisheries of the Trent catchment, often identify the industrial revolution weirs (mills and navigation) as a primary obstacle faced by migratory species, such as the salmon (Brailsford, 2016). The walk over survey of the Derwent did confirm 17 weirs relating to historic watermills, although one of those weirs, Ambergate, was a 1940s replacement weir, installed with a moveable weir to reduce flood risk for the site. The walk-over survey also identified floodgates and sluices along the Derwent, some in use but most in a poor state (Figure 3.27, Figure 5.22, Figure 5.23). However, the survey also identified several 20th century weirs and dams built to manage the waterways, with no fish passage facility in the original design, including three reservoirs in the upper Derwent, three flood and land reclamation weirs south of Derby, and four river gauging weirs.

HEP potential in the DDC

The watermill site timelines confirm that sites capable of harnessing waterpower have been of great value to individuals and communities for hundreds of years. The repurposing of former watermills, competition for sites and conflicts between the industrial mill owners (water abstraction and weir height) across Britain is well recorded (Reynolds, 1983 267), with DDC site histories providing more examples, such as the 19th century dispute between the Strutts (Belper) and Hurts (Alderwasley/Ambergate). The gazetteer and walk-over survey identified sites across the DDC that today are private residences, holiday lets, businesses or heritage sites, that may have the potential to generate HEP, supporting environmentally and economically sustainable development.

Investigating the key themes and issues

The cause-and-effect diagram (CED) was used to collate the identified waterpower impacting factors, Chapter 1. Figure 2.31 , shows the major (higher level) causes identified, that were investigated further in each of the three ages of waterpower

(Chapters 3, 4 and 5), to identify examples of the minor, more specific causes, impacting on waterpower usage in the DDC.

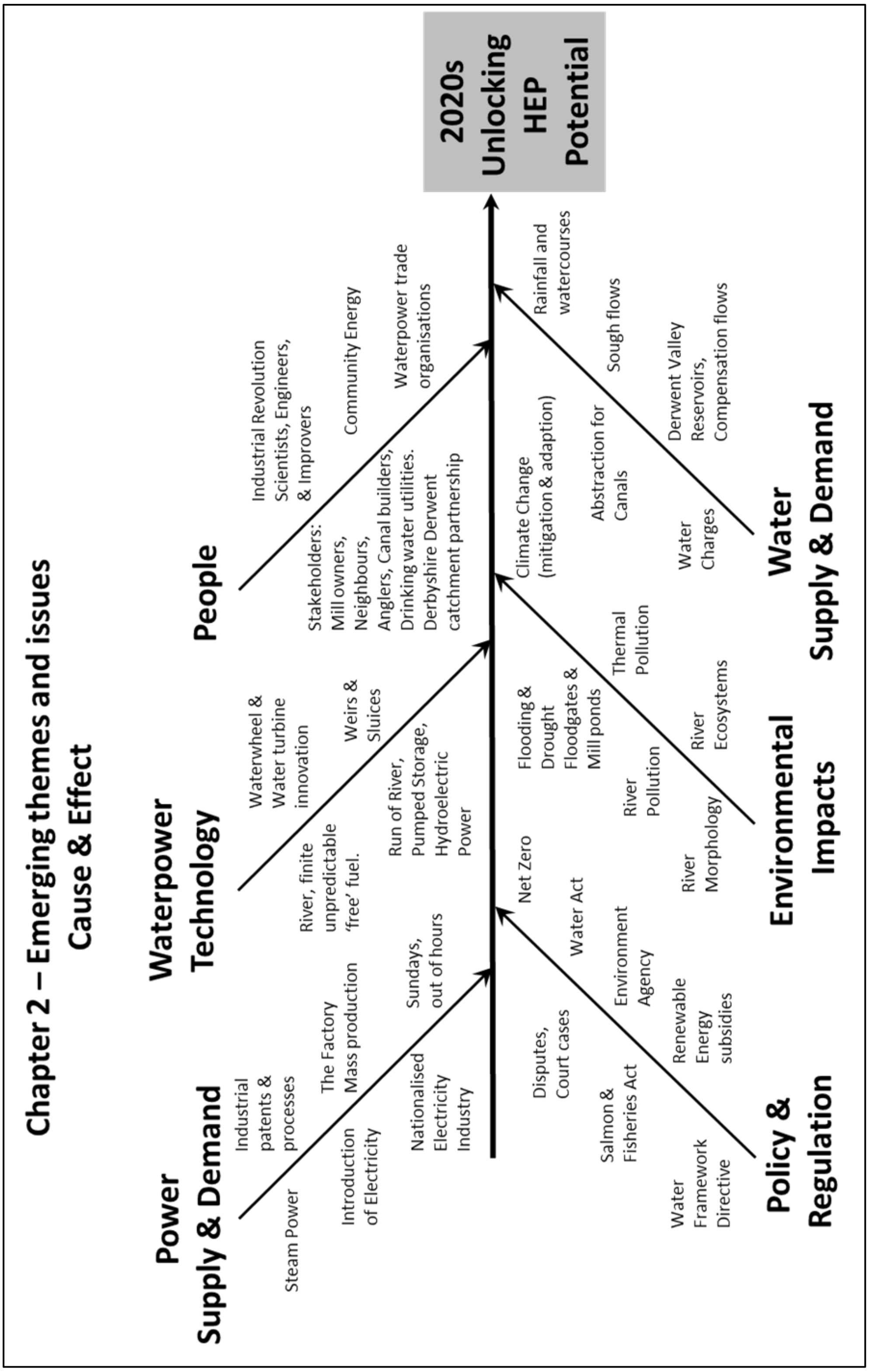


Figure 2.31 The emerging themes and issues identified in the gazetteer timelines and case studies.

Chapter 3 Waterpower: The Age of Mechanisation (1752-1878)

3.1 Introduction

Waterpower played an important role in the early industrial revolution (Trinder, 2013 49) which can be viewed as a successful period in its development and use. Given this, the main aim of this chapter is to identify the lessons to be learnt from the use of waterpower in the Derbyshire Derwent catchment (DDC) during the age of mechanisation, that could support a successful, and sustainable, period of hydroelectric power (HEP) development in the future.

As European economies moved from isolation and self-sufficiency to regional or national markets, manufacturing enterprises were encouraged to expand to serve the larger markets, which, in turn, required the development of larger water-powered manufacturing facilities (Reynolds, 2006 159). The investment in larger water-powered manufacturing establishments wasn't without risk and always faced the typical waterpower problems of capacity constraints, immobility, inflexibility, and unreliability (mechanical and water supplies, including flood and drought) (ibid).

The chapter title refers to the age of mechanisation, which, for the purposes of this research project, describes the period when waterpower enabled the development of mass manufacturing, and included the industrial scale powering, by water, of the world's first textile 'factories' in the DDC. The period starts with the scientific experimentation, understanding and development of the waterwheel and waterpower by John Smeaton in 1752, and ends with Lord Armstrong using waterpower to power electric lighting (rather than only providing mechanical motive power), at his Cragside home in 1878. Nowhere harnessed the power of water like the 'early factory masters', such as Richard Arkwright (1732-1792) and William Strutt (1758-1830) (Chapman, 1967), in the Derbyshire Derwent Valley between Cromford and Derby in the late 18th century, and the significance of this location was recognised by UNESCO and inscribed as a World Heritage Site in 2001 (DVMWHS, 2020).

Throughout the age of mechanisation, waterpower was improved to optimise its power generation but an alternative power source, steam, became dominant, mechanically driving growing industries through the 19th century (Hills, 2008).

Watermill owners also encountered challenges from other river stakeholders, identified in the DDC watermill site timelines. One of the main challenges being fellow mill owners competing to take advantage of natural falls and man-made heads (weirs) in the river (Getzler, 2004 34)(DRO D2535/M/4, 1818-44), fighting for the rights to the water (Endfield and Van Lieshout, 2018) and objecting to water abstractions for the new Cromford and Derby canals (Schofield, 1981). DDC millowners also faced litigation following flooding events (DRO D3772/T19/10/7, 1808-10) and engaged in the salmon inquiry (1860-61) following the decline in salmon populations across the country (Cowx and O'Grady, 1995). The salmon inquiry focussed on the river obstacles (weirs) and included the Trent catchment, which incorporates the DDC.

There is a rich source of waterpower related material about one site in the Derwent Valley Mills World Heritage Site (DVMWHS), the Belper Mills complex, originally developed and operated by the Strutt family (1776-1897), and then owned by the English Sewing Cotton Company (and later Tootal) until its closure as a textile mill in 1986. Many historic contemporary ‘visit reports’ include references to the development and innovative use of waterpower by the Strutts, and the Derbyshire Record Office (DRO) holds collections relating to the Strutts (e.g. DRO D1564), English Sewing Cotton Company (DRO D3638) and other stakeholders impacted by their use of waterpower. These include legal papers relating to disputes and agreements, which help to unlock some of the broader impacts and issues of waterpower use, therefore the use of waterpower at Belper is frequently referenced in this chapter.

The six factors influencing waterpower usage, identified in Chapters 1 and 2, were used to group the findings from the literature review, individual waterpower site timelines and deeper studies relating to the age of mechanisation, 1752 to 1878. The major cause findings (Figure 3.1) were investigated further to identify specific, minor, issues affecting waterpower during this period. Whilst the scope of this research was based on the DDC catchment, many of these issues identified, both natural and man-made, had wider context, e.g. the weather or government regulation, which is incorporated. These six factors also form the structure for Chapter 3.

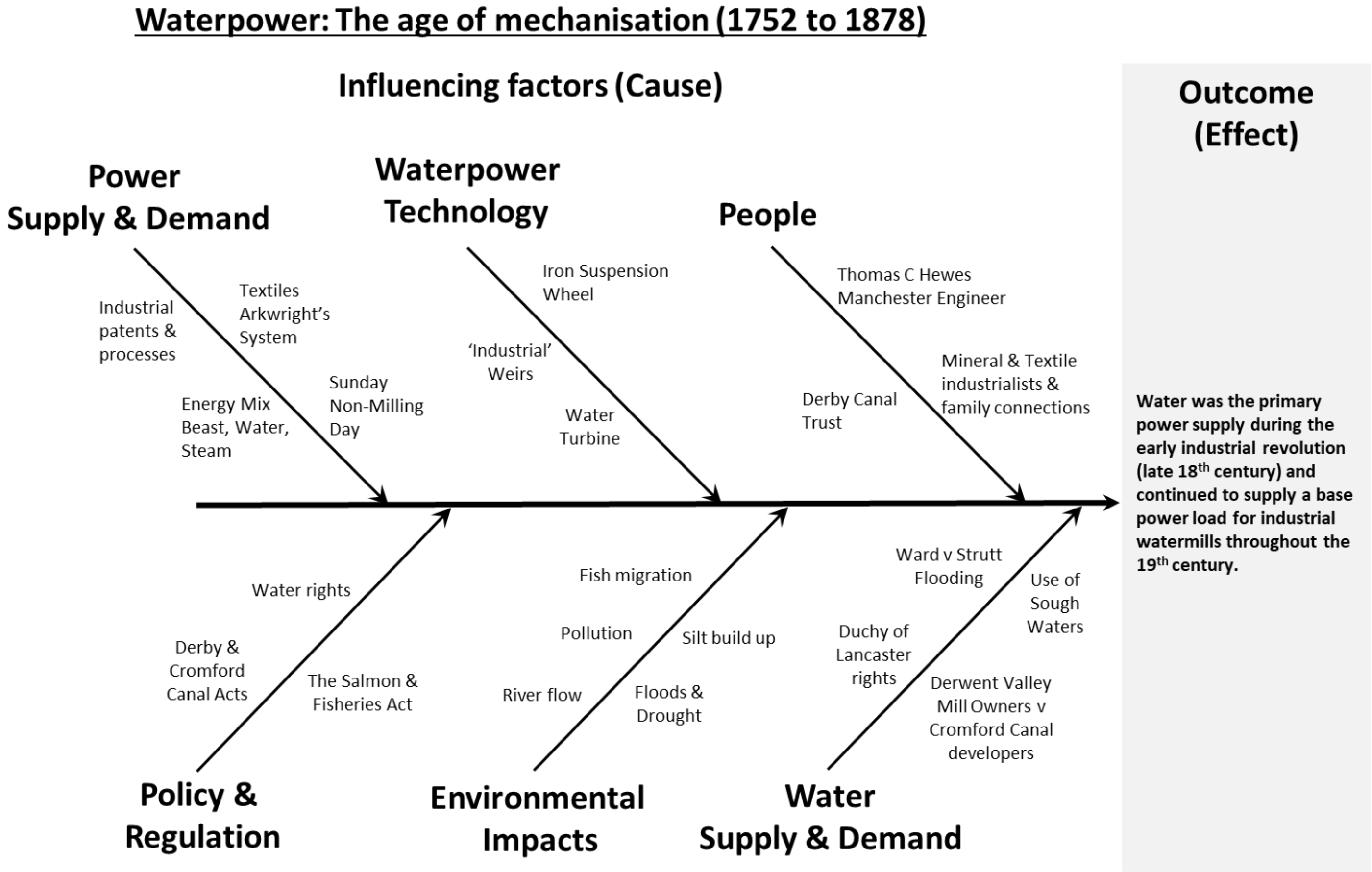


Figure 3.1 Factors and topics impacting on the use of waterpower during the age of mechanisation.

3.2 Waterpower development

3.2.1 Before 1750 in the Derbyshire Derwent catchment (DDC)

Whilst the Domesday survey (1086) includes around 100 corn mills within Derbyshire (Morris, Morgan et al., 1978), we know that prior to 1750 waterpower had many applications in the DDC. A patent infringement dispute in 1582, regarding the setting up of a watermill by Burchard Cranich in Makeney on the river Derwent in 1556 (Donald, 1961), includes a lead-ore stamping mill with a 16 ft (4.9 m) water wheel. The site was repurposed by Sir John Zouch as a wire manufactory in the late 16th century (ibid). This same site was to be developed in the late 18th century as part of the Strutt’s textile mill developments in Milford.

Waterpower was also used extensively in lead mines located in the upper DDC, from the 1680s, primarily for pumping water from lower levels but also for ventilation (Willies, 2004). Long before the industrial revolution waterpower was of great value to communities, the water-powered industries, such as fulling, grain milling, or paper making usually requiring no more than 5 hp (3.7 kW) of power (Reynolds, 1984).

George Sorocold, a genius water engineer who married and lived in Derby (Williamson, 1936), patented a water pumping system in 1693, driven by an undershot waterwheel that could be lowered and raised to suit river levels (Trinder, 2013). He used St Mary’s weir, Derby, possibly a natural feature (Figure 3.2), to divert the river Derwent (Gifford, 1999, Williamson, 1936). One or two large scale, water-powered manufacturing facilities existed before the ‘classic’ period (1760 to 1840) of the industrial revolution (Trinder, 2013). The large Derby Silk Mill harnessing the power of the river Derwent in 1717, was, in many crucial aspects, a direct precursor of Arkwright’s (ibid), Strutt’s and Evans’s cotton spinning mills half a century later, all now forming the Derwent Valley Mills World Heritage Site (DVMWHS, 2020). Indeed, the Derby Silk Mill is built adjacent to a failed silk watermill, commissioned by Cotchett and built by George Sorocold in 1702 (Trinder, 2013, Williamson, 1936), used the same St Mary’s weir. Cotchett’s former employee, John Lombe, travelled to Italy to learn the secrets of silk throwing using their water-powered silk engines (Hutton, 1817), that originated in Bologna around the mid-14th century (Comino and Gasparetto, 2020).

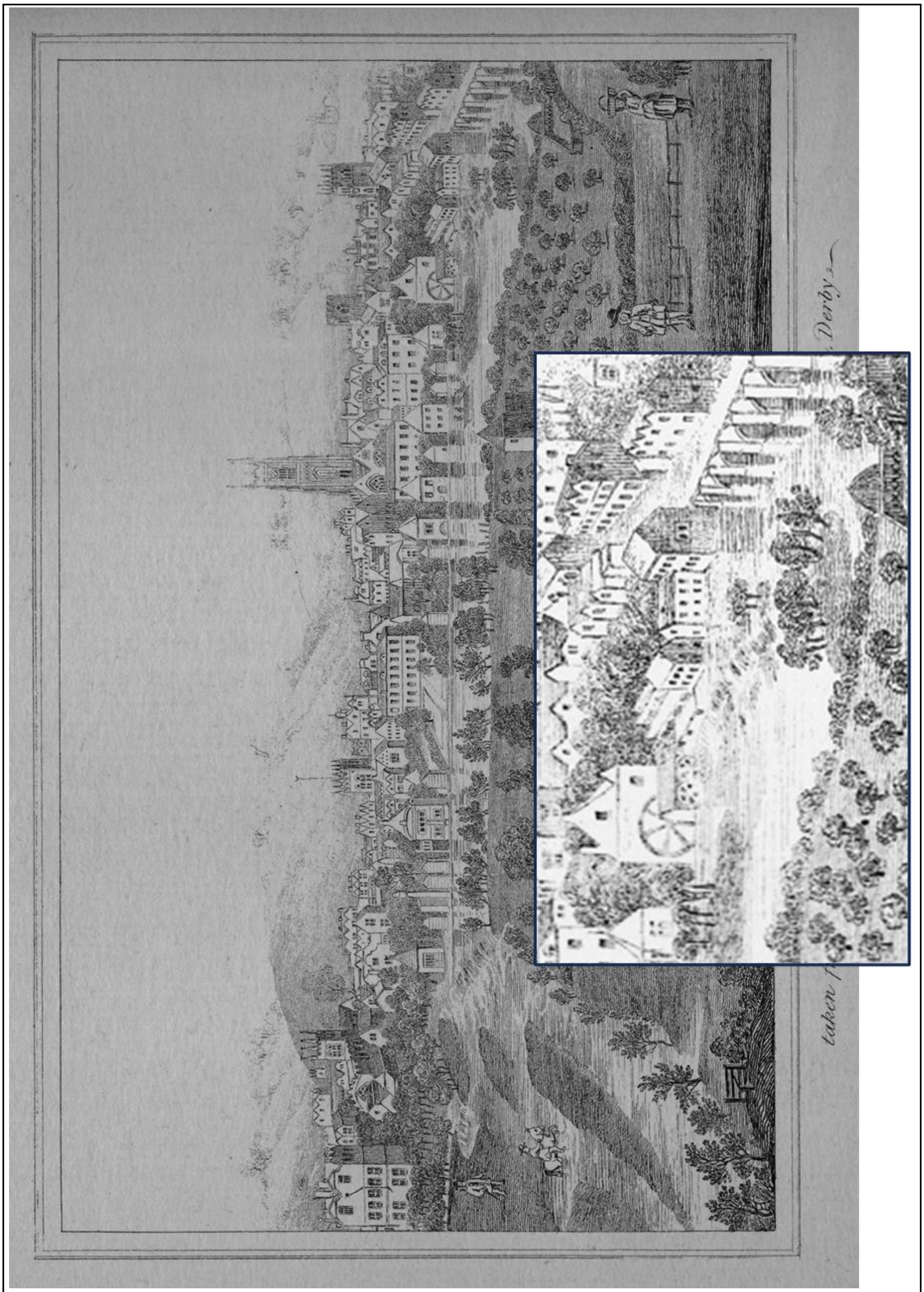


Figure 3.2 East view of Derby, painted after the Sorocold water pump (1692) (behind the two corn mill wheels) and before the building of the Lombes Mill (1717). Unknown painter and date (Keys and Gadd, 1895).

3.2.2 Industrial waterwheels

Following Richard Arkwright's first patent to 'spin Cotton Worsted and Flax into yarn' in 1769, he set up his manufacturing site in Nottingham, a mill powered by horses (Fitton and Wadsworth, 1958 64). As he made improvements to make the equipment more operational and scale up production, he needed more power. With his new partners, Jedediah Strutt and Samuel Need, he built his first water powered cotton mill at Cromford in 1771, with two sources of water available for power, the Cromford Sough (a lead mine drainage channel) and Bonsall Brook (Swindell, 1965 461). Using the sough waterpower they continued developing Arkwright's 'water-frame' and other cotton manufacturing processes (Hills, 1970). The early 'Arkwright-type' mills were based on a 1,000-spindle design, which engineers, such as Boulton and Watt, estimated required 10 horsepower (hp) (7.5 kW) to power them (Chapman, 1981).

The early British textile mill pioneers often repurposed old watermills, working with existing buildings and waterwheels, but the gradual introduction of mechanisation required larger waterwheels or, later, more powerful steam engines and new buildings. Cotton spinning by rollers was introduced in 1769, carding in 1775, mule spinning was mechanised between 1780 and 1800, devilling and stretching was introduced c.1800 (Smith, 1969). The progress of mechanisation led to a demand for increased power, evidenced by the waterpower per floor area of the Quarry Bank Mill of Styall, near Manchester (ibid) (Table 3.1).

Table 3.1 The growing demand for power intensity example (Quarry Bank Mill, Manchester) (Smith, 1969 5)

Year	Area	Installed power	Power/area
1734	11,200 ft^2 1.040 m^2	15 hp 11.2 kW	1.3 hp/1,000 ft^2 **10.8 kW/m^2**
1810	16,200 ft^2 1,500 m^2	40 hp 29.8 kW	2.5 hp/1,000 ft^2 **19.9 kW/m^2**
1820	28,500 ft^2 2,650 m^2	100 hp 74.6 kW	3.5 hp/1,000 ft^2 **28.2 kW/m^2**

Smeaton undertook experiments (Section 1.3.1.2) and improved the industrial waterwheel, working on many projects across Britain between 1753 to 1791 (Wilson, 1955). His experiments and practical case studies led to numerous improvements to maximise power output from the available water supply, by maximising overshot wheel diameter or converting undershot wheels into low breast-shot wheels (Wilson, 1972), see Figure 3.3. Smeaton also introduced the use of iron into the traditional wooden water wheel, with cast iron shafts (1769), substituting cast iron for wooden gearing (1778) and using wrought iron bucket boards rather than wooden ones (1780) (ibid). Smiles (1891) reports about Smeaton introducing iron into waterwheel construction, including at a mill in Belper (possibly for the second (1784) Belper North Mill), Derbyshire, stating that it was a ‘rough casting and imperfectly executed’ (Smiles, 1891 226).

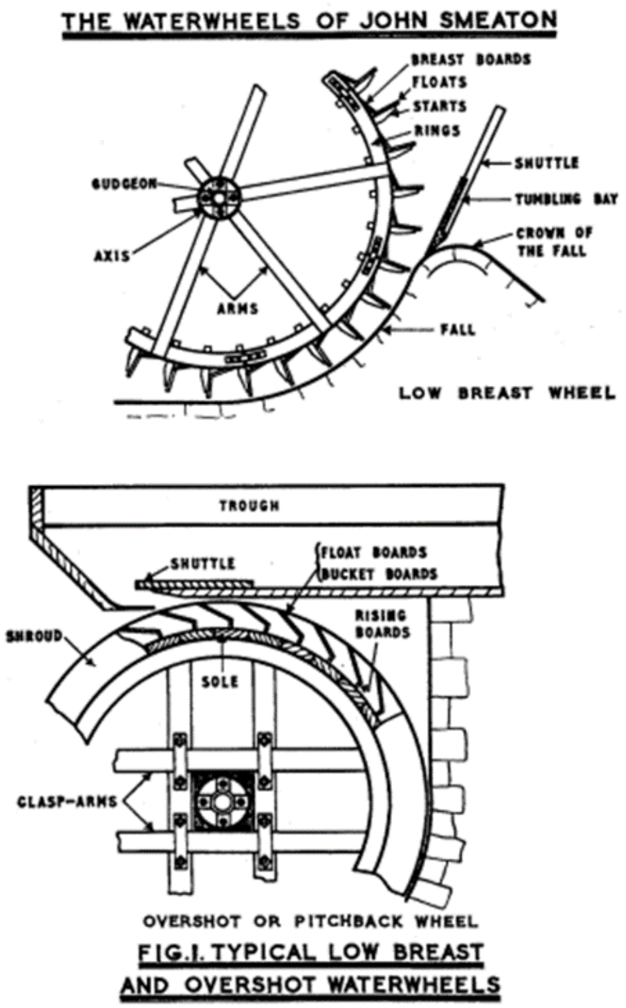


Figure 3.3 The components of the pre-1805 waterwheels of John Smeaton (Wilson, 1955 28)

3.2.2.1 The breast-shot wheel

As a result of a better theoretical understanding of waterpower, practical improvements made and the rising economic value of waterpower (Reynolds, 1984), in Britain, the breast-shot wheel was quickly adopted in the later 18th century by the industrial watermill owners, who needed additional and more controllable power. An improved understanding of the power being harnessed by using the weight of water (potential energy), rather than just using the flow (kinetic energy) of the river or stream to drive an undershot wheel, helped the adoption of the breast wheel (ibid). The most significant technical development, and often overlooked, is the close-fitting apron that improved efficiencies (from 30-35% to 60-70%) making the breast-shot as effective as the overshot wheel (which didn't accommodate variable water flows and levels) (ibid). The high first costs of the new breast-shot wheels and inherent higher operational costs and problems (narrow casings requiring covers, additional screening and maintenance), could have been a problem but the improved efficiencies, the rising cost of waterpower due to mill crowding and the scale of manufacturing growth during the late eighteenth century, made the breast wheel economically attractive in Britain (ibid). There are few iron industrial wheels in their original locations today (many scrapped during WW1 and WW2) but the close-fitting aprons, constructed with well-dressed stone giving a 6-12mm clearance (Reynolds, 1984 63) in the wheel pits, are still clearly visible at Belper (Figure 3.4).

The high breast-shot wheel was adopted as the primary power source by Richard Arkwright in his first mill in Cromford (1771) (Strange, 2008 9) and probably by the Strutts (Arkwright's partner) in their Belper (1776) and Milford (1781) mills. The dramatic growth in textile mills, across the north of England in particular, captured in the Colquhoun Census (from one Arkwright type mill in 1771 to 124 mills in England & Wales by 1787), included variations in shape and size but generally they adopted power systems similar to those of Arkwright and Strutt with a breast (or high breast) wheel, linked to the transmission system by an upright shaft and then gearing to long horizontal drive shafts (Chapman, 1981). Additional mill buildings and processes needed additional power, clearly demonstrated at sites such as William Strutt's Belper Mills in the heart of the 'Textile Area' where every new development was being tried out (Wilson, 1972).

Figure 3.4 Belper North Mill wheel pit, mill rebuilt 1804 (Photograph: Author, 2020)

The growth of the Belper Mills from the 1770s to 1830s provides clear evidence of the innovation and value of waterpower in this era. For the first two mills (the South [1776-1778] and North [1784-6]) there is little information about the waterwheels used (Hills, 1970), although it is likely they would have been wooden breast-shot waterwheels at that time, and 12 ft (3.7 m) in diameter (based on the first West Mill wheel diameter using the same weir). The 1795 estate plans for the Belper Mill complex (DRO D1564/S/3, 1796) show a 'divider' into the South Mill waterwheel inlet, suggesting two mill wheels, doubling the potential power from wooden wheels and transmission with limited powered capacity. Having two wheels would also still allow half of the mill to operate with reduced flow or in the event of technical issues. A typical Arkwright Mill would need a minimum of 2,000 spindles (20 hp, 15 kW) to be profitable (Chapman, 1981).

In the 1790s, the Strutts built their third and largest Belper mill, the West Mill, needing additional power. Using the materials and knowledge available at the time, William Strutt built two wooden waterwheels, mentioned by many engineers and authors who visited Belper around c.1800 as "extraordinary". In *The beauties of England and Wales Vol.3* Britton et al (1802) describe the principal mill [West Mill] as 200 ft long, 30 ft wide (61.0 m by 9.1 m) and six stories high and being powered by two waterwheels that:

> ‘are remarkable as well for their magnitude, as for their singularity of construction; one of them being upwards of forty feet (12.2 m) long, and eighteen feet (5.5 m) in diameter; and the other forty-eight feet (14.6) long, and twelve (3.7 m) feet in diameter’ (Britton, Brayley et al., 1802 530).

Timber could not be purchased to form axles using traditional methods, so William Strutt built a circular, hollow, cask-like structure to form the axle (Britton, Brayley et al., 1802, Gifford, 1994 12, Hills, 1970) (Figure 3.5). The wheels included other innovative features, including rim gearing and deliberately misaligned floatboards to provide a smoother power output, producing higher quality cotton thread (Glynn, 1853 91). Leaving space behind the floats for air to escape was also a new idea, developed later by Fairburn (Hills, 1970). Another interesting aspect of the wheel design is the different diameters of wheel, 18 ft (5.5m) and 12 ft (3.7 m). The first 12 ft (3.7 m) wheel was built whilst the original 6 ft 2” (1.9 m) Burton Weir was still in operation (DRO D3772/T19/10/7, 1808-10). In February 1795 a major flood caused damage along the river Derwent, including to the Belper Bridge (Davies, 1811 355). Within two years the bridge was rebuilt with an adjacent, and higher, circular weir with floodgates, allowing a greater head and wheel diameter, 18 ft (5.5m), for the second breast-shot wheel in the West Mill. Rather than the first, 12 ft (3.7 m), wheel being made redundant, it was raised and repurposed as a flood wheel (Goodrich, 1799 19). This suggests that the flood wheel may have been an accidental, but fortunate, innovation, as the Strutts continued to add flood wheels to all future developments on site, allowing them to harness waterpower in a wider range of river flows. A similar arrangement, using a smaller diameter wheel at times of water shortages and in times of flood, was added to Arkwright’s Bakewell Cotton Mill, when the water supplies were improved in the early 1800s (Wilson, 1972).

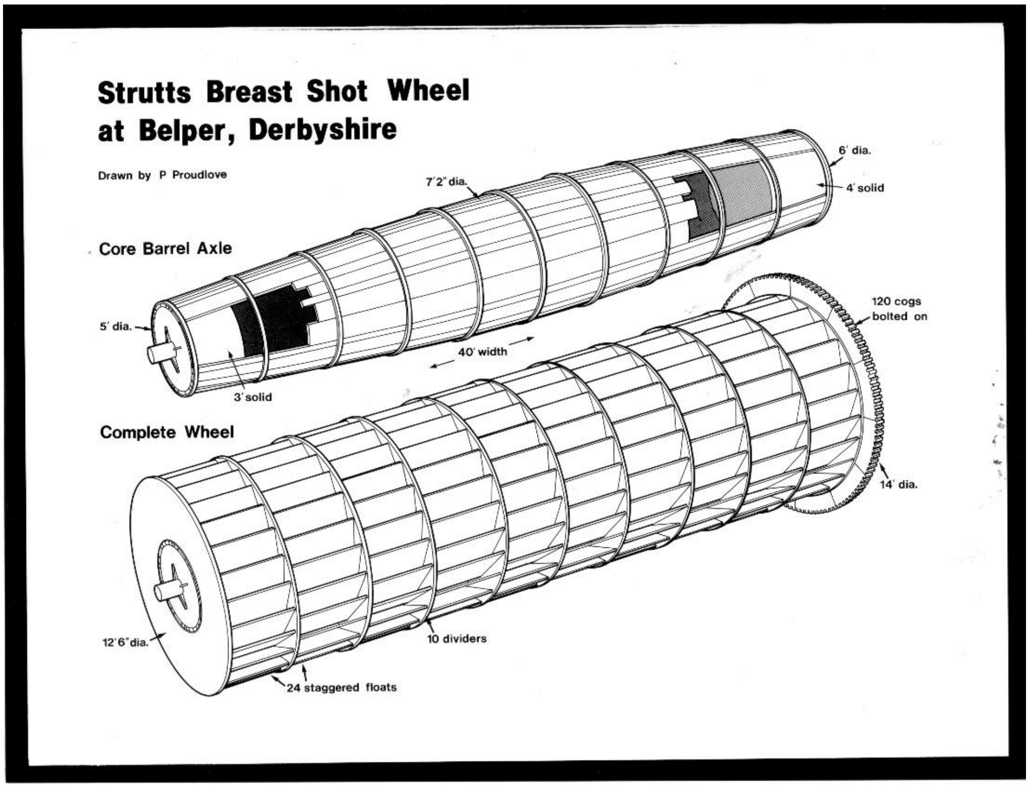


Figure 3.5 The 1790s wooden breast-shot water wheel powering the Belper West Mill, drawn by P Proudlove (Gifford, 1994 11).

3.2.2.2 Iron suspension wheel

A step change in waterpower arrived with the development of the iron suspension waterwheel, built by Thomas C Hewes (a Manchester machine builder and wheelwright) based on a William Strutt design (Reynolds, 1983). The first pair of wheels, both 21 ½ ft in diameter and 15 ft wide (6.6 m x 4.6 m) (Figure 3.6), were installed in the West Mill, Belper, between 1805 and 1811 (ibid), replacing one of the large wooden waterwheels described above. Previous references suggest that the iron suspension wheel was introduced ‘sometime before 1811’ (Hills, 1970 112) but the Belper Mills’ timeline (Section 2.3.5) suggests 1808 is a more accurate date, powering the newly added Reeling Mill (1808) (Johnson and Skempton, 1956). The new iron suspension wheel increased the capability to harness the power of water fivefold (Smith, 1969 6), potentially making the river the constraint, rather than the waterwheel design. Reynolds (1983) estimated the output for the first pair of Belper West Mill iron suspension wheels to be 2 x 80 hp (2 x 60 kW).

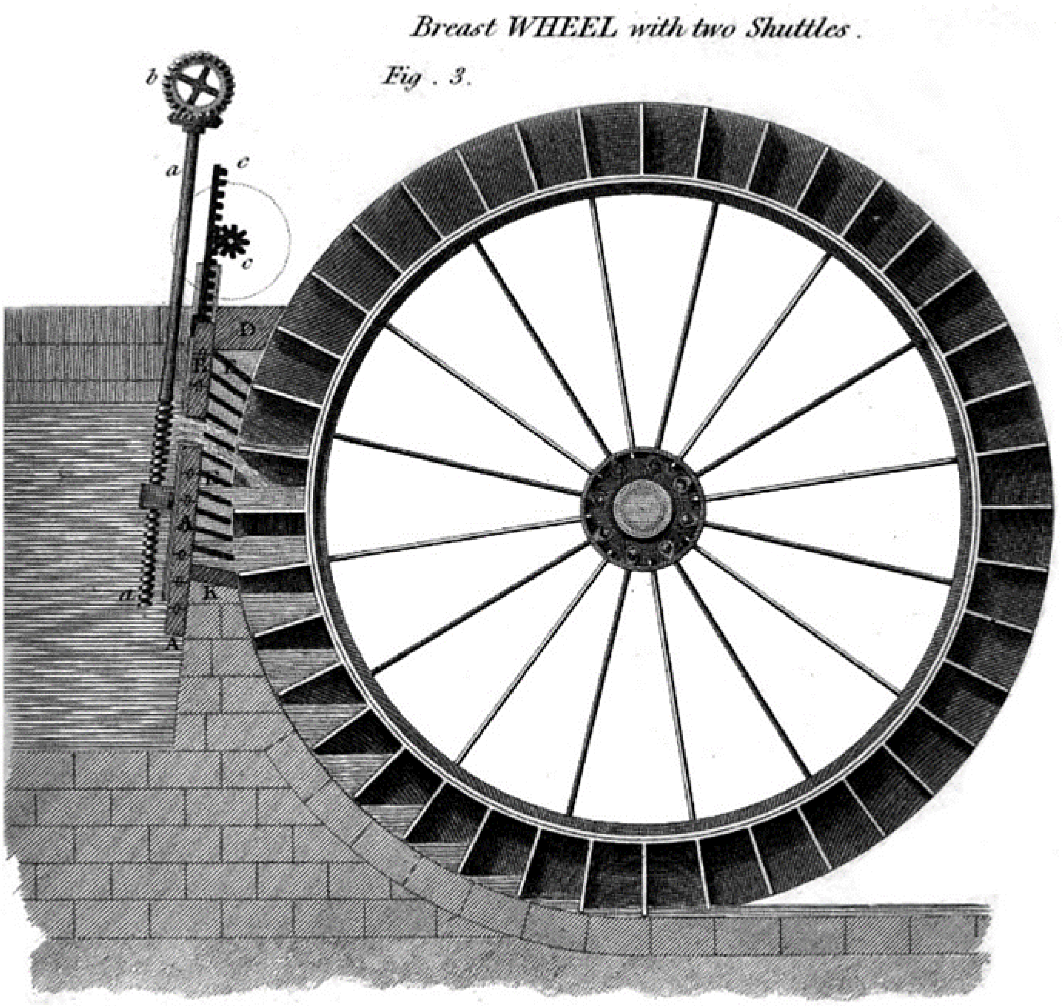


Figure 3.6 Breast-Wheel with two shuttles, Belper West Mill wheel cross-section, including the close-fitting stone apron (Cossons and Rees, 1972 Vol.5 366)

Whilst it is understood that T C Hewes built the first pair of wheels for W G & J Strutt, the Strutts went on to build new iron wheels for their Belper and Milford mills at their Milford foundry (Glover, 1829 Part II 101). The Strutts continued to be supported by Hewes's engineers in their installations (references from 1818 to 1828) (DRO D6948/A/3, 1818-60). By 1829, all of the wooden water wheels had been replaced by the larger, more efficient iron suspension wheels, with Glover (1829) noting that Messrs. Strutt cotton-mills in Belper were 'worked by eleven water wheels, principally composed of iron; six are used in the time of high water and five when the water is at the usual height' (ibid 101).

Whilst developments to the wheel, such as rod fixings and bucket design (e.g. adding ventilation), continued to be made by engineers such as William Fairbairn (1789-

1874), the iron suspension wheel remained the ‘most effective and perfect’ design (Fairbairn, 1864 Part 1 120) up to the development of the water turbine (Reynolds, 1983). Evidence of the use and continued development of the iron suspension wheel can be found at the larger industrial watermills throughout the DDC, often improved by local engineering businesses. The Strutts’ Belper mills’ wheels introduced improved buckets designed by the local Butterley Engineering Company (1887) (DRO D1564/S/140, 1887). At Richard Arkwright’s cotton mill in Bakewell, Hewes and Wren installed an iron suspension wheel (25 ft diameter and 18 ft wide (7.6 m x 5.5 m)) in 1827, producing 140 hp (105 kW) (Reynolds, 1983). A second smaller flood wheel (Wilson, 1972 6), built by the local Kirkland and Son of Mansfield, was added in 1852 (Strange, 2010) (Figure 3.7).

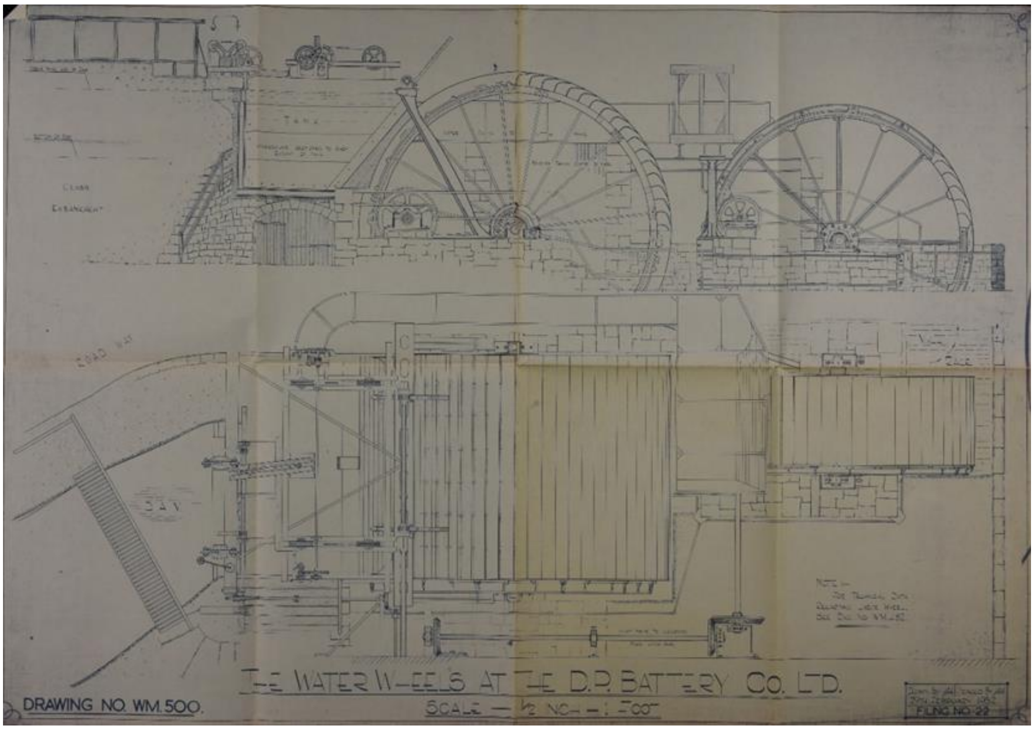


Figure 3.7 1952 DP Battery Co. plan, Bakewell 1827 and 1852 waterwheels (DRO D962/1, 1952)

The iron suspension wheels were adopted by other industries in the DDC, with a 20 ft (6 m) wide breast-shot wheel with approximately 80 hp (60 kW) capacity, being installed at High Tor Lead Mine in the early 1800s, to pump water out of the mine 200 ft (60 m) below river level (Willies, 2004). A more powerful wheel, 140 hp (105 kW), was installed in Lathkill Dale in 1836/7, which, at 52 ft (15.8 m) in diameter and 9 ft (2.7 m) wide, was one of the largest in the country at that time (ibid).

3.2.3 Water turbines

In Britain, during the 1800s, the steam-engine became established as a reliable prime mover (Section 3.3.1), and, with the abundance of cheap coal in Britain and a network of canals to move the coal, technological developments moved away from waterpower, to steam power. Elsewhere the new water turbine was developed in the early 19th century, mainly in France, the United States, Ireland, Germany and Switzerland (Wilson, 1957). As early as 1860 a Jonvall turbine was installed in America's original (1793) cotton mill, built by Samuel Slater, with a second Hercules turbine added in 1876 (Kulik, 1985 144). There is some evidence of early industrial water turbines use in the DDC, developed in-house, supplied directly, or via licences, from countries who continued to develop water turbines throughout the 19th century.

3.2.3.1 Two Dales

In 1826, the Daykene brothers, who had inherited the 900 spindle Sydnope Cotton Mill in Two Dales, built a substantial three storey flax mill adjacent to the old mill, installing three cascading waterwheels to power the extended mill site, one of two such known arrangements in England (Glover, 1829 Part II 354). The extended mill needed more power, but, rather than installing a steam engine, they recognised the potential for more waterpower from the Sydnope Brook supply higher up the valley. The problem was that a waterwheel couldn't harness the amount of power available from the upper reservoir, with a 96 ft (30 m) head, so they developed the Dakeyne Disc Engine, patented in 1830 (Nixon, 1969). It appears that this early development of a British water turbine was unsuccessful, as, despite a second Dakeyne engine being commissioned to pump water from a lead mine in Alport, Lathkill Dale, around 1831 (Wigfull, 2007), it took the Dakeyne brothers so long to produce a working engine that the mine owners selected an alternative, steam, engine (Kirkham, 1960).

3.2.3.2 Ambergate

The Alderwasley forge and works (Ambergate) were put up for auction in 1856, 'standing upon the River Derwent and worked by Five Powerful Water Wheels' (DRO D326/BT5, 1856). In 1872 Thewlis Johnson (nephew) and George Bedson (wire working engineer and innovator), from Richard Johnson & Nephew (RJ&N) Wireworks in Manchester, were looking for an additional manufacturing site and visited the forge, attracted by its location, with waterpower on tap from the fast-flowing Derwent, space for expansion and an existing, healthy, workforce (Seth-Smith, 1973, Wain, 2002). The site was redeveloped by RJ&N, 1874-6, and, following Thewlis and Bedson visiting a number of water turbine manufacturers, an order was placed for three turbines with Robert Macadam (Belfast) (Seth-Smith, 1973 70) (DRO D4572/2/1, 1900). The RJ&N Wireworks were formally opened on the 22 May 1876, with the main factory mechanically driven by power supplied through two 150 hp (112 kW) ‘Macadam patent’ water turbines (ibid). A visitor to the site a few years later described the iron being hammered under the helve, the rolling mill and the rotating disc cutters slitting mill all ‘driven by two turbines, probably the largest in England’ (Bulmer, 1895 607).

This would appear to be the first industrial site in the DDC to successfully introduce the water turbine, in preference to an iron suspension waterwheel, to mechanically drive its manufacturing processes. Once established in Derbyshire, Macadam advertised regularly in Derbyshire newspapers promoting the turbine’s ability to cope with varying flows of water between winter and summer, and provide ‘proportionate power’ without impact from floods or back water, (Figure 3.8).

INCREASED VALUE OF WATER-POWER.

MACADAM’S VARIABLE TURBINE.

THIS WHEEL (which is now largely in use in England, Scotland, and Ireland), is the only one yet invented which gives proportionate power from both large and small quantities of water. It can be made for using a large winter supply, and yet work with equal efficiency through all variations of quantity down to a fifth, or even less if required. It is easily couple to a steam engine, and in this way always assist it by whatever amount of power the water is capable of giving, and therefore saves so much fuel.

This Turbine is applicable to all heights of fall. It works immersed in the tail water, so that no part of the fall is lost, and the motion of the wheel is not affected by floods or back-water.

REFERENCES to places where it is at work will be given on application to

MACADAM BROTHERS & CO., BELFAST.

Figure 3.8 *The Derbyshire Advertiser*, 1881 30th December

3.2.3.3 Rowsley

Caudwell's Flour Mill at Rowsley, powered by the River Wye, was built on a site that had a long history of watermills, with records of a mill in 1339 and a corn mill and fulling mill in the 16th century (Gifford, 1999). Through the early 19th century the site had a sawmill and a corn mill, but in 1874 they were both demolished and Caudwell's Flour Mill was built in 1875, with 4 iron breast-shot wheels powering 8 pairs of stones (ibid). A new grinding technology, roller milling, was introduced into Britain in 1877, which Caudwell's Mill quickly adopted, installing 8 sets of roller mills, but the breast-shot wheels could not provide enough power so they 'upgraded' to a Trent water turbine in 1887 (Gifford, 1999, Walker, 2000). Figure 2.30 highlights the closure of many of the smaller 'traditional' wheel and stone corn mills, identified as 'disused' on the OS maps, following the 1881 upgrades to Caudwell's Mill.

3.2.4 Controlling the power

One of the most significant attributes of the Derwent Valley water powered industrialisation, and least understood, are the weirs that create the head (more potential energy) and divert the water to the wheel or turbine. The weirs can also create a mill pond or reservoir, helping to deliver a steady source of power during seasons when the natural flow of the river wouldn't provide the requisite supply of water, and collecting water overnight to be used the following day, effectively doubling the power of the watercourse (White, 1836 301). For all the knowledge we have about the patented manufacturing processes and the building of the fireproof mills, we have very little information about the design, build and operational use of the weirs, dams, sluice-gates, floodgates, leats and ponds, that also manage the water when not required by the watermills (Alexander and Edgeworth, 2018). Historic England consider the water control attributes, along with the mill buildings, as constituting a wider watermill landscape, which is greater than the sum of its parts (ibid).

Whilst many waterpower reference materials focus on the engineering design of the waterwheels and water turbines, the 18th and early 19th century visitors to the Belper mills recorded waterpower control innovation. This included the control of the water flowing into the breast-shot waterwheels, e.g. sliding hatch shuttles attached to governors, possibly used as early as 1784 (Chapman, 1971) (Figure 3.6). The ability to open sluice gates controlled by a governor, under the extra pressure caused by the wider wheels, was mentioned by Goodrich (1799) and was described in some detail by Farey Jnr in the *Rees Cyclopaedia* (Goodrich, 1799 19, Rees, Blake et al., 1819 Vol. 23 Mill-work np). The level of control and understanding of the power available to drive the spindles of the Belper South Mill, can be seen on (Figure 3.9), copied in 1887 from a plan on the South Mill wheel pit wall (DRO D1564/S/130, 1887). The drawing shows the power available, and therefore the number of spindles that could operate, for different dam levels, which fell during the working day.

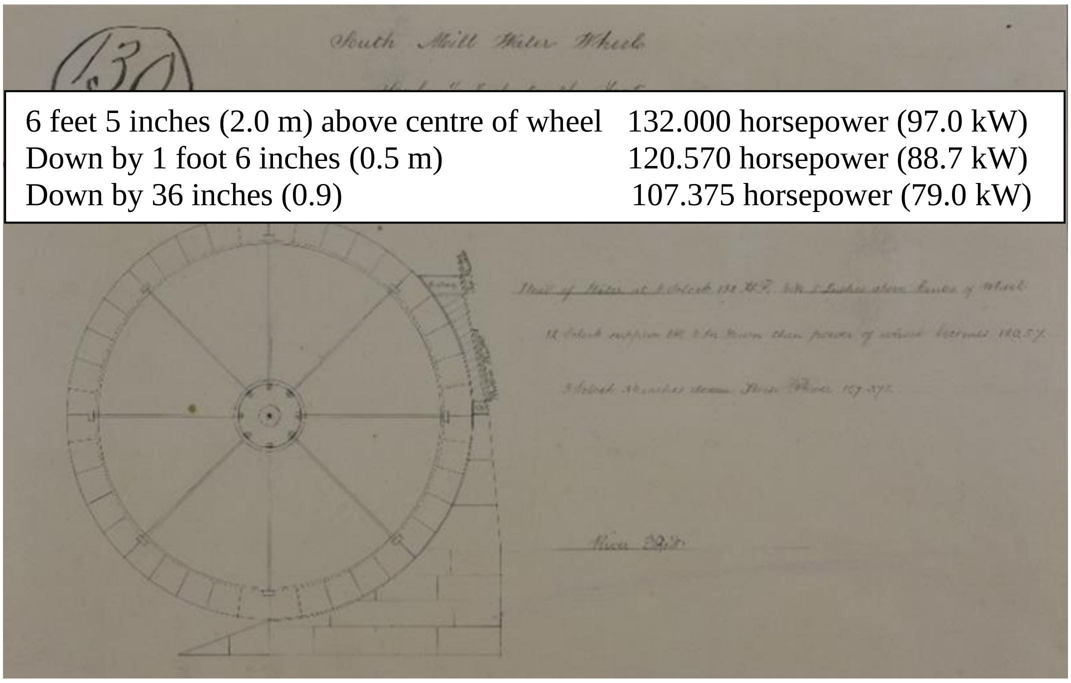


Figure 3.9 South Mill water wheel (DRO D1564/S/130, 1887)

3.2.4.1 River Derwent weirs

For centuries rivers primarily supported local agriculture and domestic water supplies, relying on natural cascades, falls and river meanders with primitive timber weirs and sluices to power the corn mills and trap fish (Watts, 2000 20). From 1600 to 1900 Petts argues rivers were managed to facilitate navigation and the growing demand for waterpower (Petts, 1990 203). During the age of mechanisation weirs were ‘improved’ to store larger volumes of water and create higher heads for the larger diameter waterwheels, and included additional water management structures, such as the floodgates, but we have little written evidence to confirm this.

A study of weirs on the River Derwent was carried out to gain a better understanding of the mill and non-mill (e.g. canal) weirs in the DDC. Figure 3.10 shows the remaining pre-1878 weirs in the River Derwent, noting that several historic industrial watermill weirs, such as St Mary’s weir, Derby, no longer exist. Apart from the natural Yorkshire Bridge waterfall, the Upper weir at Chatsworth built for landscaping reasons, and the Longbridge Weir built for the Derby Canal, the remaining pre-1878 weirs on the River Derwent all relate to watermills.

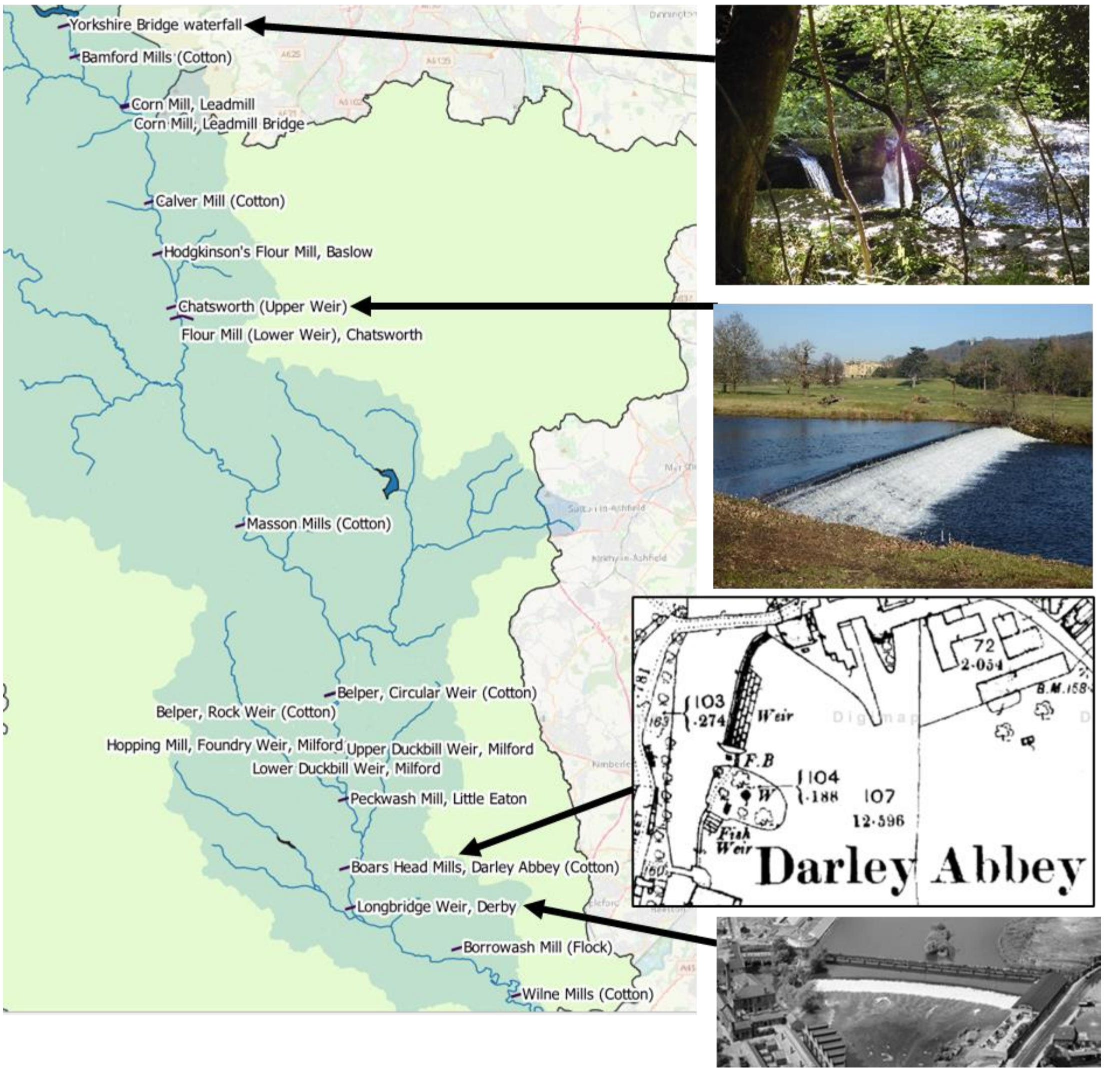


Figure 3.10 The River Derwent weirs (pre-1878), with the non-mill weirs/falls photographs and the Digimap 1880s OS showing the Darley Abbey weir.

The 1880s-1920s OS maps show sluices, floodgates and/or fish weirs adjacent to many of the Derwent weirs, such as Darley Abbey weir, above. Nicholson's millwright guide (1830) discusses Belper, where he describes the great semi-circular weir, built of substantial masonry, with a small weir under the bridge creating a pool to break the fall of the water over the weir and with three sluices drawn up in the event of floods (Nicholson, 1830 109).

Belper Mill daily reports (Watchmen Reports) recorded several aspects of the operations of the weir, sluices and floodgates which differ to those practised today (DRO D6948/R, 1821-85). River levels were largely maintained below the top of the weir, probably controlled by opening a sluice or floodgate. The mill never operated on a Sunday and at least once per month the sluices were raised (opened), lowering the river to facilitate maintenance. There is no mention in the Watchmen Reports of the impact of sluice opening at times of high water or Sundays on the river ecology, such as silt movement or fish passage.

To optimise the waterpower that could be harnessed mill owners 'improved' their weirs, sometimes temporarily, by raising the height and creating more storage. Raising the weir also raised the upstream waterway, potentially impacting on neighbouring watermills. A dispute between the Strutts (Belper cotton mills) and the Hurts (Alderwasley iron forge) continued for at least two generations. The associated legal papers (1818-1844) describe the development and use of industrial weirs, and how such disputes were resolved during this period (DRO D2535/M/4, 1818-44).

3.2.4.2 Hurt v Strutt: Raising the height of the Belper weir

The main 'upper' forge at Alderwasley was built by Frances Hurt in 1764, before the cotton mills arrived in the Derwent Valley, with a second 'lower' forge built in 1776, the same year the Strutts started building their first cotton mill in Belper, approximately 4.8 km downstream. At Belper, the original 1776-8 weir was 6 ft 2" (1.9 m) high and raised the river level as far upstream as the boundary of the Strutts' and Hurts' land (Figure 3.11) (DRO D2535/M/4/12, 1818 1). The later, 1796, Circular weir raised the river level a further 3 ft (0.9 m) and the Hurts claimed that this interfered with the tail race for their ‘lower’ forge waterwheel in Alderwasley. The Hurts’ iron forge was leased to the Molds from c.1811 who, by 1818, had three key complaints. When the circular weir was built, the Strutts had agreed to drop the river level to the Northside weir (same height as the 1776-8 weir) whenever it impacted on the Alderwasley works, but the Molds reported ‘they have declined to do it in recent times’ (DRO D2535/M/4/12, 1818 2). Since 1812 the Strutts had started building temporary weirs on top of the existing weir, using bricks and mortar, up to 18” (0.46 m) in the summer or at times of low water, effectively raising the river level by 1 ft (0.3 m) at the forge tail race (ibid 3). These temporary weirs were washed down when the rainy weather returned (ibid 3). The Molds (Hurts) wanted to increase the power available at the upper forge, by extending the tail race to the Hurts’ land boundary to increase the head, but the higher river levels (caused by the Strutts’ temporary weirs) would make this ineffective (ibid 2). In 1812 the Strutts rebuilt the original South Mill, using the new iron frame (fireproof) construction (Johnson and Skempton, 1956), accommodating heavier, more powerful machinery and new iron suspension wheels to generate additional power. It is highly likely that this triggered the Strutts to raise the height of the weir at low water periods, to power all of the mills across the site, from 1812.

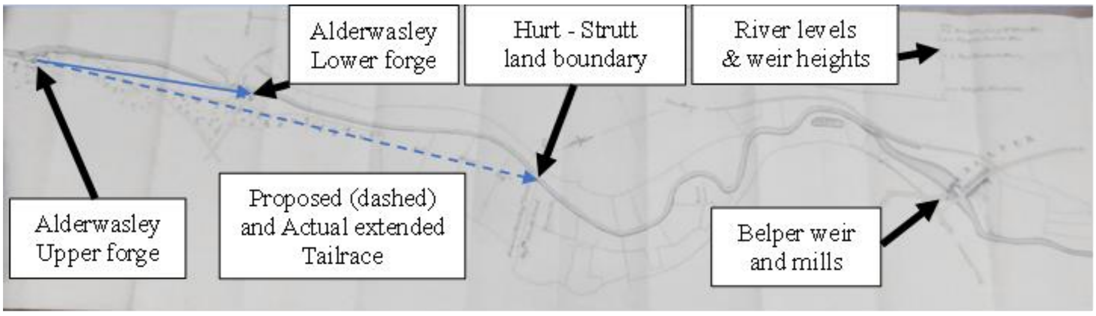


Figure 3.11 Court case plan showing the key locations, river levels and the increasing heights of the Belper weirs (DRO D2535/M/4/9, 1818).

One of the Strutts’ defence arguments was the claiming of water rights based on the 20-year rule, but the Hurts counterclaimed that the higher level of impoundment hadn’t taken place for 20 years (DRO D2535/M/4/12, 1818 3). The ongoing weir height disputes led to settlements and regular payments from the Strutts to the Hurts. It is likely that the extended tailrace constructed for the Alderwasley upper works, going as far as the original lower forge, was built following the 1818 court case (Figure 3.11). Evidence comes from a letter written in 1900 by the 74 year old William Henry Mold to the current site tenant which mentions ‘After 1810 Messrs Strutt wanted to raise the Belper weirs and paid a sum to cut the long sluice from your works’ (Judge, 1993 95).

3.2.4.3 Lathkill Dale weirs

One unusual set of weirs in the DDC (Figure 3.12) can be found on the Lathkill Dale rivers, whose character may be explained by an undated contract (DRO D504/B/L/386, c1840). The Alport Consolidated Mining Co. were concerned about the restricted flow of water from the Alport Corn Mill impacting on the trout fisheries, so they proposed to build and maintain a series of rubble weirs, at least 6” (0.15 m) higher than the riverbed (ibid) (Gregory, 2013 105). In addition to the weirs, they added sluice gates (Figure 3.12) to help remove the accumulation of sludges and reduce the risk of flooding (ibid). Similar sluices can be found adjacent to other weirs in the DDC, such as at Chatsworth House (Figure 3.13), although recent heritage impact assessments have failed to identify their original purpose (Architects, 2015, HLM, 2014).


Figure 3.12 Lathkill Dale weirs (left, BHS00644, date unknown) and sluice (Photograph: Author, 2020)

Figure 3.13 Chatsworth sluice and upper weir (Photographs: Author, 2020)

Understanding the original design and purpose of the wider waterway landscape may offer improvement opportunities for a variety of river stakeholders today, with the potential to improve the quality of the waterways, e.g. silt transfer and fish movement, as well as optimising waterpower generation, with the resources available.

3.3 Power: Supply and demand

Waterpower played a vital role in the initiation of the Industrial Revolution in Britain but there was a finite capacity, with most waterpower sites occupied and many industries outgrowing their waterpower resources (Sections 1.3.1.1), particularly during times of drought (Wilson, 1972 32), by the early 19th century. The demand for additional power led to the rapid evolution of the steam engine, initially used as a pump to drain mines, then to re-circulate the tail water of waterwheels and finally as a rotative engine to drive the line shafting of the mills (ibid).

3.3.1 Steam: Use in textile mills

The steam engine first developed by Newcomen in 1712, was a pumping engine and not able to provide the rotative power to provide an alternative to the waterwheel (Hills, 2008 39). Watt was patenting the separate, condenser system for the steam engine in the same year, 1769, as Arkwright patented the spinning frame (ibid 37). Whilst the innovative use of waterpower by the Derwent Valley mill owners is recognised, it is not common knowledge that Richard Arkwright was an early adopter of steam as an additional or alternative form of power. He was the first textile mill owner to increase the power available utilising steam in c.1780 by installing a reciprocating steam engine (locally manufactured) at his Haarlem Mill in Wirksworth, Derbyshire (Menuge, 1993). This was used to raise water from the tailrace to refill the mill pond, supporting the flow of the diminutive River Ecclesbourne (Tann, 1979). Similarly, Arkwright repeated this at his Shudehill Mill, Manchester in 1783 (Trinder, 2013) using water from the privately owned Shudehill Pits (Maw, Wyke et al., 2012).

An attempt to recycle water using another natural source of energy, wind, was trialled at a cotton mill, just 24 km outside of the DDC, at Sutton-in-Ashfield, when Samuel Unwin jnr. built a castellated gothic façade cotton mill (1770) (Figure 3.14) on the site of his father's horse-powered cotton mill. In 1771 a windmill was added to support its inadequate water supply but appears to have failed, as in 1789 a Newcomen steam engine was installed to pump water from the tail race back into the reservoir (Hills, 1970, Trinder, 2013). This could be one of the earliest attempts at pumped storage waterpower using renewable, wind, energy.

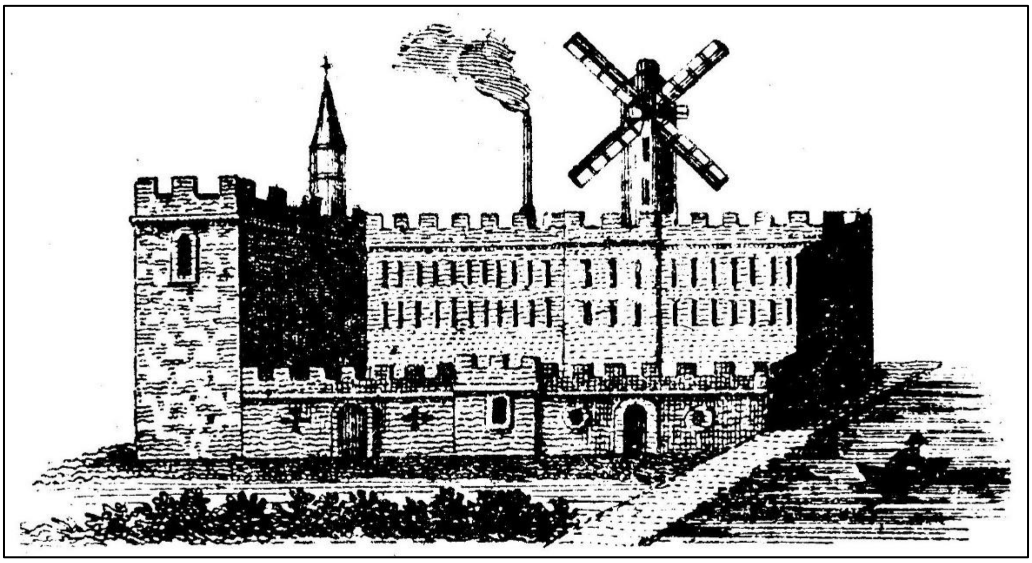


Figure 3.14 Samuel Unwin's Mill, Sutton-in-Ashfield, Notts. (Lindley, 1907)

The first successful use of steam to directly drive a textile mill was at Papplewick Mill, Nottinghamshire in 1785-6 (Menuge, 1993, Pierson, 1949), by the Robinsons, who were concerned about Lord Byron of Newstead Abbey controlling and possibly restricting the head waters of the River Leen (Hills, 2008) if payments for the water were not made (Walker, 2017 4). Despite the availability of rotative steam engines from 1786, and their wide use as they became more reliable by the 1790s, they were relatively small, no larger than 40 hp (30 kW) before 1800, the average Boulton and Watt engine being 18 hp (13.4 kW) (Smith, 1969). Investigations into the work of Hewes, a master millwright who worked in the DDC, shows that during the late 18th century the steam engine was rarely used if waterpower was available, due to its low power and expense (ibid 6). Following the improvements made to waterpower, with the Iron Suspension wheel, enabling individual wheels up to 200 hp (150 kW) by c.1810, it took until the 1840s for steam engines to be built with a 150 hp (112 kW) power output (ibid).

Factories Act returns (power – steam or water)

The growth of the factory system led to the state delivering regulation to deal with issues relating to factory labour, in particular child labour (age and hours of work). Several Acts from 1802 included some reforms but the Act of 1833 led to the most significant change, including the introduction of an inspectorate providing annual reports to the Home Office (Chambers, 1964). At the factories inquiry commission (1834), proprietors of manufacturers and mill owners, by region, were asked to respond to 79 questions about the nature of their work, workplace and the impact of the new Act on their business. One of the questions, repeated in later inquiries, has proved particularly useful in assessing the trend in waterpower versus steam usage:

> 'Q.4 – Describe the power employed, whether steam or water, or both; and if the latter, whether regular or irregular, and what are the degrees of irregularity and the extent of the power' (PA HC XIX.259, XX.1 361, 1834).

The 1834 report includes (D.1. 91 to 119) responses from 25 manufacturers from Derbyshire; 22 from Derby, one from Belper and Milford, one from Tansley and one from Wirksworth, a sample of manufacturers of the day. All three sites outside of Derby were water powered, 11 Derby sites were powered by steam, eight by hand and two by water, with one not responding. The responses from the water powered sites (Table 3.2) confirm the range of power harnessed across the Derwent's tributaries, the sensitivity to seasonal variation, particularly on the Ecclesbourne tributary, and the impacts of floods and droughts, although clearly some sites could recover from flood events more effectively than others.

Table 3.2 Responses to Q4, power sources, from the Derbyshire waterpower only sites, 1834.

Manufacturer	Industry	Power Source	Factory No.	Page No.
Walter Evans and Co., Derby	Cotton	Waterpower only	70	92
Approximately 100 hp [75 kW], supply of water irregular with stoppages up to a week due to floods and occasionally stopped for parts of every day for many weeks during dry seasons.				
J Strutt, Belper and Milford	Cotton	Waterpower only	73	96
Approximately 200 – 300 hp [149 - 224 kW], supply of water irregular, liable to be stopped by floods, sometimes for a day or more at once, and occasionally too short a supply of water.				
J Hackell, Tansley, Crich	Tapes	Waterpower only	74	98
No additional information				
W Taylor, Derby	Silk	Waterpower only	78	102
Approximately 3 hp [2.2 kW], supply of water very irregular				
Messrs Riley, Wirksworth	Tapes	Waterpower only	91	115
Irregular supply, in winter – over supply of one half; in summer, deficiency one third				

By 1835 steam was dominating textile manufacturing across the UK, with Baines (1835) *History of the Cotton Manufacture in Great Britain* calculating a 3:1 (30,853 hp:10,203 hp) ratio of steam to water horsepower in his grand summary. There were regional differences, with ratios of 20 hp [steam]:500 hp [water] at Cromford, Belper and Ashbourne (Baines, 1835 392-394), showing that waterpower continued to dominate in the DDC (Figure 3.16). Factory returns published throughout the 19th century, show the dramatic growth in overall power usage and the proportion of water versus steam through the period. Figure 3.15 shows waterpower's continued and steady growth (1832 = 7,609 kW, 1850 = 19,466 kW and 1861 = 21,851 kW) through the 19th century.

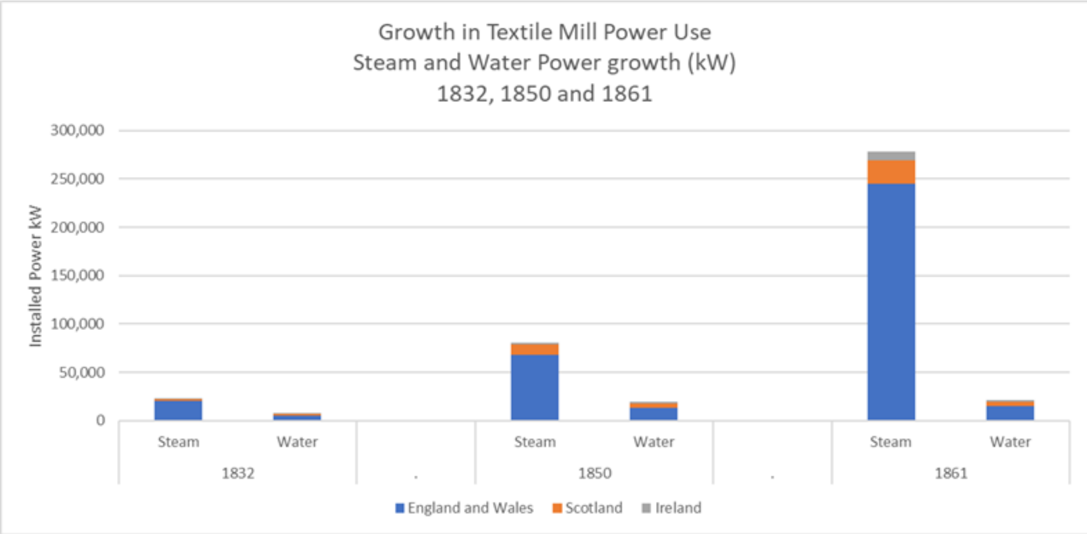


Figure 3.15 Waterpower versus steam in textile mills by country (kW)

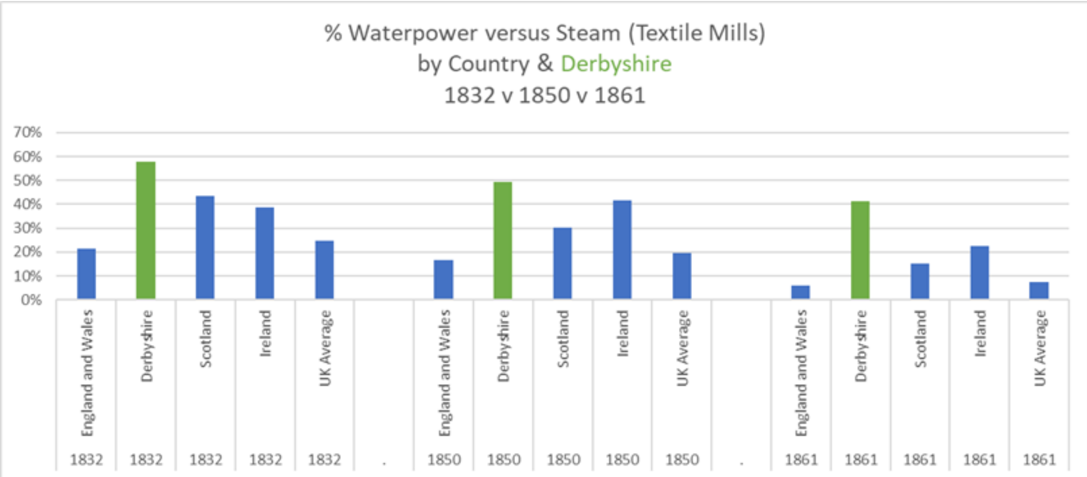


Figure 3.16 Waterpower versus steam in textile mills by region, including Derbyshire (%).

(Factory Returns data, 1832 (Hills, 2008 66) and 1850 and 1860 from the original House of Commons returns)

These findings challenge the narrative that steam caused a decline in the use of waterpower, which assumes that a site with a chimney no longer harnessed the power of the river (Jennings, 1970 17). Steam didn't replace waterpower, but it did enable the growth of industry and saw the movement of industries, better located to make use of coal resources and access to imports and exports, such as Lancashire (Phelps, Gregory et al., 2016). One constraint of waterpower is the location, having to be close to a suitable water supply. As the mills grew they required a larger workforce, which also could be a challenge in rural areas, so the locational flexibility of steam allowed the building of factories in cities, such as Manchester, with an available workforce (Cameron, 1955).

The identification of the 164 DDC watermills, using the 1880s OS map, Section 2.3.4, confirms that waterpower continued to be used throughout the 19th century, despite the availability of competitive steam. With the waterways saturated, the continued development of the waterwheel and the introduction of the more efficient water turbine increased the power harnessed. The larger industrial watermill sites that had harnessed all the waterpower available, added steam as a supplementary power source during the 19th century, in a hybrid arrangement.

3.4 Water: Supply and demand

3.4.1 The Derbyshire Derwent catchment waterways

Within the DDC there are a range of natural falls of the main river Derwent and its tributaries, offering varying waterpower opportunities. Shaw's 1965 dissertation *Waterpower in the Derwent Valley* captured profiles of the Derwent and some tributaries powering mills (Table 3.3). It should be noted that in the DVMWHS section of the Derwent this natural fall allowed weirs to be built to help create heads of around 4 m for the run-of-river schemes. In contrast, the DDC tributaries to the east of the Derwent, with much lower flows, had considerable falls available, for example the Sydnope Brook powered the Darley Dale flax mill using three overshot waterwheels (Glover, 1829 Part II 354) (Section 3.2.3.1).

Table 3.3 Waterway profiles in the Derbyshire Derwent valley (Shaw, 1965 6)**.**

River Derwent		
Yorkshire Bridge to Matlock Bath	2.0 m/km	North of DVMWHS
Matlock Bath to Derby	1.3 m/km	DVMWHS
Derby to Sawley junction	0.6 m/km	South of DVMWHS
Tributaries east of the Derwent		
Sydnope brook	42 m/km	
Hall brook	40 m/km	
Lea brook	32 m/km	

Most of the industrial watermill sites in the DDC utilised man-made weirs, but it is likely they took advantage of these natural features (e.g. falls, cascades, meanders and knickpoints) that would have been utilised for the ancient watermills. Several DDC weirs, such as the Masson Mills convex weir (Figure 3.17) and the Bakewell 'Lumford Mill' weirs, appear to be located close to the 'faults or dislocations of the strata' on the map of the great Derbyshire Denudation (limestone fault) drawn by J Farey Sr. (Farey, 1811 280). Many historic watermills have been located to utilise bedrock river knickpoints (Jonell, 2023) and a knickpoint in the River Derwent above Cromford, identified as a feature at the top of the Ambergate Terrace, could be the location of the Masson Weir (Swindell, 1963, Waters and Johnson, 1958 3). Figure 3.18 shows the natural fall on the Bentley Brook at Lumsdale, and how the fall was being harnessed in 1798 to power a variety of mills.

Figure 3.17 The unusually convex Masson Mills weir, possibly following a natural geological feature, a knickpoint. Photograph: Author, 2022

Figure 3.18 Lumsdale (Bentley brook) past Nattes, 1798 (© Royal Collection Enterprises Limited 2024, Royal Collection Trust)) and present (Photo, Author 2022).

In addition to natural waterfalls, cascades and man-made weirs, watermills created a head by utilising the natural meanders of the river, diverting water into a mill stream cut through the meander (Figure 3.19). At Milford, the upper Hopping Hill cut powered mills (iron forge converted to corn mill and fulling mill) on each side of the cut in the 17th century, before the Strutts purchased the site (Gifford, 1999 89). The lower cut in Milford likewise powered several industries before the Strutts bought the site to develop their cotton mill, bleach and dye works in 1781 (Nixon, 1969 268). An advert for the site before the 1781 auction, includes:

> ‘a Slitting and Rolling Mill, for Iron or Copper, with a Throw, and a large Building adjoining, used as a Paper or Tin Mill … The premises have lately had a considerable Sum of Money laid out upon them in Repairs; are extremely well situated for any Business or Manufactory where a constant Supply of Power of water is wanted, and may readily be converted into a Cotton Manufactory or otherwise’ (*Derby Mercury*, 1780 4).

Prior to the Evanses’ purchase of the Darley Abbey site (Figure 3.19), a meander of the Derwent had been harnessed to power a variety of mills, including corn (before 1827), fulling, flint, paper, leather and china mills (Lintott, 2007).

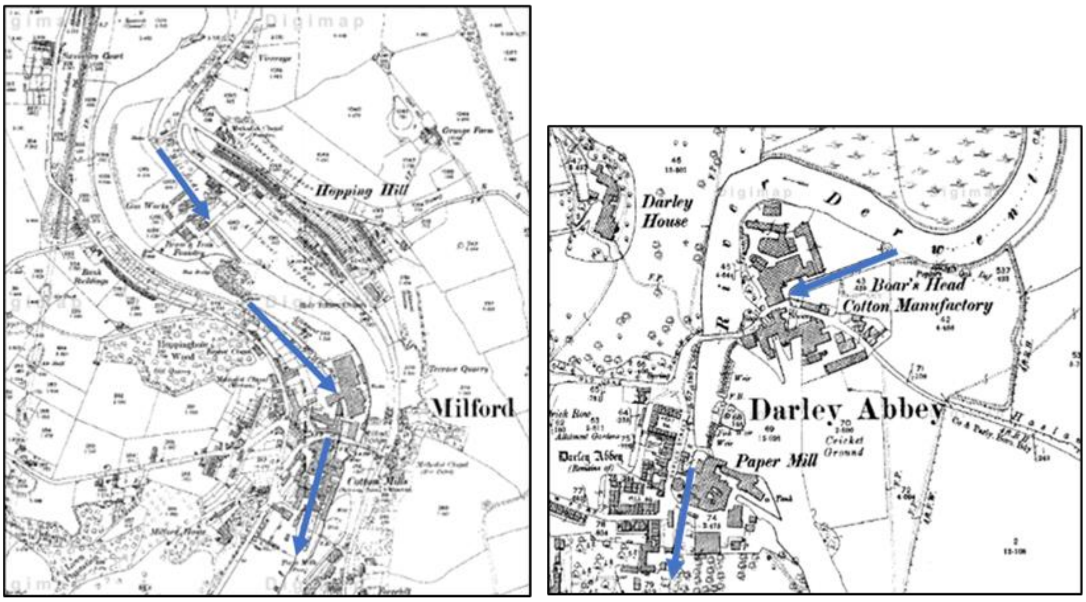


Figure 3.19 Historic and industrial watermills in the DDC utilising a river meander to create head, Milford (left), Darley Abbey (right) (Digimap OS 1900s)

3.4.1.1 Sough water

One unusual waterflow used to produce waterpower in the DDC, are the mine drainage waters, called ‘soughs’ in Derbyshire, that have flowed for hundreds of years. By the 17th century lead mines required deeper workings, approaching the water table and leading to the need for drainage channels, or soughs (Ford and Rieuwerts, 2000). Where possible natural cavities and gravity would be used to dewater the mines, possibly diverting water flows to adjacent, lower valleys (ibid). A 1794 report on the state and value of the fisheries on the rivers in the Manor of Duffield described the river Ecclesbourne as a small river, lessened by part of it being diverted by a mine sough which:

> ‘empties itself at Cromford when the discharge is estimated at 35 tons per minute and about 1/3rd is supposed to be Ecclesbourne water – by this and Bonsall Brook two of Arkwright’s great Cotton Works at Cromford are supplied’ (DRO D3772/E14/1/16, 1794 4).

The soughs may divert natural water flows, moving water volumes from valley to valley (Ford and Rieuwerts, 2000 33). These diversions may explain why some rivers, such as the Ecclesbourne, no longer appear to have the same waterpower potential, that historically supported 12 watermills (Section 2.3.1). Milne’s plan of Cromford Moor Mine shows three underground waterwheels driven by sough water for drainage and ventilation (Willies, 2004 38). Sough water also powered the bellows of the early lead smelting mills (Ford and Rieuwerts, 2000). Kirkham described the Ridgeway level sough water powering the waterwheel of the sawmill, previously powered by a stream, and later powering a turbine to produce electric lighting (Kirkham, 1957 73).

The Cromford sough water was described as more reliable and less extreme than river flows and unlikely to freeze, attracting Arkwright and his partners to the Cromford site (Davies, 1811 91, Fitton and Wadsworth, 1958, Swindell, 1965). Britton and Brayley described fifty tons of water per minute, partly fed by warm springs, working the Cromford Mills, never interrupted by the most intense frosts (Britton, Brayley et al., 1802 517). However, a new, deeper, sough, the Mere Brook was started in 1771 and, ultimately, grew to run under the Cromford Sough, with the

Cromford Sough waters eventually diverted into the Mere Brook, starving the Cromford Mills of one of their main sources of waterpower. This led to closure of the site in c.1839, after the Arkwrights elected not to install steam as an alternative power source and instead, continued to develop the adjacent Masson Mills, with the potential of harnessing more power from the River Derwent (Endfield and Van Lieshout, 2018, Petersdorff, 1844). Several soughs still flow today in the DDC (Oakman, 1979), affecting tributaries and potentially offering HEP potential.

3.4.2 Water rights conflicts

The conflict over sough water rights at Cromford (Section 1.3.2.1) is the subject of several studies (Chapman, 2013, Endfield and Van Lieshout, 2018, Getzler, 2004, Petersdorff, 1844). However, there have been other 'water' disputes in the DDC that improve our understanding of how the waterpower potential of the DDC was harnessed even when faced with the conflicting demands of multiple stakeholders.

3.4.2.1 Duchy of Lancaster (Crown) v Strutt – water and fishery rights

In the 1790s the Crown, via the Duchy of Lancaster, saw an opportunity to raise taxes for water usage and fishery rights from the new industrial mill owners, who had recently built cotton and other mills on Duchy lands in the DDC. The first John Crowder survey took place in 1792, to identify mills built on Duchy land, the amount of water used and the rents paid (DRO D3772/E14/1/16, 1794). Crowder's initial (28 December 1794) report reviewed the 'great numbers' of mills built in the last 20 years on the Derwent and its tributaries 'chiefly employed in the cotton manufactory, some few in the woollen, and some for other purposes' (ibid). The mill owners claimed that the soil on which they stood, and the weirs or dams affixed, were freehold and therefore, critically, claimed a right to take water out of the Derwent and its tributaries without paying rent. They also claimed that no rent was due as the water was being returned 'into its old course and that it has been the custom since immemorial so to do' (ibid). In an 1808 court case relating to flooding, the Strutts' defence included the statement that Jedediah Strutt built his first weir (1776) on the site of an ancient weir, called Burton Weir (DRO D3772/T19/10/7, 1808-10), potentially claiming the ancient rights of taking the water.

Crowder noted the significance of the mills on the Derwent, referencing the ‘immense factories of the Arkwrights, Strutts and Evanses’, with a specific reference to the Strutts who had invested approximately £20,000 in cotton, other mills and factories, solely dependent on the River Derwent (DRO D3772/E14/1/16, 1794). This level of investment may have influenced the Duchy of Lancaster’s decision not to tax the mill owners or charge for the water abstracted.

3.4.2.2 Cromford Canal – water abstraction

The importance and influence of the industrial watermills of the DDC are demonstrated again in the proceedings of the House of Lords inquiry, 1789, into the Cromford Canal private Act of Parliament. The millowners, including Jedediah Strutt and Sons, submitted petitions (PA HL/PO/10/3/281/41, 1789), concerned that there would be a shortage of water to power the mills, ‘of great value and importance that will be materially affected’, if the canal was constructed and allowed to abstract from the River Derwent (PA HL/PO/JO/10/3/281/18, 1789). In designing the canal and preparing the defence, William Jessop commissioned Benjamin Outram to understand the mills and reservoirs, record river discharges and investigate mill machinery on the Derwent and tributaries. The findings were presented to the enquiry (PA HL/PO/JO/10/3/280/86A, 1789) (Figure 3.20). The study, from Cromford Mill to the Trent confluence at Wilne, identified 53 water wheels in total and a fall in the river of 55 ft 3” (17 m) (Gifford, 1999).

The judge leading the enquiry challenged the mill owners, as he believed that water was being wasted due to the poor design of most of the water wheels in the valley, with only a few breast-filled wheels being used on the new cotton mills by 1789 (PA HL/PJ/JO/10/7/849, 1789 37). It was also noted that ten wheels are much better and some perhaps as good as can be made, but those mills never work on Sundays and therefore have water running waste most part of that day (cited in Schofield, 1981 250). The millowners requested that water could only be taken from the River Derwent, or any brooks, streams or watercourses that run into it, at certain times on Saturday or Sunday, and with abstraction restricted to an agreed portion of the actual flow available. The millowners’ proposal was successfully incorporated into the final bill and resulting Cromford Canal Act (1789) (DRO D29, 1789 9). The compromise reached was that topping up the Cromford Canal could only take place during non-milling times, Saturday evening to Monday morning. Traditionally, the mills had released waters on a Sunday, opening their sluice gates to facilitate navigation of the river through the locks from Derby to the Trent (Figure 3.20). The ‘sabbath’ Sunday closure seemed to be very widely observed, even at times of drought, with only smaller, seasonal, rural mills potentially operating (Figure 3.20).

The approved scheme included an aqueduct channel being built from Sir Richard Arkwright’s Masson Mill weir to supply the Cromford Canal. To transfer the water the Masson weir would need to be raised 16 ft (4.9 m) (Schofield, 1981), which would have also raised the waterpower capacity at Masson Mills. The proprietors of the canal reviewed the scheme once it became law and decided the more cost-effective water supply to be a channel from the Cromford Mill site, utilising the Cromford Sough waters and Bonsall Brook (Schofield, 1985). Despite the original petitioning, once the Cromford Canal was operational, George Benson Strutt, in 1801, proposed a railway to connect to the canal to supply the mills and coal for the town of Belper (Charlton, Holden et al., 2023 23).

List of Mill and Works - on the River Derwent from the Tail of Cromford Millsto the Place where it falls into the Front near Sawley

Place	Freehold	Wheels	Head of Water	Value of Buildings only Machinery - included	Return per Annum	Work People employed	Consist of
No1 Alderwash Mills	Mr Hurts	5 or 6	about 15'6" high				Iron Slitting forge Mill - Rolling Lead Mill
2 Belper	Mr Strutts	3 large	6 feet	£26,247	36,400 including the return at New Mills	800	Cotton Mills 2 large
3 Hopping Mill	**Duke of Devonshire and Mr Strutt**	**3 ------**	**6 feet**	**1,000**	**1000 -------**		**A Corn Mill with 2 wheels & a Leather Mill or fulling with One Mill**
4 Mackeney and New Mills	**Mr Strutt**	**9 ------**	**8 feet**	**11,000**		**Ditto**	**In hand two large Cotton Mills & a forge or Iron Mill a Slitting Mill**
5 Darley Mills	Mr Evans	7	5' 8"	13,000	20,000	450	A Corn Mill let, a Cotton Mill, a Red Lead Mill, a Paper Mill and a Fulling Mill - part of an Estate of £500 p annum
6 Derby Mills or St Michaels	Corportaion of Derby both Mills	6	4	11,000	22,151	290 sometimes 400 in full Watchtime	Large Silk Mill cost £29,000 valued at £6,000, a Corn Mill a Flint Mill a Water Engine supplying 1000 tenants Inhabitants of Derby besides common Locks for the Poor each Tenant about 20 p annum.
7 Derby or Holme Mill	Mr Evans	8	4' 1"	7,000	7,800	3 Mills	A Corn Mill, Slitting Mill, a Copper Mill * 2 for Flattening Sheet Copper
8 Borrowash Mills	Earl of Harrington	5	8	5,000	4,000 thereabouts		A Corn Mill, a Slitting Mill, a Tinplate Manufactory part of an estate adjoining of £5,000 p annum. Mr Mather Lesee not included
9 Wiln Mills	Ditto	7	8	10,000	4,940	132	A Cotton Mill, Corn Mill, a Fulling Mill a Slitting Mill part of the above estate, Mr Thacker Lesee at a small rent of 100 a year and has a considerable Interest as Tenants besides - Salmon caught here to the Extent of £500 a year
		48		84,247	97,092	1800	

A state of the Navigation on the River Derwent extendiong from the Town of Derby downwards to its junction with the Trent near Sawley and by that means with the principal parts of Hull, Boston and Lynn on the East Sea and Liverpool and Bristol on the West Sea with all the intermediate Counties & Manufacturing Towns lying between - made about 1720

Gates and Locks

No1 Below Holme Mills	One Pair of Pen Gates to pen the water up to Derby	Make 4 feet head to float the Craft uto the Town
2 at Borrowash Mills	A lock in the middle of the weir	Forms an 8 feet head
3 at Wiln Mills	A lock --------	Forms an 8 feet head

They navigate on Sundays by means of Water lett off at the Mills - All the Corn Mills, The Flint Mills and Derby Water Engine, work on Sundays in short water Season

* Copper Mill on Lease to the Company Sir Herbert Mackworth a partner

Parliamentary Archives: HL/PO/JO/10/3/281/20

Figure 3.20 List of mills and works (1789) referenced in the Cromford Canal debate (PA HL/PO/JO/10/3/280/86a, 1789).

3.5 Waterways: Environmental impacts

Waterpower has been described as unreliable and unpredictable, compared to steam power, mainly due to the variable nature of the power source, the river (Reynolds, 2006 161). River flows have always varied and the extreme weather events, drought and flood, impacted on the industrial watermill owners (Table 3.2). Extreme weather events and rainfall patterns, are the most obvious impacts of climate change today in the UK, including in the DDC (Howard, Coulthard et al., 2017, Watts, 2015). The Belper Mills Watchmen's Reports (DRO D6948/R, 1833-78) repeatedly mention the impact of drought and flood and the measures taken to reduce their impact, which today may offer lessons in resilience and adaption.

3.5.1 Drought

The Strutts' Watchmen's Reports of 1833-36 include references to water shortages to the Belper Mills, with August 1833 seeing repeated references to extending the Mill working hours to make up for time lost due to being 'very short of water' (DRO D6948/R/3/1, 1833-36 66). This includes days when, overnight, the mill pond has refilled (water up to weir level) but clearly does not have the flow to power all of the mills, all day. The fact that the Belper Mills were occasionally affected by drought was also mentioned when W G & J Strutts completed their factory return in 1834 (Table 3.2). Similarly, the Cromford Canal Act noted that corn mills, flint mills and the Derby water pump would operate on a Sunday during the 'short water season' (Figure 3.20). Drought is referenced as a key driver for the mill owners investing in early steam power on existing water powered sites (Section 3.3.1).

3.5.2 Flooding

Watermill owners accommodated the impacts of flooding, both on their mill activities and on adjacent land. Historically, floodgates were common features in mill weir design, with several mentions in Izaac Walton's '*The Compleat Angler*'(1653), of salmon forcing themselves through floodgates ((Walton and Cotton, 2010 82) and eels hiding under the planks of the floodgates during the day (ibid 109) in Derbyshire rivers. Early leases for landowners in the DDC, allowing mills to be built on their land, included floodgates within the lease conditions. G. Wentworth (Lord of the Manor of Highedge [Heage]) granted a licence for a mill with weir and floodgates to be built and maintained by the River Amber in 1753 (DRO D2535M/3/3, 1753).

The Strutts made a considerable investment in a new ‘circular’ weir, floodgates and river modifications in 1796-7, after a major flood in February 1795 (Barrass, 1994, Britton, Brayley et al., 1802 531, Davies, 1811). Following the coldest month ever recorded in central England (Endfield, 2021), a sudden thaw caused a flood leading to damage along the Derwent Valley, destroying Belper and Whatstandwell bridges (Farey, 1811 488), and across the country, with over 50 bridges destroyed (Marriott, 1886). The introduction of the flood wheel (Section 3.2.2.1), and the eventual installation of six flood wheels by the Strutts, at great expense across the Belper Mills complex, was evidence of the value of power in the early 19th century (Smith, 1969). Smith describes the wheels as ‘occasionally used’ but the investment, and watchmen’s records, suggests flooding was a frequent event to be managed by the watermill owners (ibid 6). The investment in flood management infrastructure and development of adaptable waterpower systems by the Strutts, appear to be a direct response to the catastrophic 1795 flooding event.

In August 1833 the Belper Mills watchmen’s report recorded an extra ½ hour was added to work hours at the end of August, due time lost to a flood (following a drought) on a Saturday morning (DRO D6948/R/3/1, 1833-36 81). Hours lost due to flooding and how the time was recovered was recorded for each event, such as the 15 January 1836 when 5 hours were lost due to flood or 17 March when 4 hours were lost due to high water, but the time recovered by adding one hour to the following work days (DRO D6948/R/3/2, 1836-42). The watchmen’s records were referenced in an 1886 study on flooding, with a note that the event was classed as a flood when the backwater stopped the flood wheel (Marriott, 1886 281, DRO D3772/T19/10/7, 1808-10 24). One extreme mitigation of the impact of an expected flood, records that on 26 January 1842 two courses of bricks were taken off of the weir in expectation of a high flood (DRO D6948/R/3/2, 1836-42). There was an ongoing dispute with the Hurts, upstream at Ambergate (Section 3.2.4.2), which may explain why these bricks (that may have only recently been added) were removed.

3.5.2.1 Flooding: Ward v Strutt, ‘Trial about water’

In 1809 the Wards, who had recently purchased farmland adjacent to the Derwent and upstream of the Belper Mills and weir complex, claimed damages against the Strutts following a ‘general’ flood event in 1807. The legal papers (DRO D3772/T19/10/7, 1808-10) give an insight into the frequency and degree of flooding during that period, the impact of the floods and how landowners and mill owners managed this natural phenomenon. In particular, the Strutts’ defence documents include details of the changes they had made to reduce flood impacts for the wider community in previous years, and the engineering design of their 1796-7 Belper Mills’ flood management systems, which are still in place today and used whenever the River Derwent rises above flood risk levels.

Following the flooding of lands and farms upstream of the original Belper Mill weir in 1789, during what they described as a common (regular) flood, the Strutts paid compensation to farmers, landowners and tenants (DRO D3772/T19/10/7, 1808-10 9). As a result the Strutts made some flood resilience improvements on the adjacent farmland, with two creeks ‘stopped’ and a 1 ½ mile (2.4 km) land drain built to help drain an area of ‘boggy’ farmland (ibid). William Jessop corroborated the Strutts’ account of the weir and flood management, called as an expert witness (ibid).

The 1796-7 rebuilt and relocated weir included many features to reduce the impact of flooding. The river approaching the weir was widened in several locations (see the purple sections on Figure 3.21) and the new ‘circular’ weir was effectively five times wider than the original 1776 weir (70 ft to 350 ft, 21 m to 107 m) (DRO D3772/T19/10/7, 1808-10 10; DRO D1564/7, c1810). The new weir arrangement included the ‘northside’ weir, behind a set of floodgates, built to the same height as the original Burton weir. The legal papers reference three levels of flooding; a ‘trifling’ rise of water that would flood low lying lands, ‘common’ (nine out of ten) floods impacting on mill activities, and the one in every seven year ‘general’ floods (ibid). An additional arch under the bridge (not currently in use) was added by the Strutts for excess water in the worst ‘general’ floods (ibid 10).

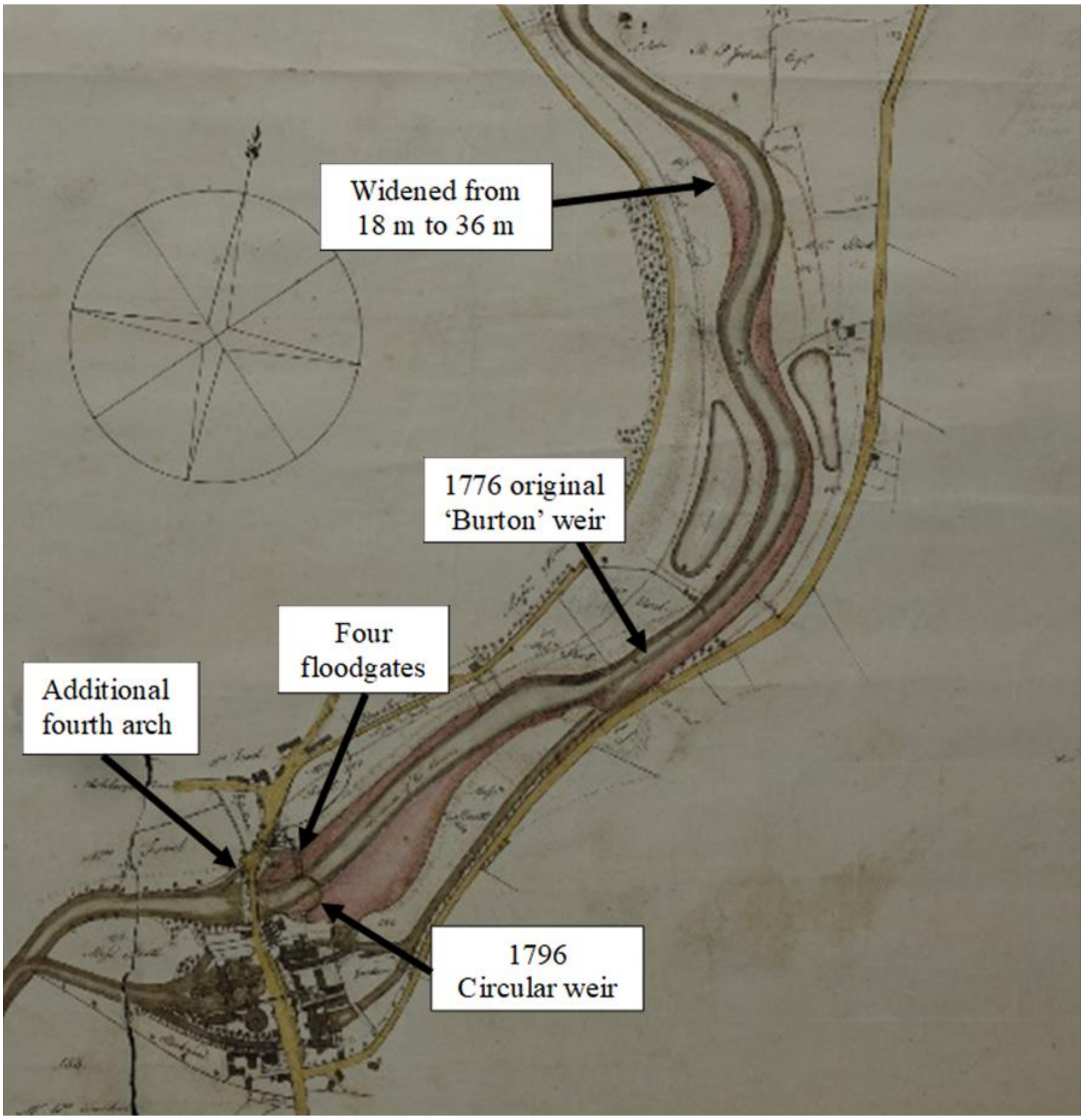


Figure 3.21 Modification to the River Derwent at Belper (DRO D1564/7, c1810).

3.5.3 Fisheries in the Derbyshire Derwent catchment

Mill weirs have a long association with the fisheries of a river (Section 1.3.3), with sites such as Borrowash, milling in the 13th century, including rights to fish caught at their weir as early as 1572 (Johnson, 1996). There is not a clear account of the historic fisheries of the Trent catchment, including the Derbyshire Derwent catchment (DDC). However one aspect that seems undisputed is the suitability of the upper Derwent (including waters belonging to the dukes of Rutland and Devonshire) for trout and grayling (possibly introduced to the Derwent by monks (Adam, 1843

173)). There have been differing opinions over the challenges that migrating fish have faced in the Trent catchment historically, including poaching, ‘legal’ fish weirs, the sport of angling, land drainage projects, river barriers (watermill, transport and river management weirs) and pollution (Easton, 1979).

There are few pre-industrial revolution records, but there is evidence that a rich fishery in the Trent was farmed for the family larder, with Fiskerton, a village near Nottingham, deriving its name from the old English “Fiscera-tun”, farm of the fisherman (ibid). A commission in 1442, set up to enquire into the alleged over-netting of salmon in Nottinghamshire and Derbyshire, confirms the high volume and value of salmon fisheries in the Trent catchment at that time (ibid). The early 16th century records of the Corporation of Nottingham, include the first reference of ‘fishing’ as a rod and line sport taking place in the Trent (ibid). Charles Cotton in *The Compleat Angler* (1676) described the Trent as ‘doubtless one of the finest rivers in the world, and the most abounding with excellent salmon, and all sorts of delicate fish’ (Walton and Cotton, 2010 160). He describes the Derwent, upstream of its confluence with the Wye at Rowsley, as abounding with trout and grayling, with salmon downstream of Rowsley (ibid). The first comprehensive record of the Trent fisheries, in *The History of Nottingham* by Deering (1751), mentions fish coming from the sea as high as Nottingham, including sturgeon, shad, salmon and flounders (Easton, 1979).

3.5.3.1 Salmon in the Derbyshire Derwent catchment

Historical evidence of changes in salmon numbers, in particular, in the River Trent catchment, have been collated below to help to identify when migration numbers have changed and the potential cause(s) impacting on the fisheries, and in particular salmon, an important consideration in hydroelectric power consenting today.

One source of information relating to salmon in the River Derwent are the leases associated with the Borrowash Mills site, just 7 km upstream of the Derwent – Trent confluence (Johnson, 1996). The site has harnessed waterpower for centuries, with the earliest records, from 1276, reporting the problem of the weir built between two natural islands hindering navigation (Brown, 2011, Johnson, 1996). Leases reference the weir including a fish trap (ibid), impacting on the fisheries upstream in the Derwent.

The significance of the Borrowash fishery, and the fact that salmon would migrate to Borrowash, is highlighted in a 1687 lease for the site, where the tenant has the fishing rights (including the fish caught in the gates), ‘except for salmon’, which the landlord John Stanhope of Elvaston reserved for himself (ibid 18). Plans for a lock to support navigation past the Borrowash weirs were challenged by Stanhope, who was concerned that the salmon may go through the lock, so grating would be required (ibid). The 1722 corn mill lease includes the following information:

> ‘a Lock or penn for water is now erected and made and also liberty to take Salmons and Eels at the said Corne Mills and likewise at the Fulling Mill adjoining by such Salmon Gates or Leapes and in such manner as the occupyers of the said Salmon Fishery have formerly done’ (cited in Johnson, 1996 21).

Transfers of leases and sales of mills at the site after 1722 don’t mention fishing rights, but the 1861 lease to the Towle family did include the fish-gates near the north-western corner of the Great Strine, the island in the River Derwent, the access bridge (Figure 3.22) and a requirement for the lessees to co-operate in the prosecution of poachers (ibid).

Figure 3.22 Location of the Borrowash ‘Fish Gates’ adjacent to the weir, Photograph: Author, 2022

Further upstream on the Derwent, Jedediah Strutt contacted Paul Jodrell (1780-1) to ask if he was leasing Hopping Hill weir, including the fish-gates, when investigating Hopping Mill Meadow near Milford, for expansion of his operations (DRO D3772/T2/3/7, 1780). The site of ancient watermills at Hopping Hill appears to have used a ‘natural weir’ (Figure 3.23). The ownership and rights were complicated, with the Duke of Devonshire owning the corn Mill on one side and, by paying 2/3rds of the cost of weir maintenance, holding the rights of 2/3rds of the water from the stream to power his mill (DRO D3772/T2/3/5,9, 1780).

The land being purchased for expansion of Strutt’s textile mill business incorporated the weir’s fish-gates (DRO D3772/T2/3/1,2,4,14, 1780-81). A few years later, in 1788, Jedediah Strutt raised concerns over Walter Mather’s misuse of the fish gates at the New Mills [Milford] weirs, downstream of the Hopping Hill weir. An agreement was reached that Mather would pay Strutt £10 10s per annum and half of the fish captured at the New Mills and Hopping Weir fish-gates (DRO D3772/T8/8/33, 1788). Figure 3.20 includes the comment about Wilne Mills (closest to the Trent), ‘Salmon caught here to the Extent of £500 a year’ (PA HL/PO/JO/10/3/280/86a, 1789). Clearly there was a value in the salmon in the late 1780s, but fish movement was being restricted, and the mill owners intended to catch fish using the existing fish gates.

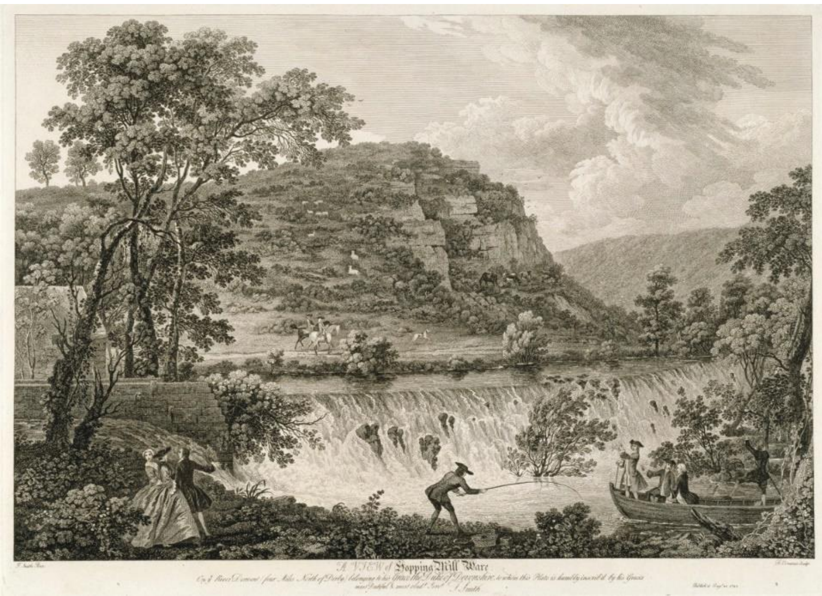


Figure 3.23 Thomas Smith (c.1744) ‘A View of Hopping Mill Ware’ (© Royal Academy of Arts, London; photographer: Prudence Cuming Associates Limited)

John Crowder's 1794 report for the Duchy of Lancaster (Section 3.4.2.1), investigating the value of the fisheries of the Rivers Derwent and Ecclesbourne within the former Forest of Duffield, and the Wye within the Hundred of High Peake (DRO D3772/E14/1/16, 1794), included a summary of fishery ownerships (Figure 3.24) (ibid).

His Majesty
W Archer (late Eyre, paying Crown rent)
Mr Shuttleworth (Lord of the Manor of Upper Padley)
Duke of Devonshire (Lord of several manors)
Mr Maynard (Lord of Nether Padley)
Duke of Rutland (Lord of several manors)
Mr Eyre (Lord of Calver)
Lady Bradford formerly Simpson (Lady of Stoke)
Mr Arkwright and others
R P Jodrell Esq. (Lord of the Manor)
Mr Nightingale and others
Frances Hurt Esq. and others (Lord of several manors)
Earl Thanet and others
His Majesty **[section Belper to Breadsall approx. 10 km]**
Sir H Harper (Lord of Breadsall)
Mr Mundy of Allestree
Derby Corporation
Earl of Harrington (Derwent falls into the Trent fishery)

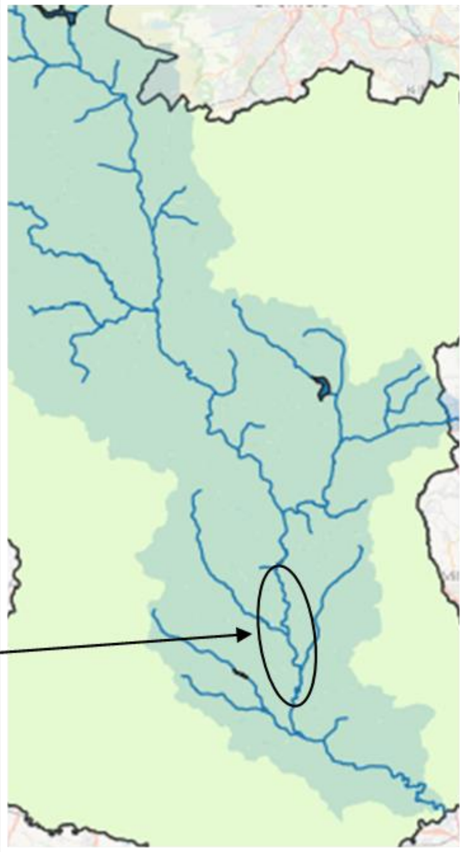


Figure 3.24 Fishery owners on the Derwent, north to south (DRO D3772/E14/1/16, 1794).

Significant parts of the Derwent fisheries were owned or leased by the mill owners who were responsible for the weirs in the river. Crowder comments that 'the rights of the fisheries are very little attended to because in many places they are of little value and owners of lands, miners and others, fish without control'. In addition 'the rivers are much poached so that a fishery is not worth preserving either for profit or pleasure' (ibid). Crowder struggled to value the Duffield (mid-Derwent) fishery for the Duchy of Lancaster as, despite Derby being so ‘far from a supply of sea fish’, the best fishery in the Derwent, Lord Harrington's Borrowash Mills near the Trent confluence, was let for no more than £6.10 per year, Crowder was therefore at a loss how to value the fishery within the royalty of Duffield (ibid). He did confirm that ‘some salmon do get past Derby but they will be caught at the Mill belonging to Messrs. Strutt, where a Frame or Heck is constructed for the purpose [likely to be the Hopping Mill or New Mills weirs at Milford], that has anciently been the practise’ (ibid).

A number of contemporary guides and directories of Derbyshire mention salmon ascending the Derwent in the early 19th century. Farey described fish-related works at Belper:

> ‘Messrs. Strutts, in their very capital Weirs and Flood-gates at Belper’s Bridge have constructed a very complete *pass* for the *Salmon* in going up the Derwent to spawn, which prevents the necessity of their leaping the Weir, and a *trap* for taking them as they come down again, after spawning; and the same at their works at Milford’ (Farey, 1817 Vol. III 205).

These weirs were constructed in the 1790s and the passes were operational during Farey’s visit but no other references to the passes, their design, details of construction or operation have been discovered in the Strutt archives. We only have the physical weirs and ancillary assets in place today, to try to understand how they worked.

Adam’s guide to the *Fishing Streams of Derbyshire* (1861) references trout and grayling as the main angling interest on the Derwent and its tributaries. Sections of the river, such as Cromford to Hotstandwell [Whatstandwell], contained many ‘finny tribes’, including trout, grayling, pike, barbel, chub, roach, dace, perch and gudgeon, (Adam, 1861 84) but there is no mention of salmon.

3.5.3.2 Royal Inquiry into Salmon Fisheries of England and Wales 1860

Commissioners from the Royal Inquiry into the Salmon Fisheries of England and Wales visited Burton on Trent on the 17 December 1860, to take statements from witnesses regarding the salmon fisheries in the Trent catchment (*The Derby Mercury*, 1860 26 December). At a time of growing populations outstripping meat-producing capacity (MacLeod, 1968), the inquiry report included key economic findings; the price of fish had greatly increased; the rents for fisheries had diminished; and the decline of persons and boats employed in the fisheries (PA 2768 2768-1 vi, 1861). The inquiry interviews with Trent catchment anglers and fishery owners, summarised below, give further information about the timing of the decline in salmon numbers, including the possible causes.

The only witness questioned about the Derwent directly was Joseph Peach, angler, of Derby on the 17 December 1860. When asked about the character of the River Derwent as a salmon river his response was:

> 'The river Derwent is a most beautiful tributary to the Trent, and it contained a great number of salmon in years gone by; but since the town of Derby has increased, deep sewers have been made, and inland weirs for commercial purposes, and now it is a very great rarity to see a salmon' (PA 2768 2768-1, 1861 525),

This statement focussed on the Wilne weir (Figure 3.25) as the first barrier that would prevent salmon going up the Derwent, (apart from during floods), with the salmon trap in the weir only catching one or two salmon in 1859 (ibid).

Evidence regarding the Trent catchment, which included a reference to the Derwent, was from Ashworth who had surveyed the whole catchment summarising salmon movement:

> 'Salmon pass over six [Trent] weirs and get up to Burton; they also pass over four or five mill weirs in floods up the river Dove as far as the weir at Rocester, which is impassable. Salmon are prevented passing up the Derwent by locks below Derby … The Derwent is navigable to Derby; and salmon are prevented passing up the tributaries by mill weirs beyond

a certain distance … But we know that salmon only migrate during floods' (ibid 526).

Ashworth identifies the weirs of the Derwent as precluding salmon passage. However, he notes that if salmon were to pass Derby during the November or December floods the river habitat upstream is as good as the Dove. He further describes the Wye at Buxton being as good for spawning as rivers in Ireland. In fact the largest potential spawning ground in the Trent catchment is the River Derwent and its tributaries (ibid).

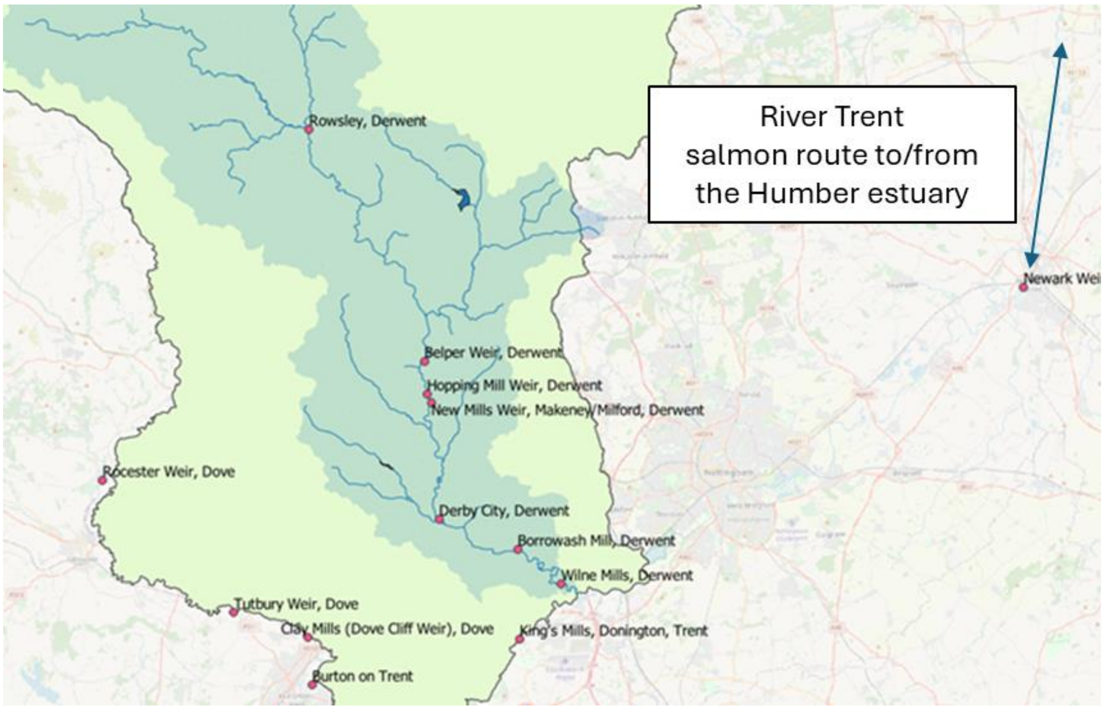


Figure 3.25 Weirs identified in the 1860-1 Royal Salmon Fisheries inquiry (PA 2768 2768-1, 1861 519-526).

In the inquiry, Sir Oswald Moseley, who lived by the neighbouring River Dove, claimed that 50 or 60 years ago [1810-1800] there were great quantities of the 'last brood' of salmon but the numbers now were 'greatly diminished' (ibid 519). In the 1860s the Dove was viewed as a river of little importance, with no close season or conservator. Thomas Clarke, labourer, was familiar with the Dove fisheries for 70 years and whereas he could capture 'cart loads' of salmon in 1821 he had seen a gradual decline, with only three or four fish in the last five years [1855-60] (ibid 522).

The only witness to offer salmon catch numbers in the 20 years prior to the inquiry for the Trent catchment, was T Bradley, gamekeeper to the Marquis of Hastings. The weir, belonging to King's Mill at Donnington Park on the Trent after the Derwent confluence (Figure 3.25), included two fishing traps 'six rows in one of the gates and four in the other' (ibid 524). He recorded total catches of 845 between 1840-50 and approximately 355 between 1850-60, noting very few being caught in the last few years [1857-60] (Table 3.4) (ibid 524) (*The Derby Mercury*, 1860 26 December).

Table 3.4 T Bradley, gamekeeper annual salmon catches (PA 2768 2768-1 524)

Salmon taken at the Leaps' King's Mills, near Castle Donnington, on the river Trent :—

	No.		No.
1840	44	1851	47
1841	42	1852	28
1842	55	1853	82
1843	143	1854	1
1844, account of number missing.		1855	7
		1856	39
1845	100	1857	30
1846	66	1858	16
1847	151	1859	8
1848	150	1860	54
1849	51		
1850	43		1157

From 1840 to 1850 = 845 salmon taken.
From 1850 to 1860 = 355 salmon taken.

Messrs J and W Sorseby occupied a fishery on the Trent, between the Derwent confluence and the Donnington weir, and declared a similar decline in salmon catches to the inquiry. They had captured 300 salmon between 1839 and 1849 and only 93 between 1850 and 1861 (PA 2768 2768-1, 1861 525). Soresby also leased the salmon gates at Wilne mill on the Derwent and, having taken 33 fish between 1846 and 1853, only five fish were caught between 1854 and 1860 (ibid).

The inquiry evidence suggests a serious decline in salmon numbers from the 1840s-50s in the Derwent and wider Trent catchments. The inquiry, and other contemporary accounts, also record the good health of the northern section of the Derwent and its tributaries in maintaining other fish populations. The Derwent northern division anglers were keen to protect their valuable trout-fishery from the possible, protected, salmon parr nuisance as a result of the new Salmon Act (*The Field*, 1864). Their proposal was to use the Strutts' mill [weir] at Belper as a limit to the salmon's movements, leaving sufficient length of suitable waterways for spawning (ibid). In setting up the new Trent Fisheries Association, the Duke of Devonshire declined the offer of the presidency, as he felt others had more interest in salmon-fisheries (Trent Fishery Association, 1864), suggesting that the Chatsworth estates were not seeing many, if any, salmon at that time.

Watermill and weir owners on the Derwent continued to take an interest in the fisheries through the 19th century. Following the inquiry and resultant *Salmon Fishery Act* (1861), local and national newspapers did report on efforts to improve fisheries on the Derwent by Messrs Strutt (4th generation cotton mill owners) and the Duke of Devonshire (Chatsworth), working with the fishery inspectors (*Nottinghamshire Guardian*, 1863, *The Field*, 1863). Quantities of salmon were still entering the Trent as late as the 1880s, with the total catches recorded in 1884, 1885 and 1887 (2,700, 3,050 and 3,120) averaging 10 lb to 12 lb (Wentworth Day, 1957). By the 1890s there were only occasional sightings of salmon in the upper Derwent.

3.5.3.3 Fish Passage

An important element of the water powered mill is the weir or dam that creates the head, stores the water and diverts the flow to the waterwheel or turbine. Weirs in strategic locations (tributary confluences) were often dual purposed, both powering the mill and capturing fish (Wilding, 1997). Discussing the challenges faced by salmon returning from sea to the rivers, in 1676, Walton noted the salmon 'will force themselves through the floodgates, or over weirs' to get to the fresh rivers (Walton and Cotton, 2010 82).

That some salmon were passing up the River Derwent up to the 1840s, decades after the industrial weirs of the Derwent Valley were built, suggests that the mill owners (often the fishery owners, Figure 3.24) were able to facilitate some fish passage, possibly using their floodgates or sluices as well as at times of flooding. Giving evidence relating to the Dove in the Trent catchment in the Royal Fisheries Inquiry in 1860-1, Mr Chawner (Lord Vernon's former agent) discussed fish traps being removed and sluices being opened at particular times of the day to 'give the fish every opportunity of running up the river to spawn' (PA 2768 2768-1, 1861 521). Mr Hay, Lord Vernon's agent, also mentioned weekly close time, with the opening of sluices to allow fish to pass after 6 o'clock on a Saturday night [after the mills were shut down until Monday am] so that upper proprietors might get a few fish (ibid 522). Thomas Webb, owner of Tutbury Mill and weir on the River Dove, stated that his mill didn't operate on the Sabbath [Sundays] and would be happy for water to pass the weir on that day (*The Derby Mercury*, 1860), supporting a weekly close time. The inquiry report summarises the conditions around the country, the key challenges and includes historical impacts on the fisheries and legislation, including reference to a fisheries statute of 1710 mandating:

> 'all owners and occupiers of corn, fulling, paper, and other mills, to keep constantly open one scuttle or small hatch of one foot square in the waste hatch or watercourse in the direct stream wherein no water-wheel standeth, sufficient for the salmon to pass and repass freely up and down the said rivers from Nov. 11th to May 31st …' (ibid xiii).

The report's recommendations also mention the negative impact on millers if they were required to observe a 'Saturday slap' (or weekly close time), or to leave an opening, often described as the 'Queen's share' (ibid xxxiv). The *Salmon Fishery Act* (1863) required sluices allowing water for milling power to be closed on Sundays and at all times when not required for milling purposes, to allow flow through the fish pass or free gap (Willis Bund, 1873 163). Free gaps are not defined in the Acts but seem to refer to gates being opened, which would also facilitate flood management and maintenance (ibid 171).

The inquiry report recommendations acknowledged that mill and navigation weirs:

> 'although at present offer serious obstacles to the passage of the fish in the rivers, ought neither to be removed nor interfered with in any way that would make them less serviceable for the purposes for which they were constructed' (PA 2768 2768-1 xxxii, 1861).

In Ireland, the source of much best practise guidance and home of the lead commissioner F Ffennel, the fisheries authorities had the power to enforce the construction of fish ladders on weirs but they could not interfere with the action of the mills or diminish the waterpower (ibid). Irish experience suggested that there should be no incompatibility in maintaining the full efficiency of the mill weirs whilst facilitating fish passage for salmon (ibid). To deliver the improvements, methods of raising funds to pay for fish passes, again drawing on Irish experience, were proposed. The first was the fishery owners paying rates and the second was a licence duty to be applied to any method of catching salmon, e.g. nets, fishing weirs and rods (ibid xxvi). The declining state of the fisheries limited the potential financial income and alternative sources of income would be required for the initial, significant, investment in fish ladders required. As the use of state grants had already been ruled out in the setting up of the commission, it instead proposed a loan system (on the credit of the rates and licence-duties) to improve the fisheries (ibid xxvi).

Several examples of prioritising fish passage without impacting on milling power existed in the legislation. These included the conservators having the power to require ‘gratings’ at inlets to mill races (at specific times of the year and subject to secretary of state approval), although mill races could be widened, at the cost of the board, to ‘compensate for the diminution of the flow of water caused by the erection of any grating’ (Willis Bund, 1873 175). Another clause gave the Board of Conservators the power to install a fish pass in any weir or in the adjoining bank, subject to a number of steps being taken, including Home Office approval. These regulations attempted to ensure ‘no injury is to be done by such fish pass to milling power …’ (ibid 159).

During Derwent and Ecclesbourne fishing rights discussions (1823), the attorney general of the Duchy of Lancaster offered the opinion that any watermills (including weirs) that have worked for more than 20 years without any acknowledgement ‘cannot now be disturbed’ (DRO D3772/E14/1/14, 1823). However any weir built with less than 20 years of ‘acknowledgement of right’, causing obstruction to His Majesty’s right of fishery, and not agreed in the form of rent, may be removed (ibid). Similarly the 1861 Act treated weirs constructed before 6th August 1861 differently, with requirements, including fish passage to be incorporated into any weirs built post the new Act (Willis Bund, 1873 146).

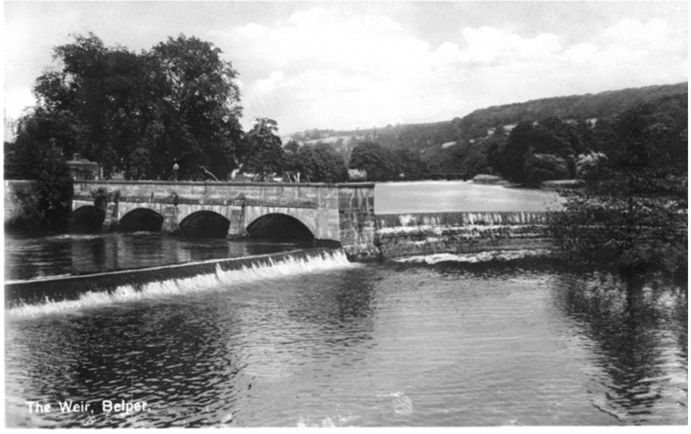
There were many angling associations and committees in the Trent catchment but, following the *Salmon Fisheries Act* (1861), an attempt was made to create one association with local committees, to view the 'whole length of the water; one scheme from one end to the other' (Trent Fishery Association, 1864 5). The main priority for the Trent Fisheries Association, at their meeting on the 7th July 1864, was to encourage the installation of fish ladders and passes at the key obstructions, including Tutbury Weir (ladder already installed), Dove Cliff Weir (dual purpose fishing weir and mill dam), Newark Weir (suggesting ladder in addition to current opening of the sluice on Saturday/Sunday weekly close time), Donnington Weir, Colwich Weir, Beeston Weir (including a sluice) and Thrumpton Weir. The inspector also suggested that sluices could be 'open half-an-hour or so twice a week' to allow fry to go down, with no material injury to the miller (Trent Fishery Association, 1864 7). Adding salmon ladders to existing weirs risked water and power loss to the mills which led to innovative solutions, with patented Water Economisers being advertised in Derbyshire newspapers (Figure 3.26).

TO FISHERY PROPRIETORS AND WEIR OWNERS. – By the use of WATER ECONOMISER a flow of water down fish-ladders, to form a LEADING CURRENT, can be obtained when migratory fish "run," and any waste of water avoided when rivers are low.
Headingley, Leeds J.H.HORSFALL (Patentee).

Figure 3.26 Water Economiser advert (*The Derbyshire Advertiser*, 1864 1).

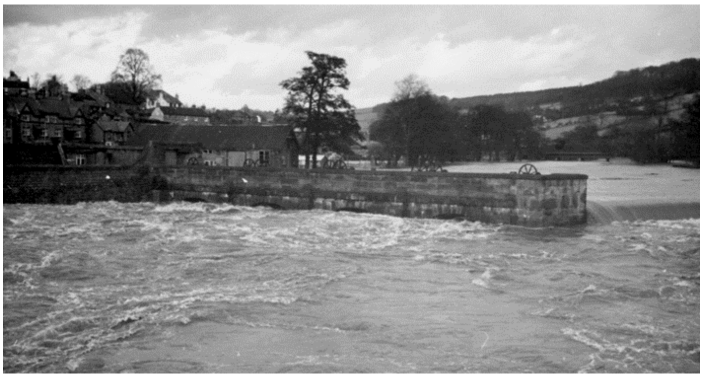
Whilst not visible today, and despite the significant decline in salmon by the 1850s, it would appear that Home Office approved fish passes were introduced into the DDC in the 1860s. At the 1864 Milford Garden Society annual exhibition G H Strutt presented a copy of the Milford salmon-ladder model sent to the Home Office, that proved to be a great attraction (*Derbyshire Advertiser and Journal*, 1864 12 August). In 1866 the Darley Dale fishing club placed a large number of young salmon into the river, below Rowsley, hoping the salmon would use the Strutts' newly installed salmon-ladder at Milford. Plans had been submitted to the Home Office for a ladder at Belper and they were also hoping similar ladders would be added at Borrowash and Wilne weirs (*Derbyshire Advertiser and Journal*, 1866 15 February).

One other mode of fish passage, frequently referenced, are high floods facilitating fish passage by weirs. In the fisheries act consultation, Sir Oswald Moseley stated that the numbers of salmon arriving at Tutbury on the River Dove, depended on the numbers that arrive in the annual high floods, allowing them to pass over Mr Thorneywell's weir (PA 2768 2768-1, 1861 519). Floodgates, although not specially mentioned, offered an additional route for fish passage during floods, with the reduced relative weir height also allowing easier passage over a weir (Figure 3.27).



Belper: Weir in normal conditions Photograph: BHS01242 (date unknown)

Belper: Circular weir in flood Photograph: BHS04442 (1965)



Belper: Flood-gates open in flood Photograph: BHSb1271 (1965)

Figure 3.27 Belper Weir, normal conditions compared to the 1965 flood.

The 1860 Salmon Fisheries inquiry and 1861 Act suggest ‘free gaps’, in the form of sluices and floodgates, were the primary method of facilitating fish passage. Fish ladders on industrial weirs were introduced as additional methods in the mid-19th century, following the major decline in salmon numbers. The opening of gates during non-milling time, especially ‘sabbatical’ Sundays and during specific fish migration periods (including night-time), was critical to fish passage in the 18th and early 19th centuries. Today, reusing the remaining historic sluices and floodgates at appropriate times, may provide an opportunity to improve fish passage without a major impact on waterpower generation or heritage assets.

3.5.4 Pollution

The Salmon Fisheries Inquiry (1860) focussed on the barriers and weirs on English waterways as the main problem inhibiting fish migration, but, when collecting evidence on the Trent catchment fisheries, Mr J Peach (angler), talking about the Derwent, focussed on the impact of ‘nuisances’ from the growing city of Derby as the main cause (PA 2768 2768-1, 1861 525-6). He identified sewage from the town, including the ‘waterclosets’ and the very large railway station, as the main issues. Peach felt that the local dye works, with dyes produced from logwood, caused less harm than the sewage (ibid). When questioned about specific industries, Peach confirmed that there was a paper mill at Darley Abbey and it ‘most decidedly’ caused harm to fish and similarly the tin works may have discharged lime as the river ‘is all sorts of colours in the summer’ (ibid). Peach’s final observation was that they:

> ‘have been at vast trouble and expense in trying to make the Derwent a trout river, but the dyeworks and sewage from the town [Derby], and the paper works above have destroyed not only the trout, but even the coarser fish. Sometimes the water stinks so that you could not bear to be near it’ (ibid).

The observation regarding industrial pollution was challenged by T Ashworth, who had surveyed the whole Trent catchment and believed the only nuisance [pollution] in the river was the sewage you would expect for a town the size of Derby (ibid). However, a further witness, T Bradley, a Trent fishery man also mentioned the loss of the Derwent as a source of salmon, due to refuse from the gas, dye, and bleaching works (ibid).

A newspaper report of the inquiry in Burton confirmed that the commissioners disagreed with Peach and believed the diminution of salmon was 'rather owing to the weirs than the sewerage' (The Derby Mercury, 1860 2). One of the commissioners, W J Ffennel was chief of the Irish Fishery Board and came from Ireland 'with a considerable reputation in Salmon fishery matters' (*The Standard*, 1871 28 December). His main priority was to open up the rivers for fish passage (*The Field*, 1863 626). Nonetheless, the impact of pollution was known, with one MP, a Welsh manufacturer who relied on using the river for his factory's waste, protesting against 'damaging the great commercial interests of the country for the sake of preserving a few fish' (cited in MacLeod, 1968 119). The inquiry concluded that the main challenges were the obstructions (natural and artificial), fixed engines (fish traps), close time (no capture during breeding season), illegal modes of fishing, absence of management and conservation, pollution (mines, manufacturers, gasworks etc.) and confusion over the regional laws (PA 2768 2768-1 ix-xxi, 1861).

The fact that only one witness was called to discuss the fisheries in the Derwent, compared to the six for the River Dove, suggests that the Derwent was already not viewed as a salmon river, possibly due to the industrial weirs and the presence of industrial and domestic pollution.

Following the introduction of the Salmon Fisheries Act a follow-up meeting took place in Derby in 1863 to identify the measures needed to restore and preserve salmon on Derbyshire rivers. W J Ffennell, now one of her Majesty's inspectors of fisheries, again refuted the idea of pollution being a problem in Derbyshire, quoting examples of weir removals that had already started making improvements in other waterways. One of the local conservators, Capt. Macdonald, had heard that simply cleaning the waters in Devonshire had done much good, but Ffennel disagreed (The Field, 1863 626).

The River Derwent was one of many waterways that had industries involved in textiles, chemicals and mining (e.g. lead), which have historically polluted waterways with heavy metals and other contaminants (Howard, Coulthard et al., 2017). Specifically, the River Derwent drains Carboniferous limestone bedrock that, in the 17th, 18th and early 19th century, played host to a rich base-metal mining industry, principally lead and zinc, draining into the waterways via the soughs (ibid). This pollution may have impacted on fisheries whilst the mines were active, possibly leaving a legacy in the rivers today, which could become an issue if weirs were to be heavily modified or removed (Howard, Coulthard et al., 2017). Research into the environmental impact of weir removal in the DVMWHS (ibid) viewed the historic weirs as fixed barriers (trapping all sediments upstream), not considering the impact of the opening of floodgates and sluices (on Sundays and during high flows), either in past operations or as a future opportunity (fish movement), or potential risk (movement of contaminated sediment).

Specific industry Acts were introduced to reduce the pollution of rivers, such as the Gas Works Clauses Act, 1847, including punishments for any gas washings or substances flowing into any stream (Bund, 1873). Across Britain polluted waters became a major source of disease in the towns and cities, with John Snow 'famously' identifying the source of a cholera outbreak in London in 1854 as a contaminated hand pump (Barty-King and Angel, 1992 98). The best way of neutralising the pathogens was to move sewage from the locality, often by discharging into fast-flowing rivers (Jopson, 2023 8). Accordingly, The *Salmon Fishery Act* was updated several times and by 1873, it was observed that,

> 'pollutions are perhaps the most deadly enemy that the fisheries of this country have to encounter, and the one of all others in respect of which boards of conservators have the least power' (Willis Bund, 1873 338).

An attempt to strengthen the Act regarding pollution was made, making it unlawful to maliciously put lime or other noxious material in any salmon river (including a potential prison sentence of up to seven years), hopefully also stopping the new practise of throwing dynamite into rivers to kill and destroy the fish (ibid 342).

In 1865 the Royal Commission on River Pollution was established and resulted in the Rivers Pollution Prevention Act of 1876. Unfortunately at that time, the technology had not been developed to prevent pollution of the rivers in the face of rapid industrial development, with the best 'technology' available being land filtration

(Jopson, 2023). The public health authorities' priorities were the chemical purification of water for human consumption, giving no consideration to biologists' concerns about the impact of river pollution on salmon (MacLeod, 1968 146) or other components of the river ecosystem.

An article in *The Field* (1889), discussing the national pollution problem impacting the fisheries, includes references to two incidents in the DDC; the chair of the Belper Rural Sanitary Authority, the Hon. F Strutt (1843-1909), raised the issues of discharge of poisonous liquids from the Ambergate Wire Works causing destruction of fish, and the pollution of Oakerthorpe Brook by the Alfreton Urban Sanitary Authority discharging sewage (The Field, 1889 147). These cases highlight the endemic contemporary problem of manufacturing (industrial) and municipal (domestic) pollution impacting fisheries. In addition to these bodies polluting the rivers, concerns were raised about a growing trend of 'fish poisoners', slaughtering fish on a large scale and leaving more dead in the river than those taken. The favourite chemical used in the Midlands, chloride of lime, also destroyed large quantities of fish food (ibid). An example of one trout stream, severely impacted by the frequent use of chloride of lime and dynamite was quoted on a Trent tributary, the River Leen, at Papplewick Grange, whose proprietor having restocked the stream with Loch Leven trout offered a £20 reward 'to discover the miscreant' (ibid).

The 1886 *Annual Reports of the Inspectors of Fisheries* recorded an official communication being sent by the inspector to the Secretary of State to the Local Government Board, following a visit to Derby finding:

> 'the injury inflicted on the fisheries of the Derwent by the discharge of the town sewage into that river. Thirty years ago [1856] there was good fishing here; now not a fish can live' (Inspectors of Fisheries, 1887 17).

Different forms of pollution clearly impacted on river quality, and therefore fish populations, at different times on different waterways. Domestic (from a growing population) and industrial pollution from Derby (including Darley Abbey) down to Borrowash, indicate that the Derwent was in a very poor state by the 1850s and may have additionally been subject to pollution from mining further upstream, above Cromford. By the mid-19th century any attempts to improve fish passage by the industrial weirs in the lower Derwent would likely offer little improvement, due to the pollution, despite the original fisheries inspector insisting that opening up the rivers was the only way to improve the fisheries during the Salmon Fisheries Inquiry, with Home Office approved fish ladders continuing to be deployed.

3.6 Policy and regulation

Reviewing the chronology of relevant parliamentary acts during the age of mechanisation (1752 to 1878), identified the key issues and priorities of the day and how they changed over time. The Factory Acts (1802 to 1831), The Salmon and Fisheries Acts (1861 to 1873) and Rivers Pollution Prevention Act (1876) have been discussed but the earlier Calico Acts, help to explain the sudden extraordinary demand for power in the late 18th century, that at the time could only be met by waterpower.

3.6.1 Calico Act

The Calico Acts (1701 and 1720) came into being as a response to the threat to the English wool industry, and the wider national economy, from the importation of cotton into Britain, and aimed to revive the wool and silk industries (Fisher, 2012 18). Cotton was imported from India by the East India Trading Company, mostly in the form of calico, a dyed or printed textile that could be used for drapes, bed sheets, dresses and other clothing (ibid 2). The original, 1701, ban on importation of dyed calicoes saw an increase in un-dyed imports, leading to the second Act, 1720, banning the import and selling of most cotton items (ibid 3).

Having developed water powered manufacturing processes capable of mass-producing cotton thread, the British textile mill owners, including Arkwright and Strutt, lobbied the government to repeal the Calico Acts (Fitton and Wadsworth, 2012). Following significant periods of time spent lobbying the government, the acts were repealed in 1774 (ibid 58), effectively creating a marketplace for cotton thread and launching the investment in the new cotton watermills across Britain. Arkwright's carding patent followed in 1775, when 'he tried to "sew up" the whole spinning process' (ibid 76)

3.7 People: Individual, businesses, communities and society

The more famous individuals, families and factory owners who influenced the development of waterpower during the age of mechanisation in the DDC, have already been discussed in this chapter. Whilst investigating the archives relating to the larger industrial textile mills within the DCC, one millwright's name was repeated, Thomas C Hewes (1768-1832), a master millwright from Manchester (Smith, 1969). He worked on many different aspects of textile mills, and, critically, played a key role in the development and use of waterpower, in the DDC, nationally and potentially internationally. Smith (1969) describes Hewes' arrival into the Manchester textile industry as part of the second generation in the history of textile mills (ibid 4). It was a time when the cotton industry had insufficient power to drive improved machinery in larger mills. The improvements in mechanisation in the late 18th century led to development in mill building, mill work and power supplies (ibid). The second generation (1790s) focussed on the structures and utilised iron rather than wood in machine and structures development (ibid 4).

3.7.1 Thomas C Hewes

There are few written records of the work of Hewes (or indeed any millwright), comparable to those for Boulton and Watt, so past research has been based on compiling information relating to activities at mills that Hewes' businesses (Hewes & Wren 1821, Wren & Bennet 1832) completed. Hewes first worked in the setting up of an early cotton manufactory, based on Arkwright's patents, in Belfast in the early 1790s, gaining his knowledge of textile machinery and waterpower (ibid 3). He moved to Manchester during the cotton industry boom in 1792, where there was great demand for millwrights and machine makers and by 1797, he was running his own business with four employees (ibid). By 1840 he had become a Master-Millwright employing 140 to 150 men (40 engaged in heavy millwork e.g. water wheels) (Byroms, 2015 46). At this time Hewes was probably the largest millwright in the country, supplying machinery, building fire-proof mills and waterwheels all over the UK and even sending an iron suspension wheel to America (Smith, 1969 12).

Hewes and the Derwent Valley Mills

It appears that Hewes worked with clusters of mills, such as the Derbyshire Derwent valley, as well as Aberdeen, Manchester, Leeds and Ireland (an iron waterwheel, possibly an early version iron suspension waterwheel in 1802) (ibid 55). Archives of the millowners show how Hewes helped to solve problems and how the mill owners worked together, potentially through Hewes as a third party. One letter from Walter Evans (Darley Abbey) to Hewes, asked for modifications to frames currently on order, based on what he had seen at Arkwright's Cromford mill the previous week (DRO D5231/7/1, 1804). Hewes supplied cotton thread machinery (1804-1807) for carding, spinning processes, drawing frames, skeleton frames and stretching frames to Darley Abbey. An urgent request in 1805 for a 'model' to allow a replacement water wheel shaft, from wood to iron, was made to Hewes by Evans (ibid). William Strutt, Evans' brother-in-law, may have been involved in casting the shaft at his Milford forge and may have incorporated an iron shaft in his own 1804 rebuilt (following fire) North Mill wheel. This could also have initiated the design of the iron suspension wheel installed in Belper (1808) (Section 3.2.2.2).

Hewes also supplied machinery to Arkwright (the original patentee) for his mills at Shudehill, Manchester, Rocester (Tutbury) and Cromford (Smith, 1969 40). At Bakewell Mill Hewes replaced an undershot wheel(s) with an iron suspension wheel (25 ft (7.6 m) in diameter by 18 ft (5.5 m) wide, approximately 100 hp (75 kW), powering 12,000 spindles) in 1827 (ibid) (Figure 3.7). At Masson Mill, Wren & Bennet (formerly Hewes & Wren) supplied their iron suspension wheel in 1847 (Figure 3.28)

Amongst the many improvements that Hewes worked on, he was widely recognised for his role in using iron in mill construction and machine building (ibid 8-9). One of the most significant developments in the DVMWHS was William Strutt's development of the 'fireproof' Belper North Mill, constructed using iron columns, (now a Grade I Historic England listing, number 1186846). With Hewes working with several millowners in the Derwent valley, at the time of the North Mill construction, it is likely he either helped with the iron frame design or learnt from the construction, to develop his own business. In his later career Hewes became known for improvements to many aspects of factory operations, including fireproofing, gas lighting, steam heating and other operative improvements (Smith, 1969), many of which are recorded in the development of the Strutts' Belper Mills.

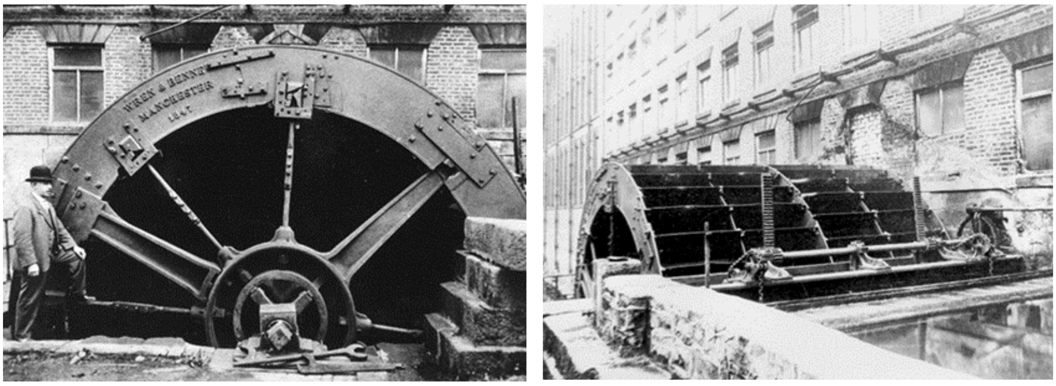


Figure 3.28 Masson mill iron suspension wheel (1847) (with kind permission of Masson Mills).

3.7.2 First and second-generation engineers and mill owners

Comparing Hewes' timeline with some of the key engineers and mill owners associated with waterpower and Derbyshire, there is an alignment with the second-generation mill owners (Figure 3.29), whose emphasis turned from process machine developments to the factory and power structures (Smith, 1969). The influence gained by these early factory master families can be seen with the third-generation representation in the House of Commons.

Investigating Derwent Valley archive materials during the age of mechanisation has identified an opportunity for future research into the inter-relationships of the engineering and manufacturing company owners within the Valley. Unfortunately, there wasn't time to fully explore the associations but there were some interesting discoveries, confirming their close working relationships and collaboration.

Individual millwrights and engineers not only led innovation, they also shared best practise, supported by key engineering businesses. The improvements achieved by the mill owners relied on collaboration, despite occasional disputes, particularly in their optimisation and use of waterpower in the Derwent Valley. Today, there isn't an obvious regional, DDC, body for HEP generators, current and potential, to collaborate.

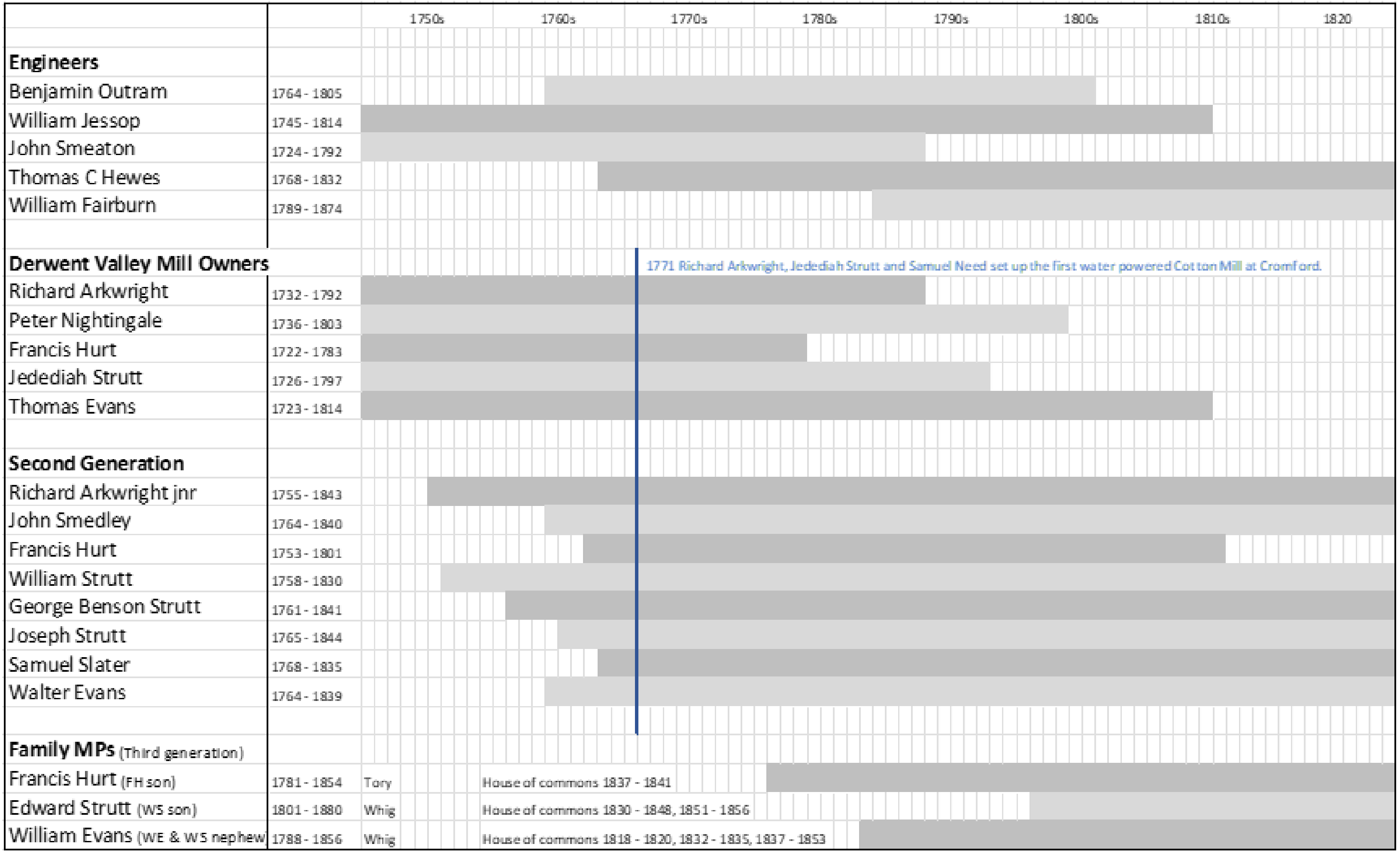


Figure 3.29 Generations of Derwent Valley millowners and key engineers.

3.7.3 Derby Canal Trust

The development of the Derby Canal provides a good example of local collaboration (including treasurer Evans and engineer Outram) supported by parliament, enabling the development of key infrastructure. The Derby Canal Act (1793) utilised local private investment, with financial controls in place to limit the costs to users of the canal and limit the profits to be made by the investors. The Act included maximum tolls that could be charged on each class of goods, and restricted the maximum dividend the local ‘gentleman’ shareholders could withdraw to 14% (although they never drew more than 10.6% between 1837 and 1842) (Smith, 1980 50). The Act also included the clause allowing abstraction from the Derwent at times limiting impact to mill owners on the river.

3.8 Lessons to learn

Waterpower has been an important resource for communities across Britain for hundreds of years, often using the available natural falls and flows of the waterways. Run-of-river waterpower became a valuable asset as the new textile factories of the late 18th century demanded more power, with the power available to be harnessed determining the size and output (revenue) of the mill. By the early 19th century the industrial millowners competed for, and developed, all of the suitable and available waterpower sites, often redeveloping existing smaller watermill sites; a good starting point to look for future run-of-river waterpower developments.

In addition to the natural waterways, man-made waterflows, such as the lead mine drainage channels (soughs), drove waterwheels to generate power.

A combination of science, innovation, early adoption and sharing of best practise, saw waterpower (storage, control and generation) rapidly improved. Man-made weirs and dams were raised to maximise storage and increase power, with water released to match the demand of the mills. The storage of water (power), extending hours (to match low flow) and occasionally releasing water from upstream reservoirs at times of drought, could all be relevant for future river management, utilising all of the 20th century water storage reservoirs as pumped storage HEP facilities. One of the benefits of waterpower is its availability 24 hours a day, but by utilising the available flow more flexibly, as the original millowners did, the value of waterpower could be increased, by matching power generation to demand.

Whilst we were aware of the natural challenges faced by the industrial watermill owners, their ability to minimise the impact of flooding, by floodgate design and building flood waterwheels, alongside their resilience, recovering from major floods in hours, offers lesson to learn. Some of these lessons may have been learnt by the millowners in adversity following the great 1795 flood. Crucially, it would appear many of the Georgian watermill owners also had interests in the fisheries and, as a result, were the primary stewards of the river, apparently through the use of their flood and sluice gates, redistributing fish on Sundays (when mills were not operating) or nights (suiting fish migration patterns), managing silt build up and supporting navigation of the waterways.

Steam was first used to increase waterpower outputs, with textile mill owners recycling water from the tailrace to the mill pond using steam pumps. Even Boulton and Watt recycled water for the waterwheel at their Soho steam engine manufactory (Demidowicz, 2022). Despite the common misconception that steam replaced waterpower, this research shows that through the 19^{th} century waterpower continued to be a valuable source of power, using the free fuel of the river, with industrial watermill sites adding steam in a hybrid power arrangement, used only once all the available waterpower was being harnessed (Malone, 2005 32); another lesson to learn.

Parliament valued waterpower during the age of mechanisation, monitoring its use through the Factories Act, and not harming the new textile economy by introducing charges for the water and listening to the industrial millowners when faced with water abstraction conflicts (e.g. Cromford Canal) to find suitable compromises. The most striking evidence of parliamentary support relates to the most controversial aspect of run-of-river waterpower today, the impact of weirs on the rivers' ecology, and in particular salmon migration. This research suggests the final decline in salmon numbers occurred c.1850, many years after the building of the industrial weirs, identified at the time as the main problem. The salmon commission and resultant Act (1861) did require improvements such as gratings and fish passage (similar to today's requirements), but the act identified improvements to be made working with the mill owners (e.g. close times matching out of hours mill times and the use of open gaps) to facilitate the 'distribution' of fish. Critically the *Salmon Fishery Act* (1861) was produced to deliver fishery improvement without harming milling power, with many clauses remaining in the current (1975) version.

One of the more concerning aspects of the salmon inquiry and regulatory development during the 19^{th} century, was the focus on the weirs as the main problem. Concerns were raised about the impact of domestic and industrial pollution by local anglers, but they were dismissed by the commissioners. Industrial watermills invested in new fish passes following the 1861 Act but to no avail: by the 1870s pollution was identified as the primary cause of fish depletion. Improvements in fisheries in the Trent catchment today are again focussed on the weirs, with fish passes and weir removal projects, despite other aspects, such as climate change (marine and river warming) and pollution, potentially being responsible for the global decline in salmon since the 1970s.

The Georgian period was a period of great change and this research confirms the role of the more famous ‘factory masters’, but it also highlights the role of the engineers in developing the new technologies and sharing best practice. There is also evidence of the factory masters and their local communities working collaboratively, to both defend their use of waterpower but also to build new infrastructure, such as the canals. The parliamentary act enabling the Derby Canal, restricting the profits and charges to be made by the developers, may offer a model for locally led and funded projects. Communities developing green power stations at the historic watermill sites offer cultural, environmental and economic benefits; a form of sustainable development for heritage sites.

Chapter 4 Waterpower: Hydroelectric power (HEP) (1878 – 1989)

4.1 Introduction

In his paper, '*The Phoenix and its Demons*' (2006) Reynolds states that waterpower has twice gone into sharp decline, only to recover 'like a phoenix'. The first decline, during the 5th – 7th centuries, followed collapses of central government and market economies, which saw the return of 'human and animal muscle' power (Reynolds, 2006 155). Reynolds claims that the second decline occurred because of the development of the steam engine (ibid 161), effectively replacing waterpower in the 19th century. However, my findings (Figure 3.15) indicate that waterpower continued to be used, with slight growth, throughout the 19th century, albeit with steam meeting most of the growing demand for power and ultimately becoming the primary source of power. This chapter provides evidence that a second decline did happen in the UK, but during the 20th century, as other factors almost eradicated hydroelectric power (HEP) generation in England and Wales by the 1970s (Francis, 1978 318, Wilson, 1974).

The Derbyshire Derwent catchment (DDC) waterpower site timelines (Figure 2.28) show the decline in HEP generation in the mid-20th century, with sites generating electricity using the 'free' fuel of the river, apparently switching off and often removing their turbines. This decline is also captured in the 20th century UK sales of Gilkes turbines (J Chaplin [Gilkes], personal communication, 7 December 2022). Despite being recent history, there is little information explaining why this happened, with few records of individual sites in the DDC switching from self-generation to the purchasing of electricity from local or national grids. Trends and events external to the DDC, e.g. national energy policy, were compared to DDC waterpower site timeline changes, to identify the potential causes of HEP decline. During this period DDC watermill stakeholders, such the English Sewing Cotton Company (ESCC) and the Arkwright Society did participate in regional and national HEP initiatives, offering some insight into the challenges faced by local HEP generators.

This chapter starts where Chapter 3 finished, in 1878, with waterpower now generating electricity, energising a new form of lighting. For the next century HEP was one method of producing electricity, competing with fossil and later nuclear fuels. Many factors determined the effectiveness and competitiveness of HEP in a particular location, but predominantly it would need to be economically viable and reliable, to be chosen as the electricity generation power source. As the world became more aware of energy security and environmental concerns, including global warming, there was a demand for non-fossil fuel, renewable energy sources, and in the 1980s the only readily available renewable energy in the UK was HEP. In 1988 Margaret Thatcher, UK Prime Minister, spoke to the Royal Society to raise her concerns about global warming and environmental change (Mahony and Hulme, 2016 451). This chapter therefore explores the new application for waterpower, generating HEP, and its decline in use during the 20th century, before its new role as a low carbon renewable energy (Chapter 5).

Populating the cause-and-effect diagram, for the 1878 to 1989 period (Figure 4.1), highlighted a wide range of local and national influences on the usage of waterpower in the DDC. 20th century contemporary literature and archives helped to identify the key influencing factors, which form the structure for this chapter, and contextualise the decisions made by the key stakeholders, such as mill owners and parliamentarians, regarding the use of waterpower, particularly its decline in this period. Researching this period also identified several challenges faced by the key stakeholders, similar to those faced today, such as energy security, water abstraction and river quality.

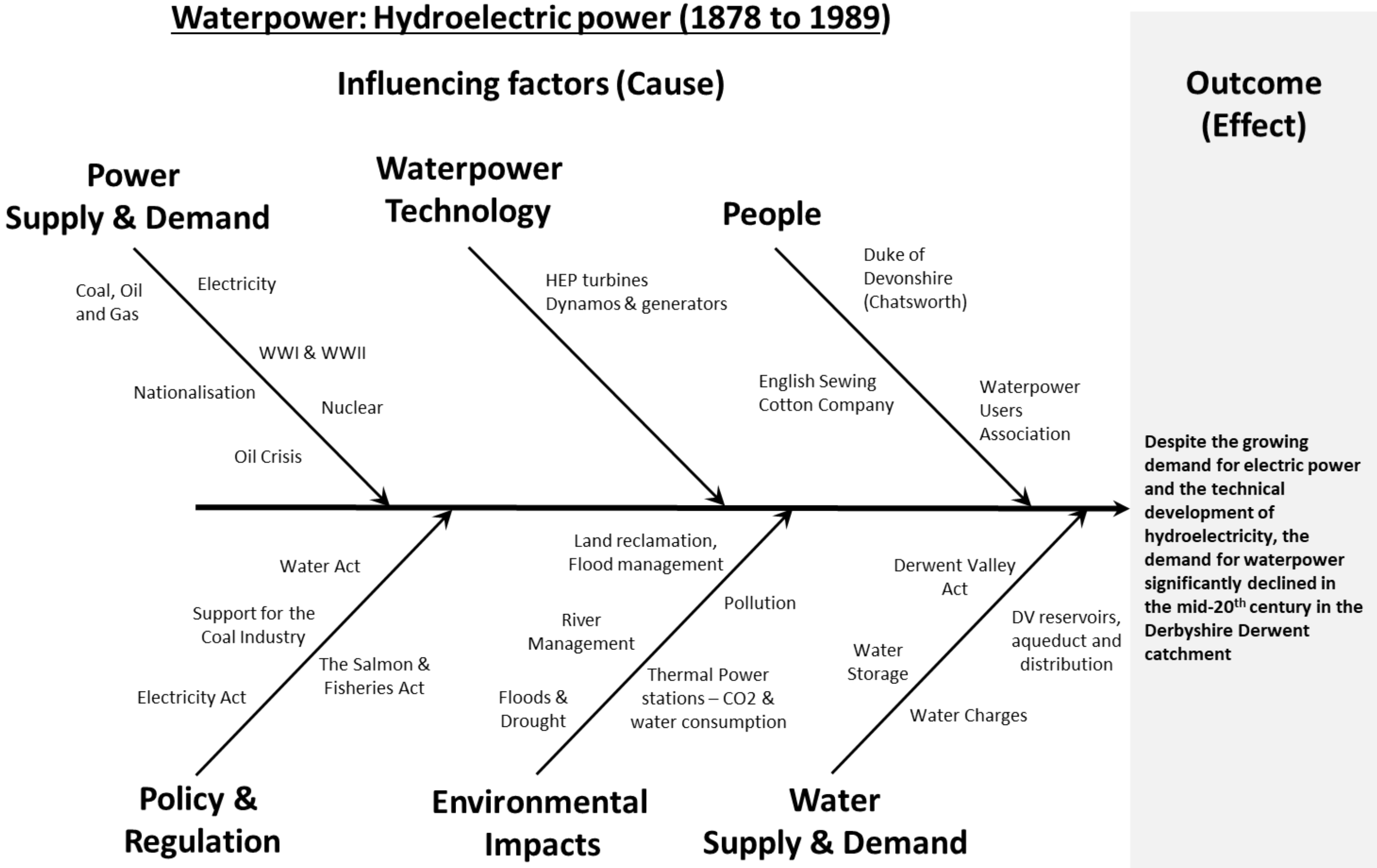


Figure 4.1 Factors influencing the use of waterpower between 1878 and 1979.

4.2 Waterpower: Hydroelectric power (HEP)

4.2.1 Early hydroelectricity (electric lighting)

Michael Faraday's discovery of electromagnetic induction in 1831, opened up the possibility of converting mechanical power into electricity (Hannah, 1979 3). By the 1850s small generators were developed to produce electric arc lights for lighthouses (ibid). During the 1870s domestic illumination still relied on paraffin lamps, candles and, in urban areas, the gas light (ibid). Waterpower generating electricity to produce light was competing with the existing gas companies, which produced town gas from coal, and with shares in gas companies collapsing, they set up a committee to investigate the threat in 1878 (Arapostathis, Carlsson-Hyslop et al., 2013 28, Hannah, 1979).

In 1878 Joseph Swan, a self-educated Newcastle chemist, demonstrated that a carbon filament in an evacuated glass globe would glow when electric current was passed through it (incandescent light) (Hannah, 1979 4). On hearing about Swan's invention from Lord Armstrong, who was about to install incandescent lights at Cragside, the Marquis of Salisbury challenged his estate workmen at Hatfield House, Hertfordshire, to be the first private house in England to have incandescent lighting. A sawmill on the River Lea, approximately 1 ½ miles (2.4 km) from Hatfield house provided the waterpower, continuing as a sawmill during the day but generating electricity at night (Cecil, 1971 4). In *The Wonders of the Universe* (1889), an article on Electric Incandescent Lamps describes 'possibly the most perfect' private mansion installation as that of Sir W G Armstrong, at Cragside, Northumberland (Barnard, 1889 253). 'This eminent engineer has the advantage of getting his motive power free of cost' using a brook 1.6 km from the house that turned a turbine (6 HP [4.5 kW]), actuating a Siemens dynamo-electric machine, that lit 45 incandescent lamps (ibid 253), described by Swan as the first proper installation of his bulbs (Irlam, 1989). At Cragside, Armstrong had previously attached the Siemens unit to a Williamson (pre-cursor to the Gilbert Gilkes) water turbine in his Debdon sawmill, to power an electric arc light in the picture gallery, potentially making it the first hydroelectric plant in Britain in 1878 (ibid). A second generator was added later to power an electric motor on the sawing machine in the mill (ibid Figure 4.2).

Figure 4.2 The Cragside turbine with both generators on the turbine output shaft (Photograph: Author, 2023).

4.2.1.1 Private HEP generation in the DDC

One of the earliest mentions of the use of electricity in Derbyshire is the *Derby Mercury* newspaper report (1882) on a Chamber of Commerce exhibition at St James's Hall, Derby, attended by approximately 300 'influential' members, exhibiting the goods of local manufacturing businesses. One of the exhibitors, Messrs. Davis and Son, lit half of the hall with incandescent light, to show the difference between the electric and gas lights. They also exhibited an "electro-dynamic motor" for driving sewing machines and were thanked for spreading knowledge of electricity, the 'power of the future' (*The Derby Mercury*, 1882 26 April). Another exhibitor, Richard Johnson & Nephew (RJ&N), had built their new wireworks by the River Derwent in Ambergate in 1876, mechanically driven by two water powered turbines (Bulmer, 1895, Seth-Smith, 1973). An 1895 visitor to the site reported that RJ&N's manager's house, Oakhurst, was lit throughout by electric light powered by a small turbine, worked from a nearby reservoir (Bulmer, 1895 609, Jewell, 1995), possibly powered by the third 'high head' turbine purchased by RJ&N in 1876 (DRO D4572/2/1, 1900).

Other country houses and industrialists in the DDC introduced electric lighting, with turbines and dynamos being installed onto existing waterpower sites. G H Strutt (1854 - 1928) powered electric lights for his Makeney House, Milford, using a 12 hp (9 kW) turbine installed in the Makeney forges, adjacent to his Milford Mills (DRO D3772/T21/9/1, 1898); the Gilkes' turbine sales records confirm a 12 hp water turbine being installed at Milford Mills (No. 998 c.1895, Gilkes Derbyshire). One of the more extraordinary early HEP installations was at Chatsworth House, which, rather than generating electricity using the nearby flour mill driven by the Derwent, diverted water from the Emperor Fountain (originally built in 1844 and the highest gravity fountain in the world), fed by the man-made Emperor Lakes 100m above the House (Cooper and Cooper, 1991). The fountain feed was extended in 1893 to drive three Gilkes turbines (Figure 4.3) (*The Electrical Review*, 1893), meeting the needs of the house for over 40 years (Gilbert Gilkes & Gordon Ltd, 1998). The 8th Duke of Devonshire (1833 - 1908) installed HEP following his succession in 1891, harnessing the power of the water that 'had always been a force for beauty' at Chatsworth (Devonshire and Rogers, 1999 89). Another interesting aspect to this early installation was the use of a bank of DP lead acid batteries (Strange, 2001), probably supplied by the Dujardin-Plante Battery Company (DP Battery 1888-1972), Lumford Mill, Bakewell. Two turbines provided electricity to the house whilst the third, smaller, turbine charged the batteries and, by 1898, 1,174 lamps were being supplied in the house (ibid).

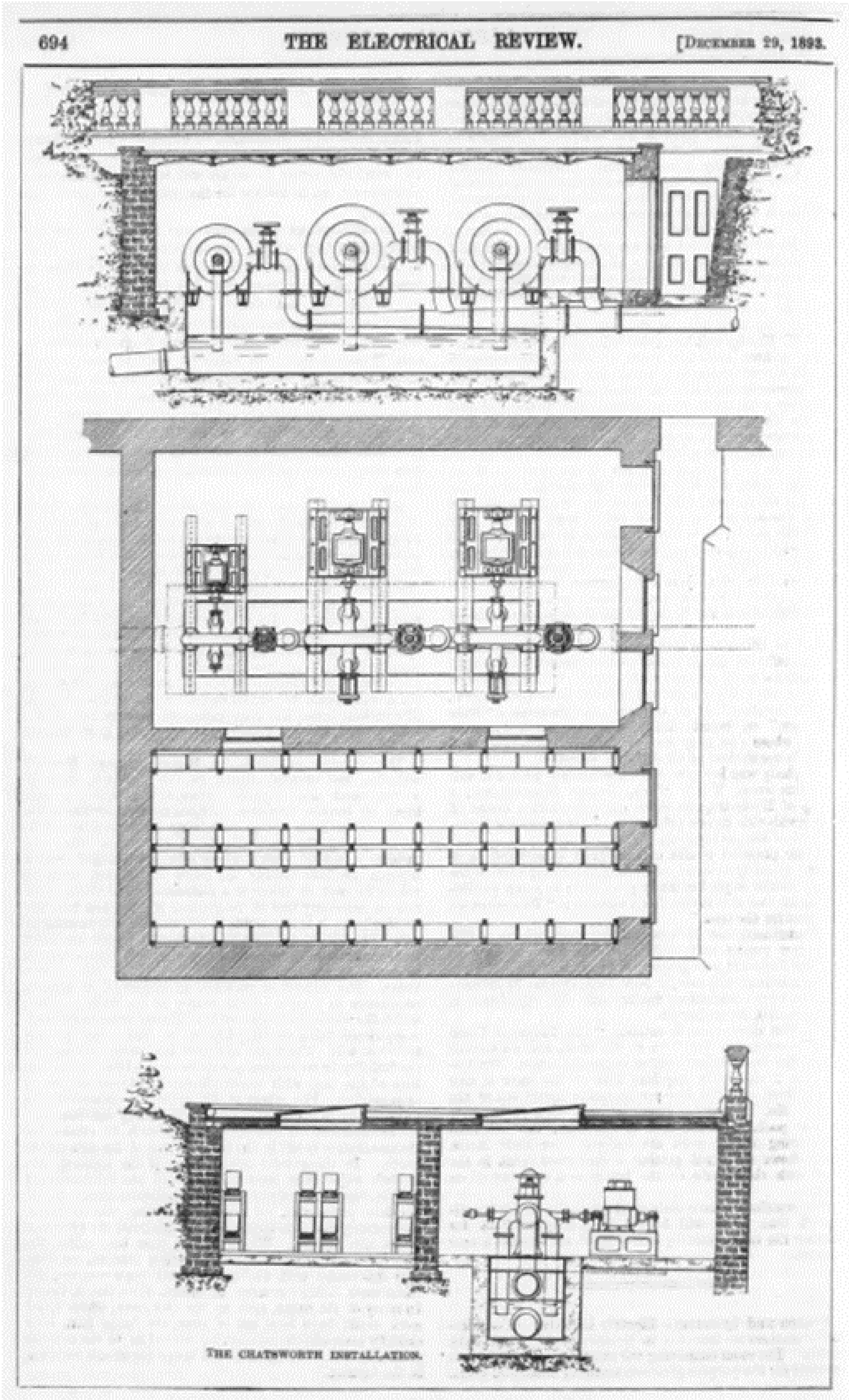


Figure 4.3 Electric Lighting at Chatsworth article (*The Electrical Review*, 1893 29 December)

4.2.2 Early (hydro)electricity (public lighting, transport and power)

Between 1877 and 1881, over 100 experimental electric street-lighting schemes were set up in Britain, but few achieved any permanence (Strange, 1979). Two towns that lay claim to being the first in Britain to be solely lit by electricity are Godalming, Surrey and Chesterfield, Derbyshire, between 1881-4 (ibid), with Godalming using waterpower with a steam backup and Chesterfield using steam power alone. The Godalming electric lighting scheme replaced gas lighting by repurposing an existing watermill, Westbrook Mill of Messrs Pullman Brothers (leather dressers), to generate the electricity (ibid). The Godalming Mill replaced its water wheel with more efficient Poncelet water turbines, with an auxiliary steam engine to supplement the waterpower (ibid). The Godalming station had many problems, typical of a water powered supply, such as a storm creating high water levels requiring the auxiliary steam engine to power the lighting (ibid 866). Problems with the system, and disputes with the local gas company, led to the town being in darkness, leading ultimately to a mix of electric and gas lighting by 1884. Ultimately Siemens offered an alternative electric solution using a different power source, probably a steam engine (Gardner, 2008, Strange, 1979, Tucker, 1977). Tucker's research identified eight hydroelectric power (HEP) stations providing supply of electricity for street lighting and consumers by 1894, although only five really offered a 'public' supply (Tucker, 1977). By comparison, by 1894 there were at least 91 public supply stations driven by steam engines (ibid 126), evidence that coal-fired steam engines quickly became the dominant technology option for reliable, predictable and scalable public electricity supply in the UK.

4.2.2.1 Public HEP generation in the DDC

Two DDC towns were included in a list of 45 towns considering the early adoption of HEP to provide electric lighting, Matlock Bath (1891) and Baslow (1894), but neither progressed their projects (Tucker, 1977). At Matlock Bath, a proposal to replace 'the apology for gas in the street lighting', by utilising the 100 hp (75 kW) of HEP available from existing works on the River Derwent to power 1,000 electric lamps, was presented to the local board in 1891 (*The Derby Daily Telegraph*, 1891

15 January). The project apparently did not progress, with a similar report presented to the Matlock Council thirty years later, in 1921, proposing the installation of turbines in the River Derwent adjacent to the High Tor (Matlock Dale) weir, to ‘supply the whole needs of Matlock for lighting and power’ (*The Engineer*, 1921 565). The scheme would have also provided ‘cheap’ power for the cable tramways that had been running at a loss (ibid). Concerns were raised at the meeting that special authority from the UK government’s Board of Trade would be required (ibid), suggesting some state influence or control in the 1920s.

In 1920, six hundred lots of the Duke of Rutland’s Derbyshire estate were auctioned, including DDC water powered mills, such as Lot 670, Victoria Mill, where ‘Special attention is drawn to this Valuable Water Power which is of INCREASING VALUE in these times of high-priced fuel’ (DRO D504/113/1-3, 1920), suggesting that, during the 1920s, waterpower had an economic advantage over the rising cost of coal. With the introduction of public electric lighting, Lot 493 [Baslow] Flour Mill, included ‘the Valuable Water Power available for Supplying Electricity in Baslow’ (ibid). Electrical engineer Sebastion de Ferranti (1864-1930) had purchased Baslow Hall in 1907 and took advantage of the Rutland auction to purchase more land (Dalrymple-Smith, 2022), intending to turn Baslow Hall into an ‘All-Electric House’, to demonstrate his vision of the ‘All-Electric Age’ (Wilson, 2000). There are conflicting stories regarding Ferranti’s use of the water powered mill but, as he installed a steam engine to develop his All-Electric Baslow Hall (ibid), rather than using the HEP from his nearby mill, it is likely that stories of the weir (Figure 4.4) being in too poor a state for Ferranti to use (Derbyshire Heritage) are accurate. The flour mill was purchased and upgraded by the Hodgkinsons (farmers, maltsters and millers) following Ferranti’s death (1930), probably installing the, currently inactive, turbine that remains on site today, (Figure 4.5).

Figure 4.4 Bubnell weir and Baslow Mill with two waterwheels c.1833 (Copyright The Francis Frith Collection)

Figure 4.5 Baslow Mill turbine output shaft (not operational). Photograph: Author, 2023

Early, wealthy, adopters of HEP, such as Lord Armstrong, Queen Victoria, the prime minister and the Duke of Devonshire, played a key role in both developing the technology and promoting its use. Examples such as Godalming highlight how early-adopter local authorities faced significant risks and challenges in introducing electric lighting. The Matlock Council proposal considered ownership options (i.e. authority-led versus private installations), but reliability was a critical factor in public electricity supplies, which proved to be too difficult to achieve by HEP alone. Even so, the 1920s auction of watermills also suggests that the varying and increasing cost of coal offered waterpower an economic advantage where good infrastructure existed.

4.2.2.2 HEP use in Industry in the DDC

Whilst HEP doesn't appear to have been a suitable technology option for public supplies in the DDC, many established water-powered (mechanical) industrial sites c.1900 had the option of self-generating electricity for lighting (initially) and power (later), in addition to, or in place of, the mechanical power already harnessed. Existing iron suspension wheels could be replaced by newly available, more efficient water turbines, as electricity was introduced (Wilson, 1957). A Scottish engineer, John Turnbull, who built and supplied Turnbull Hercules turbines (a US turbine development) between 1880 and 1913 (Ritchie, 1980 17), installed turbines at a number of DDC mill sites to self-generate electricity, although the dates and sizes of turbine are not available for most of those sites mentioned (Table 4.1).

Table 4.1 Hercules turbines installed by Turnbull in the DDC (Ritchie, 1980 18-22)

Listing in the article	Location
English Sewing Cotton Company's Mills, Belper	Belper South mill
F C Arkwright, Cromford	Possibly Masson mills
Biddulph Brothers, Cromford	Corn Mill, Bonsall Brook
S Evans & Co Ltd, Derby	Darley Abbey paper mill
Lord Harrington, Elvaston Castle	Unknown (Waterwheel at Elvaston)
J Towle & Son, Derby	Borrowash mill

Many of the Turnbull (Hercules type) turbines do seem to have been installed on industrial sites, although they could have been generating electricity for local houses, e.g. those of the mill owners. Ritchie (1980) also includes a summary of the largest installations in the UK at the time, including the second largest by Messrs Turnbull at ESCC's Mill at Belper (600 hp [450 kW]) (*The Glasgow Herald*, 1900 22 December). A later article suggests that some of the Turnbull turbine capacity at Belper was retained to provide mechanical power (direct rope drive for the upper floors) and some to provide electric lighting (Copeland, 1991 573). It is likely that the turbine supplied to F C Arkwright was installed in Masson Mills, as a 1910 feature article about Masson described 'a water-driven Castle dynamo that supplies many of the machines all the night, working the electric light installation' *(The Derbyshire Advertiser*, 1910 2 July).

The most significant example of the value of harnessing the natural power of the river in the DDC, relates to the use of waterpower to generate electricity at the Milford, Belper and Masson mills. As a result of international events, including the American Civil War (1861-65) and European tariffs on British manufactured goods, the Strutts had lost 75% of their market by 1885, making it more of a 'philanthropic concern than a going business', and leading to the closure of the Milford thread site (G H Strutt cited in Derbyshire Advertiser and Journal, 1913 4 July 9). Facing the same challenges, a significant consolidation of the 'English thread makers' took place (Blyth, 1947 9), leading to the formation of the English Sewing Cotton Company (ESCC), with G H Strutt initially retaining ownership of the Belper and Milford sites, and responsibility for their power provision. Continuing to take an interest in the business's performance and impact on the communities of Milford and Belper, and determined to encourage ESCC (based in Lancashire) to maintain their presence in the Derwent Valley, G H Strutt invested in waterpower at the Milford site, replacing the 'old-fashioned water wheels' with 'modern turbines', producing 340 HP (250 kW), capable of generating electricity to power the machinery. The opening of the 'new' turbine house in 1908 was a grand event in Milford (Figure 4.6), with executives of the ESCC invited (Derbyshire Advertiser and Journal, 1908 10 July 6).

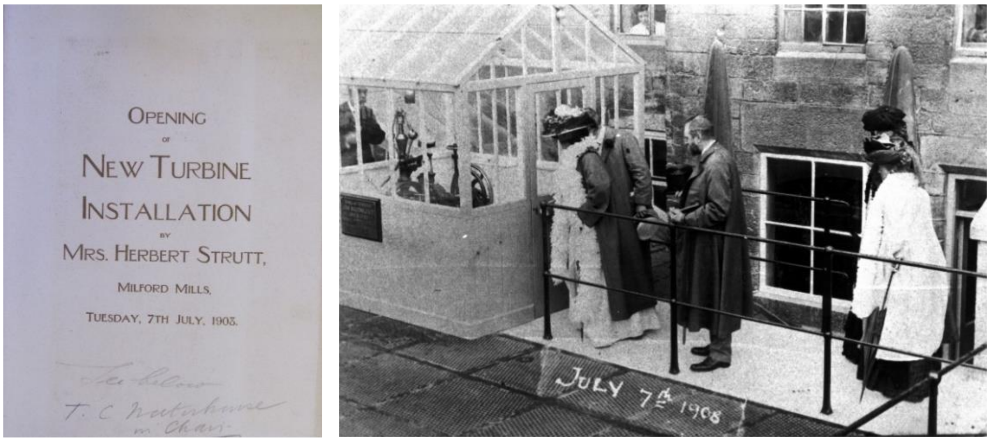


Figure 4.6 Milford Mills turbine installation 1908 (Photograph: BHS00987)

Five years later, G H Strutt, spoke at the opening of the Belper East Mill, a significant investment by the ESCC. He declared that his investment in a turbine at the Milford Mills helped ESCC to understand the value of water in the Derwent Valley; ‘he felt sure that when they got tired of burning coal in Lancashire they would come back to Belper and re-develop the power there’ (cited in Derbyshire Advertiser and Journal, 1913 4 July). The chairman of ESCC confirmed this observation, adding that, owing to the success of the Milford turbine installation, ‘the directors decided to make similar improvements at Masson Mills’ (ibid). G H Strutt’s introduction of modern HEP had saved the Derwent Valley sites from closure and facilitated the expansion of the Belper and Masson mills in 1912-13. The construction of the Belper East Mill required more electric power, supplied by 2,000 hp (1,490 kW) of steam power in addition to the existing 500 hp (373 kW) of HEP, to be ‘distributed to thirty motors’ (*Belper News and Derbyshire Telephone*, 1913 4 July).

The most comprehensive sources of water turbine installations information in the DDC, are the sales ledgers (manual ledger for Derbyshire [pre-1900] and the UK sales list [1900-2021]) shared by Gilbert Gilkes & Gordon Ltd, the largest UK water turbine manufacturer (J Chaplin [Gilkes], personal communication 7 December 2022). Table 4.2 lists the sites in the DDC installing Gilkes turbines between 1893 and 1973, indicating that all of the larger industrial sites along the River Derwent harnessed the power of the river in the first half of the 20th century to generate electricity (Figure 4.7).

Table 4.2 Gilkes water turbine sales to DDC sites plus information in other archive materials (in italics).

Year	Turbine No.	Customer Name	Site Name	Type	Power kW	Net Head	Flow l/s
1893	*874*	*Duke of Devonshire, Chatsworth House*	*Chatsworth House*		*37*		
1893	*875*	*Duke of Devonshire, Chatsworth House*	*Chatsworth House*		*15*		
1894	*908*	*Duke of Devonshire, Chatsworth House*	*Chatsworth House*		*37*		
	913	Chatsworth surveyor			7	33	
	957	Towlson J & Co.	Park Mill, Wingfield		6	8	
	998	W G & J Strutt	Milford Mills, Belper		9	3	
	1070	Fletcher Bros.	Pentrich Mill		19	2	
1896	1088	W G & J Strutt	Milford Mills, Belper		67	2	
	1219	E E Twigg	Ashford Marble Works		19	2	
	1305	Cressbrook Mills & Co (via Buxton)	Cressbrook Mill		75	7	
	1306	Duke of Devonshire, Chatsworth House	Ashford Mill		1	37	
	1307	Duke of Devonshire, Chatsworth House	Ashford Mill		3	37	
1900	1413	Cressbrook Mills & Co (via Buxton)	Cressbrook Mill	Vortex	52	8	896
1902	1527	W R Oliver & Sons Bamford		Lunedale	149	6	3113
1902	1558	M Dickie Junior Ltd	Litton Mills	Vortex	66	9	382
1903	1603	Sibley & Son	Parret Iron Works, Matlock	Vortex	3	7	55
1905	1736	Morrison/Mason Ltd, Bakewell Road		Pelton	7	30	28
1906	1785	E H Bailey, Matlock Mills	Matlock Mills	Vortex	11	6	249
1907	1905	E H Bailey, Matlock Mills	Matlock Mills	Vortex	11	6	238
1909	1987	Via Gellia Colour Co Matlock Bath		Lunedale	8	2	707
1912	2275	Matthew Dickie Jr Ltd	Litton Mills	Trent	9	5	242
1912	2305	Matthew Dickie Jr Ltd	Cressbrook Mill	Trent	149	8	2641
1915	2607	Duke of Devonshire, Chatsworth House	Chatsworth House	Turgo	19	2	1278
1918	2731	Chadburn Brookfield Manor, Hathersage	Brookfield Manor	Vortex	1	7	20
1919	2748	George Fletcher & Co, Derby		Francis	63	10	849
1920	2823	Matthew Dickie Jr Ltd	Cressbrook Mill	Francis	90	8	1603
1922	2904	Sir R Arkwright & Co Ltd		Turgo	31	24	163
1924	3118	Sir E Arkwright & Co Ltd		Francis	116	3	4528
1924	3133	Duke of Devonshire, Chatsworth House	Chatsworth House	Pelton	22	91	32
1924	3134	Duke of Devonshire, Chatsworth House	Chatsworth House	Pelton	3	91	4
1924	3157	Jerram & Co. Babbington Lane, Derby		Pelton	1	24	4
1925	3209	C L Drury, 172 Almond St Derby		Pelton	2	64	4
1926	3288	English Sewing Cotton Co. Ltd	Belper Mills, Belper	Francis	34	4	1202
1927	3409	Derby Corp Water Works	Little Eaton	Turgo	32	40	104
1928	3505	English Sewing Cotton Sir R Arkwright	Masson Mills, Matlock	Francis	153	3	5990
1928	3506	English Sewing Cotton Sir R Arkwright	Masson Mills, Matlock	Francis	153	3	5990
1929	3597	Marcus Astle (Earl of Harrington)	Wilne Mills, Derby	Francis	102	2	5424
1929	3627	Capt Fitzherbert Wright	Alderwasley Hall	Turgo	9	40	30
1930	3772	R Johnson & Nephew Ltd	Ambergate Mills	Francis	174	3	6556
1931	3814	J A Taylor	South Wingfield Mills	Francis	14	2	754
1931	3815	J A Taylor	South Wingfield Mills	Francis	8	2	426
1933	3965	R Johnson & Nephew Ltd	Ambergate Mills	Francis	174	4	9103
1936	4175	English Sewing Cotton Co. Ltd	Milford Mills, Belper	Francis	254	4	7263
1945	4567	The Harland Eng Co. for DVWB	*Ladybower reservoir*	Francis	222	40	818
1945	4568	The Harland Eng Co. for DVWB	*Ladybower reservoir*	Francis	222	40	818
1945	4569	The Harland Eng Co. for DVWB	*Ladybower reservoir*	Francis	37	40	131
1948	4736	W G Sissons Ltd	Calver Mill, nr Grindleford	Francis	112	6	2160
1948	4752	Chatsworth Est Co. Bakewell	Chatsworth Estate	Pelton	7	61	15
1949	4829	County Bor. Of Derby, Water Works	Derby Water Works	Pelton	87	87	125
1950	4894	Derby Oxide & Colour Co Ltd		Francis	33	2	2207
1955	5376	The D P Battery Co Ltd, Bakewell	Lumford Mill	Francis	112	7	2110
1959	5576	Derby Corp	Spondon No. 2 Res	Pelton	31	85	283
1959	5601	English Sewing Cotton Co. Ltd	South Mill, Belper	Francis	209	4	6202
1959	5602	English Sewing Cotton Co. Ltd	South Mill, Belper	Francis	209	4	6202
1973	6166	English Sewing Cotton (Manchester)	Mason Mill, Matlock	Francis	168	3	5990

The presence of historic chimneys on these sites, has led to misunderstandings that mill sites switched from waterpower to steam power, alongside observations such as ‘steam power, not water power, in this case was the driving force’ of the 1913 East Mill (Jennings, 1970 17). This research demonstrates that HEP was used in combination with steam, in a hybrid system, harnessing the free energy of the river as a base power load, with steam meeting the additional power demands of the site, into the 20th century.

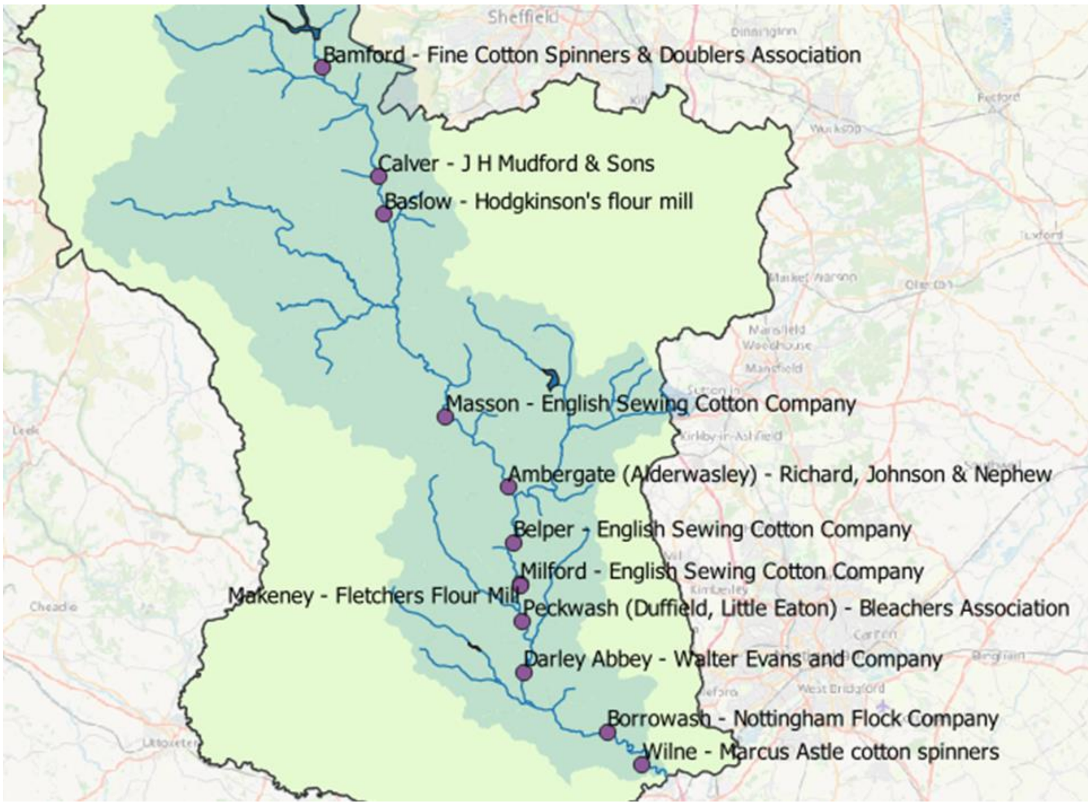


Figure 4.7 Industrial sites on the river Derwent generating HEP in the early 20th century

One less obvious factor affecting HEP's continued usage was the inconvenience of switching on the electricity. During the 1940s, the 1901 Belper South Mill water turbines (mechanical drive plus 300 kW), the 1910 West Mill water turbines (designed at 400 kW, loaded to 250 kW) and the 1912 East Mill steam turbines (Hargreaves 1,200 kW or B.T.H 1,000 kW) had to be started and synchronised manually at 7am, six days a week, by a team of engineers (c.12 men) on the sluices and turbines, in all weather conditions (Figure 4.8) (Copeland, 1991 573). The estate manager of the Chatsworth Estate believes the house switched from self-generation to a local grid in 1936, due to the inconvenience of the maintenance team having to climb the 90m escarpment, to open sluices to switch the electricity on (B Garstang, personal communication, 1 September 2021).

Figure 4.8 Belper Mills (1921) powered by 10 water turbines and 2 steam turbines (Blyth, 1947 44).

4.2.2.3 The decline of HEP generation in the DDC

The DDC gazetteer and waterpower site timelines reveal references to many turbines being installed in the late 19th century and early 20th century. Figure 4.9 shows the sites with evidence of a water turbine being installed between 1890 to 1940, probably to generate electricity, compared to the sites actively generating electricity in the 1980s. The Gilkes UK sales figures (Figure 4.10) support the research findings (Figure 2.28) of a significant decline in the UK-wide HEP industry during the mid-20th century. Figure 4.10 also highlights the impact of WWI and WWII on HEP sales and installation. Two research projects in the Derbyshire Derwent Valley in the 1960s, which included mill site visits, produced some useful, and rare, contemporary information about sites still operating their HEP. Shaw (1965) noted that the Ambergate Wireworks turbines were operating, Matlock Mills turbines were disused, and Darley Abbey mills had three turbines in place but only one in use (Shaw, 1965, Swindell, 1963).

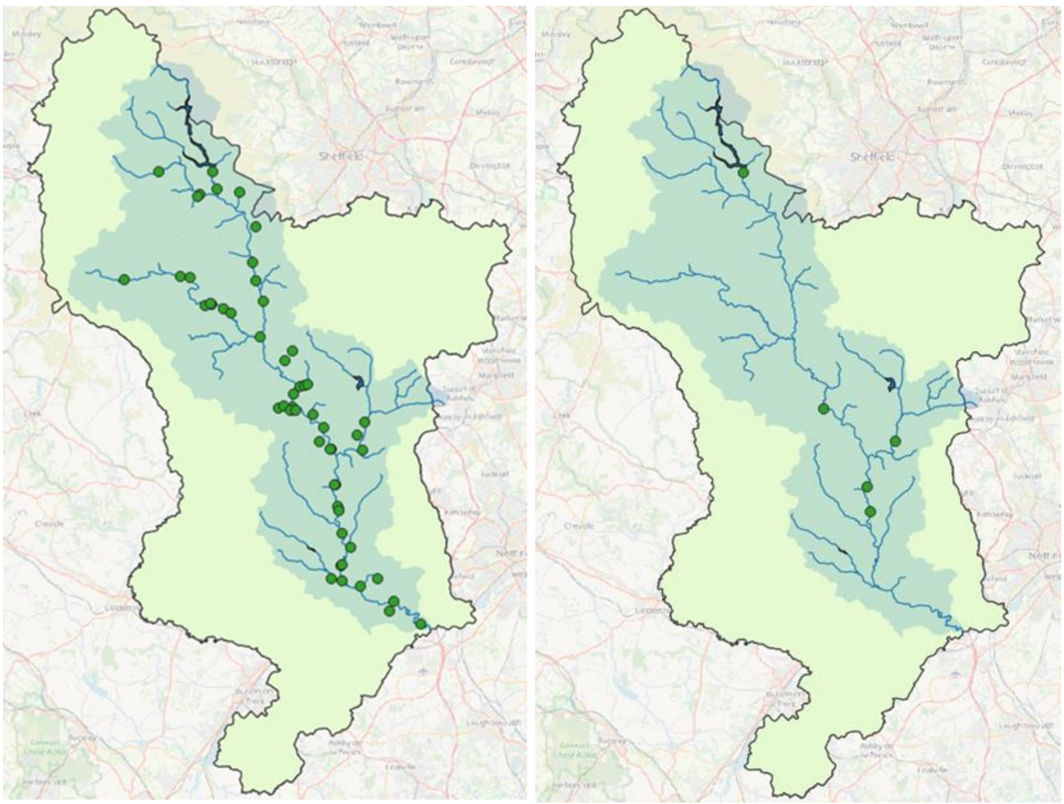


Figure 4.9 55 water turbines installed between 1890 and 1940 (left), five water turbines still generating HEP in the 1980s.

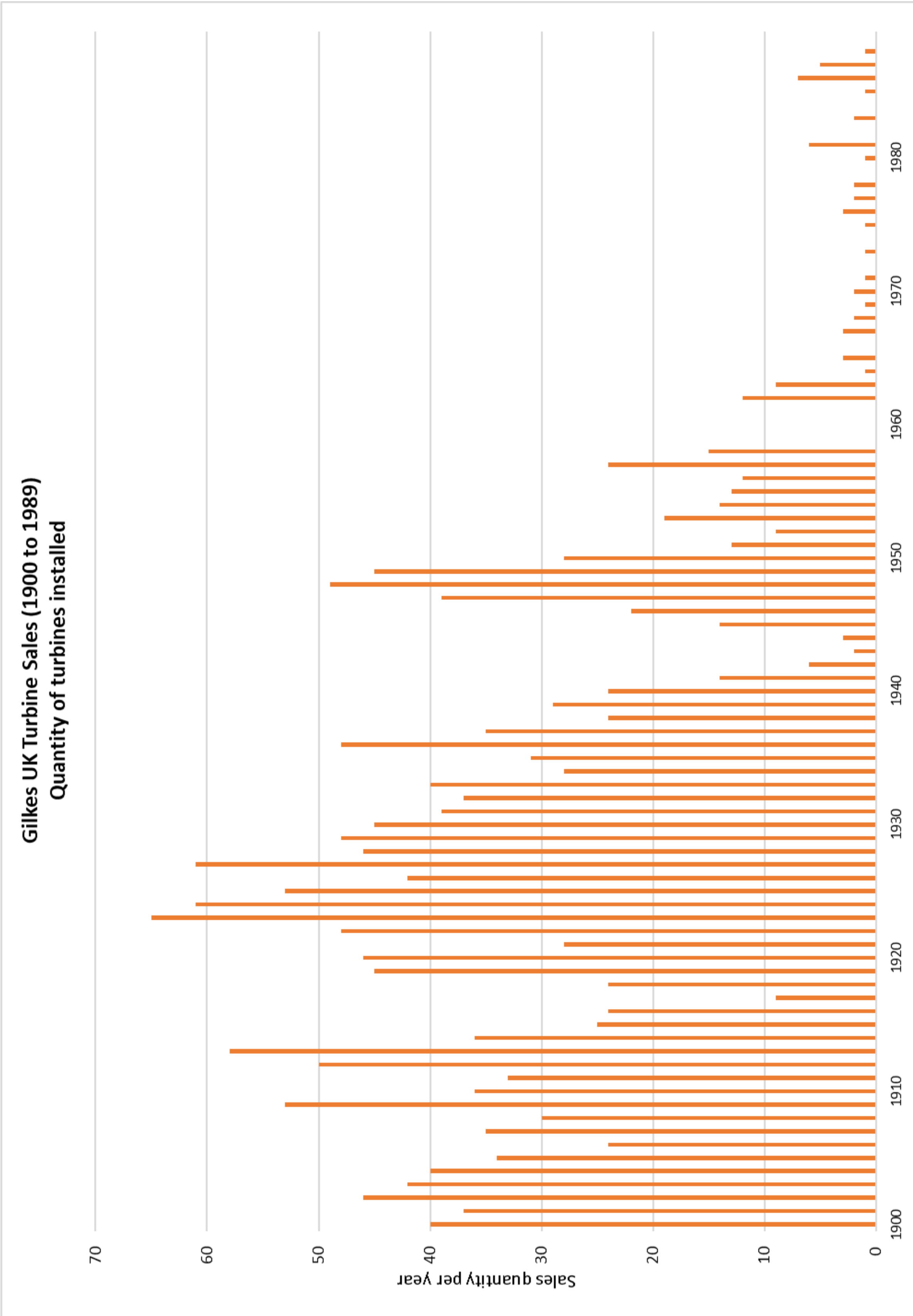


Figure 4.10 Gilkes turbines - UK sales 1900 to 1989 (Gilkes UK)

Despite the general decline in Gilkes' turbine sales across the UK between 1950 and 1989, in the DDC, ESCC, RJ&N in Ambergate and the Derwent Valley Water Board installed turbines at their sites. ESCC upgraded and consolidated HEP generation, investing in new, larger, turbines in the 1930s, 1950s and 1970s at the Milford, Belper and Masson Mill sites. The narrative of HEP decline during the mid-20th century is confused by this ESCC investment, as they continued to use HEP as a base power load until their site closures in the 1980s and 1990s.

An investigation of external events that impacted textile mills in the 20th century identified the Cotton Industry Acts (1936, 1939 and 1959). These Acts were a response to the significant challenges the important UK cotton industry faced, due to imports of goods and developments of alternative materials (Dupree, 1990). The Acts were designed to support the cotton industry to reorganise, modernise, introduce new thread materials and market British cotton (Clayton, 2010). Government grants, managed by the Cotton Board, supported the changes, including scrapping old machinery and buildings, and reducing the work force (PA HC Deb 29 November 1971). The Cotton Board's committee in 1959 included Sir Cyril Ernest Harrison, chairman of the ESCC (Singleton, 2004). New turbines installed by ESCC in the 1930s and 1950s in the DDC, may have been part of a wider government support programme, that, in Belper, led to the demolition of old mill buildings and the building one of the largest nylon stocking factories in the country (*The Financial Times*, 1961 9 November). Grants, supporting the transition from the mature and significant natural textile industries struggling to cope with cheap imports, to modern textiles, may have inadvertently helped to maintain HEP generation at key sites in the DDC.

In addition to the industrial sites, Gilkes water turbines were installed in the new, man-made, water storage and distribution networks in the DDC, to reduce electricity consumption at the individual locations, described as 'energy recovery' rather than energy generation by Derby Corporation and the Derwent Valley Water Board (County Borough of Derby, 1959). Gilkes turbines were purchased by the Derby Corporation for use in the treatment and distribution works in Little Eaton, (1927, 32 kW), Derby Water works (1949, 87 kW) and Spondon Reservoir (1959, 31 kW) (Table 4.2). The Derwent Valley Water Board had two pump-as-turbine sets (2 x 222 kW) installed in 1945 by the Harland Engineering Company (Table 4.2), recovering energy to power the pump transfer of water from Ladybower Reservoir to Derwent Reservoir (Street, 1950, STWA, 1978). These examples paralleled the way that the man-made water drainage soughs were used to produce waterpower during the age of mechanisation (Section 3.4.1.1), and how the Duke of Devonshire used his water garden feature at Chatsworth to generate HEP.

4.3 Electricity: Supply and demand

Whilst the self-generation of electricity for lighting for country houses or small industries could be met by waterpower, demand for electricity grew quickly, requiring public scale supplies, initially to provide street lighting.

4.3.1 Electricity – Lighting, transport and power

In the years between 1896 and 1903 electrical lighting spread to provincial towns in the UK, with every town with a population over 100,000, bar two, having an electrical supply by 1903 (Byatt, 1979 25). This supply initially supported public lighting schemes, with very few private residences lit by electricity by 1910 (ibid).

After lighting, the next big developments for electricity were the AC polyphase motor and a reliable DC motor (initially developed in the 1870s) from Tesla (Westinghouse) and Dobrowolsky (AEG) (Byatt, 1979, Hannah, 1979 15). The first application for motors was the replacement of horse drawn carriages by electrically powered tramways. Whereas the development of tramway electrification was effective in the United States, with 90% of tramways electrified by 1897, it took Britain a further 8 years to achieve this as a result of the initial legislation, the Tramways Act 1870, requiring private investors to hand over the assets to the local authorities after 21 years; that later changed to 42 years (Byatt, 1979 30). The first electric railway in the UK ran between Portrush and Bushmills in Ireland, with the electric option being taken, due to the abundant HEP available from the Portrush HEP station built by the waterfall of the River Bush, powering two 50 hp (37 kW) water turbines (Bowers, 1982).

This was also a period of experimentation for public utility regulation and municipal trading and enterprise, with mixed results. Many local authorities in larger towns were competent and progressive, and, whilst they weren't great pioneers or innovators, once shown the way they could follow the lead (Byatt, 1979). Although sales of electricity for power had overtaken those for lighting by 1909, and by 1913 had overtaken those for lighting and traction sales combined (Figure 4.11), most electricity used for power before 1914 was self-generated (ibid). Derby's coal fired power station electricity sales in the early 1920s shows the development of uses for power, lighting and domestic (15%), public lighting (1%), traction (9%) and power

(75%) (Electricity Commissioners, 1925). The UK was relatively slow in providing connections for domestic electricity use, with 18% of British houses connected to a power station in 1926, compared to 96.5% in Switzerland, 73.4% in Japan, 62.3% in Canada and 20.4% in Germany (Wilson, 2000 214).

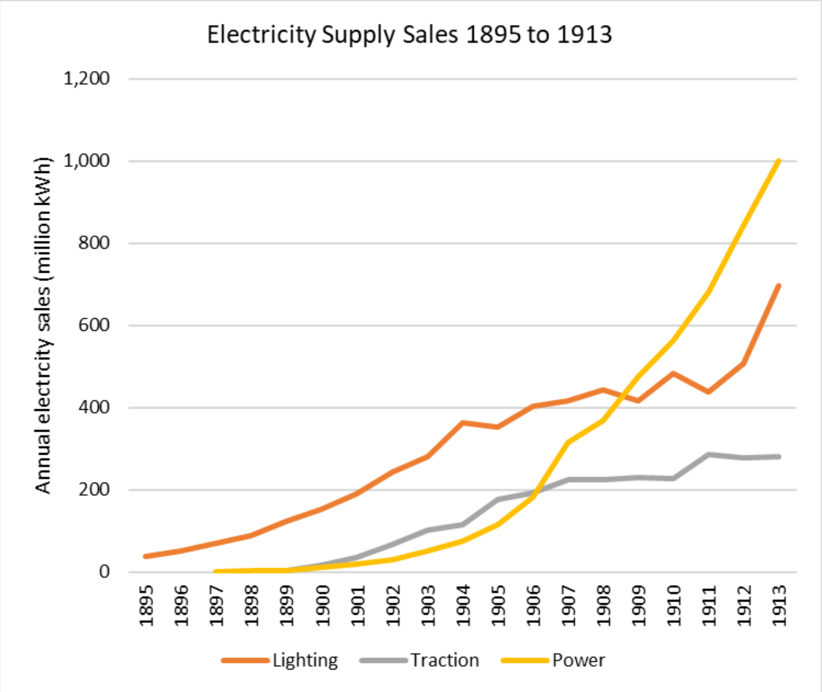


Figure 4.11 Electrical supply applications in Britain (Byatt, 1979 98)

4.3.1.1 Local electricity grids in the UK

The major expansion resulted from the use of electric motors in industry. The Manchester Corporation became a leader in the selling of electricity to large power users in 1894, and, by the turn of the century, factory inspectors were remarking on the extensive use of electricity for lighting and power in the factories they were visiting. Businesses saw significant benefits in switching to electricity supplied by a third party, including cost (incorporating depreciation and running costs of site plant), economy of space, cleanliness, ease of starting and stopping and general adaptability (Hannah, 1979 18). Expansion of the electrical supply network led to conflict and challenges, including competition between local authorities and private enterprises. A parliamentary sub-committee viewed the distribution of electricity by local authorities for domestic lighting, as quite different to the potential supply to large industrial users, so enabled the private companies to supply electrical energy over an area including many local authorities (Byatt, 1979, Hannah, 1979 25).

The benefits of economy of integration and scale were most obvious with the success of Newcastle-upon-Tyne Electric Supply Co (NESCo). The company developed from a local electricity supplier for lighting covering 16 square miles (40 km^2) in 1900, to running a power system covering 1,400 square miles (3,600 km^2) by 1914, introducing standard supplies and attracting new businesses, mainly associated with the shipping, transportation and supply of the coal to the power stations (Hannah, 1979 32). The NESCo network was the biggest integrated power system in Europe at the time, and its success in attracting future development could only be compared with the American system being powered by the cheap hydroelectric power of Niagara (ibid).

4.3.1.2 Local electricity generation and distribution in the Derbyshire Derwent catchment (DDC)

The waterpower site timelines identify two electricity suppliers in the DDC, the Derby Corporation, a municipal, and the Derbyshire and Nottinghamshire Electric Power Company (D&NEPC) (1901-1949), both relatively small compared to other supply undertakings across Britain by 1912 (Byatt, 1979, *Derby Evening Telegraph*, 1949b, *The Derbyshire Courier*, 1903).

D&NEPC

Local electrical power companies developed when opportunities arose, and, as their capacity grew, they were able to provide electricity to more remote areas (Strange, 2001 12). The D&NEPC's first steam power station was located in Ilkeston, to power the tramway and street lighting in 1903, with a second steam power station built in Newark to power 40 miles of electric tramways *(The Derby Daily Telegraph*, 1904 11 August). The D&NEPC submitted an application to Alfreton Council to supply electric lighting to Alfreton, Ripley, Heanor, Eastwood, and other towns in and around Basford, but the local newspaper reported that there was no chance, with so many councillors with interests in the local, competing, gas company (*Alfreton and Belper Journal*, 1914).

The original bill to set up D&NEPC in 1901 was supported by petition from rural districts, such as Stoney Middleton (Stoney Middleton Parish Council, 1901), but rural electrification took a while. Chatsworth House switched off their HEP turbines in 1936 to purchase electricity from the D&NEPC (Strange, 2001) once their local grid reached the Chatsworth Estate (Figure 4.12). D&NEPC became part of the larger Midland Counties Electricity Supply Company (MIDESCO) in 1922, as the coal-fired Spondon Power Station, a 'Super Power Station', became the primary electric power source for the Derbyshire and Nottinghamshire region (Heath and Hunt, 2017). The D&NEPC supply network map, for a project in 1940 (Figure 4.12), relied on the one power station at Spondon. From its original 12 MW capacity (2 turbines), the station was extended to have a capacity of 154 MW (8 turbines) by 1940 (ibid), supplying the electricity needs of Derbyshire. In general, apart from Newcastle, power companies were financially unsuccessful, with D&NEPC falling into the category of poorly engineered with small stations and small plant (Byatt, 1979 115).

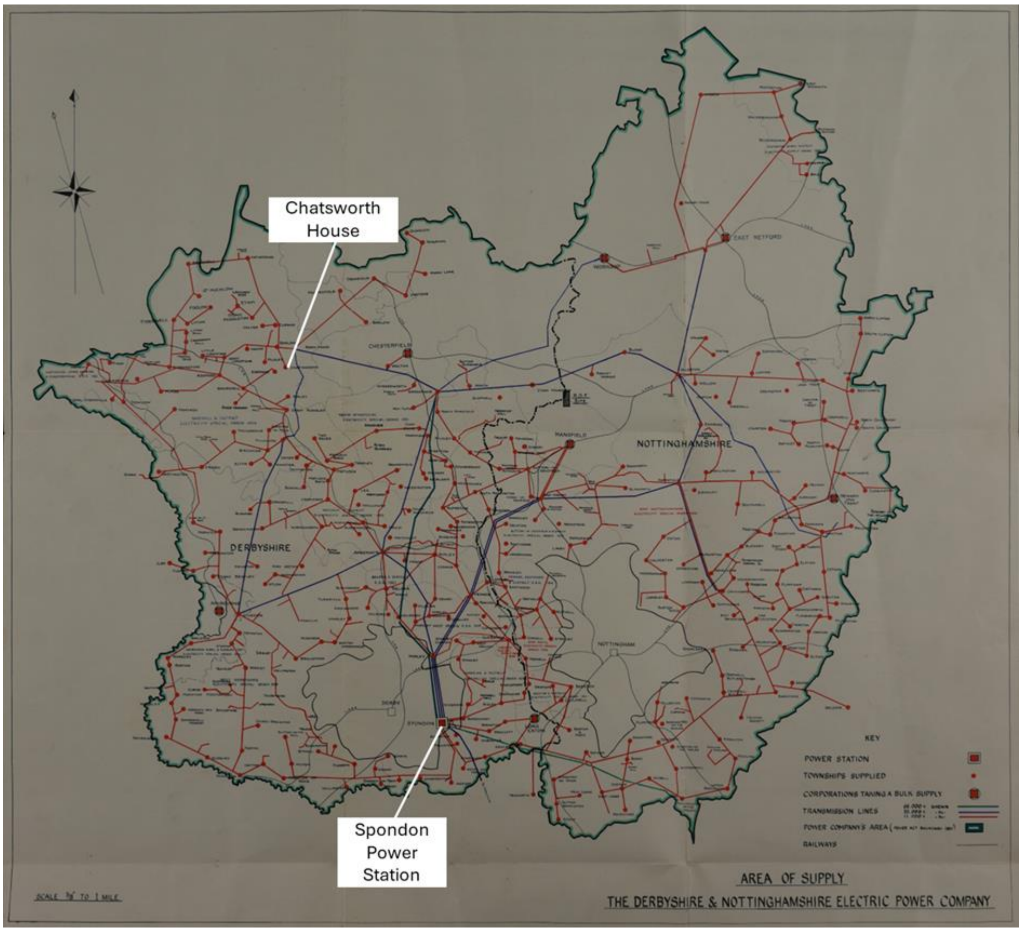


Figure 4.12 The D&NEPC 1940 network map (DRO D3184/M/1/28/1, 1940)

Adverts promoting D&NEPC during WWII included useful methods of managing limited resources at a time of crisis, which may be relevant as we transition to a low carbon economy with concerns over energy security. Measures such as minimum price control, energy efficiency and variable tariffs dependant on the type of use, e.g. lighting and industrial power, were introduced, with a reminder that ‘IT IS MORE THAN EVER ESSENTIAL THAT CONSUMERS SHOULD EXERCISE STRICT ECONOMY IN THE USE OF ELECTRICITY’ (*The Nottingham Evening Post*, 1943).

Spondon Power Station (British Celanese, Courtaulds and D&NEPC)

The development of fossil-fuel power generation during the 20th century can be seen in the D&NEPC Spondon site, located in Derby by the River Derwent. During its >100-year life it had many owners and technologies, generating power initially for self-supply, then local use and finally exporting to the national grid. As a fossil-fuelled power station it also illustrates the different scales of power production available.

Preparing for WWI, the British government invited the Swiss Dreyfus brothers to England, to build a factory to produce their newly patented product that would make aircraft wings safer, setting up British Cellulose & Chemical Manufacturing. Whilst most references suggest they built Power Station A, a coal-fired power station, in the 1920s, Hansard includes a reference to some of the £5 million government grant given to the company being spent on the power plant (PA HC Deb 4 March 1920), and the original two 6 MW steam turbines were installed in 1917 (Heath and Hunt, 2017). The coal fired power station produced electricity and steam to be used in the factory’s processes. Over the life of the manufacturing site (1916 to 2012) different products were manufactured, including coatings, textile fabrics (synthetic silk) and cigarette filters, that required both electricity and steam in their processes (ibid). Power Station A (1917 to 1980s) was purchased by D&NEPC in 1929 (Figure 4.13), supplying steam to British Celanese and electricity to the factory and the new local power grid. Spondon H (1959 to 2017), built to replace Station A, was a gas-fired power station producing steam and electricity for the Celanese site and some export to the Central Electricity Generating Board (ibid).

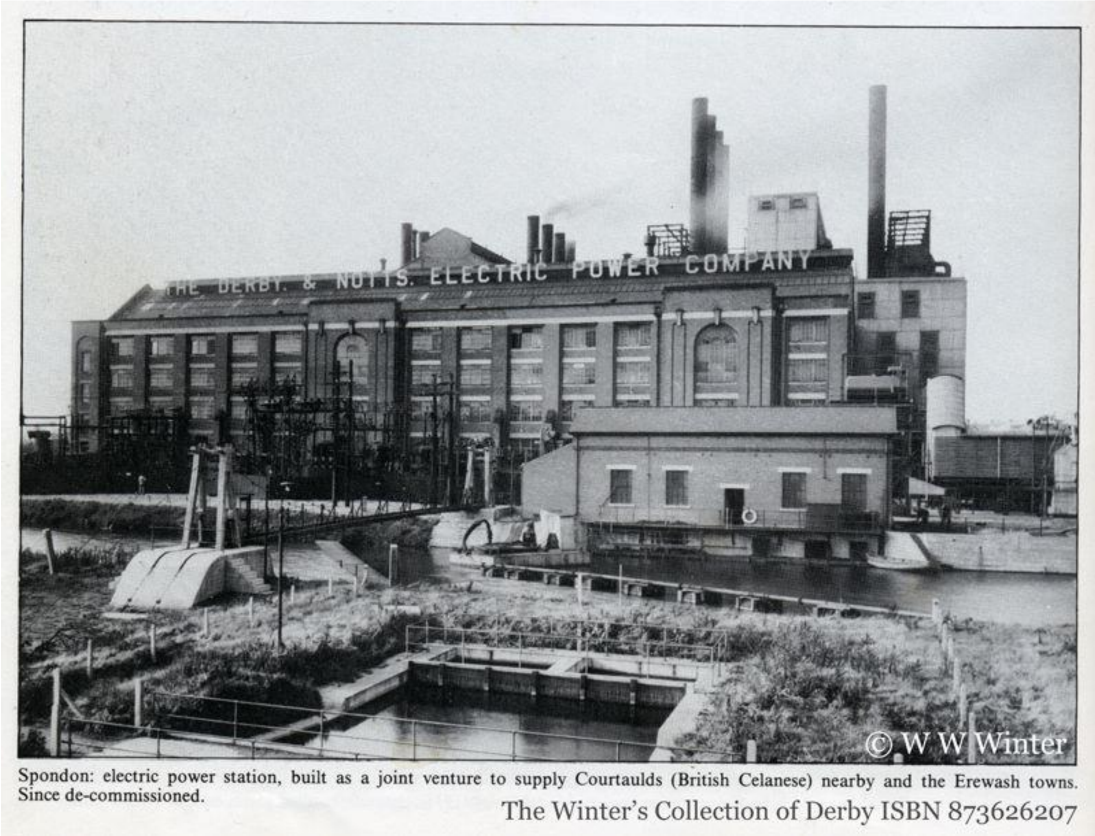


Figure 4.13 The Derbyshire & Nottinghamshire Electric Power Co. power station at Spondon (Copyright © The Winter's Collection of Derby)

Derby Corporation power station

Derby city's first electrical power station (1892-3), built to provide electric lighting, was on a site adjacent to a mill race that had a long history of water powering mills and pumps, including Sorocold's Water engine (1693) and Lombe's silk mill (1721) (Figure 4.14). In May 1892, approval was given to the Electric Lighting Committee's proposal to provide power to 7,500 eight-candle incandescent lamps for private lighting and 45 public arc lamps for street lighting (Figure 4.15) *(The Derby Daily Telegraph*, 1892). At the meeting the Hon. F Strutt asked if the use of waterpower had been considered, as there was no mention in the report, but he received the response that engineers had decided it would not be desirable to attempt anything but with steam power (*The Derby Daily Telegraph*, 1892).

Figure 4.14 1928 photograph of the Derby Power Station, with the Silk Mill in front (Source: Historic England Archive, EPW021122).

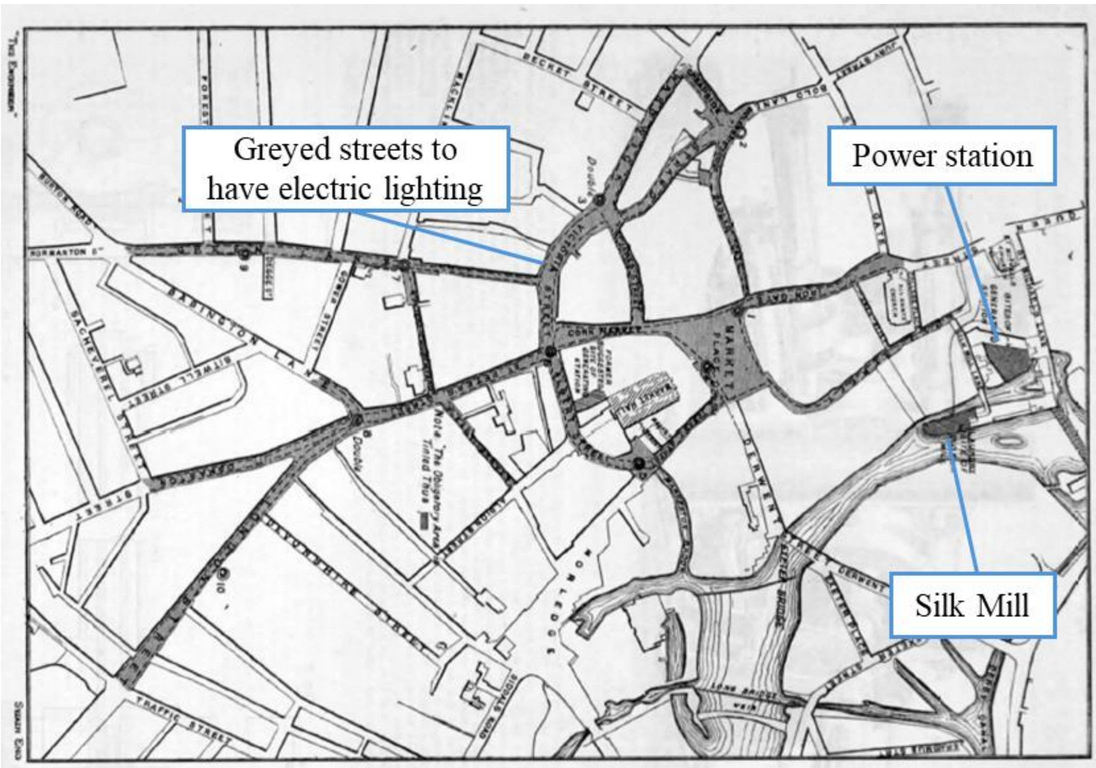


Figure 4.15 The Derby electric lighting supply area (*The Engineer*, 1893 330)

4.3.2 Fuelling the growth in electrical power

4.3.2.1 Pre-nationalisation (before 1948)

Estimates of the amount of wind, water and steam power used in Britain between 1760 and 1907 (Figure 4.16), show steam catching up and eclipsing the natural power forms of wind and water during the 1830s (Hills, 2008 185). They also show the dramatic rise of steam through the later 19th century and further acceleration c.1900, to produce electricity. By contrast, despite the extra demand for power, a decline in waterpower usage between 1870 and 1907 can be seen from c.1870 (Figure 4.17, ibid).

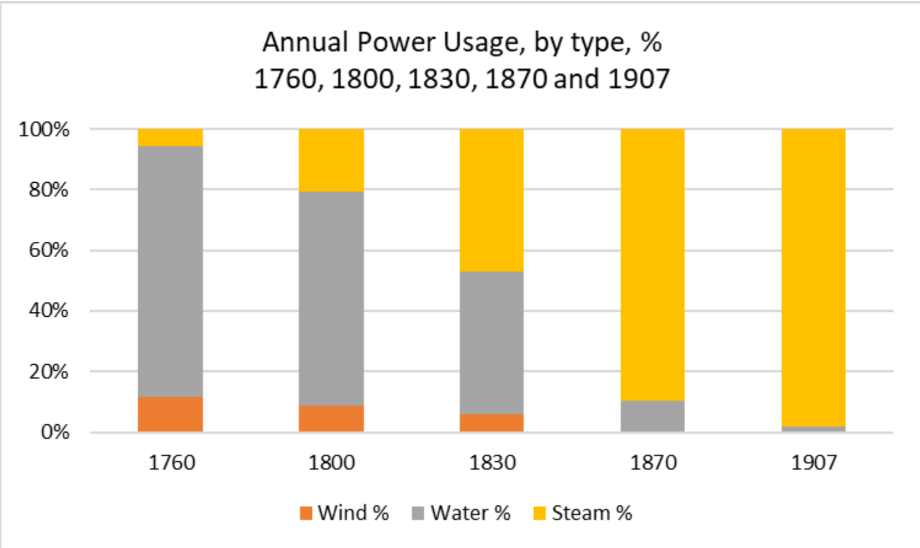


Figure 4.16 Estimates of wind, water and steam power usage in Britain, %. (Hills, 2008 185)

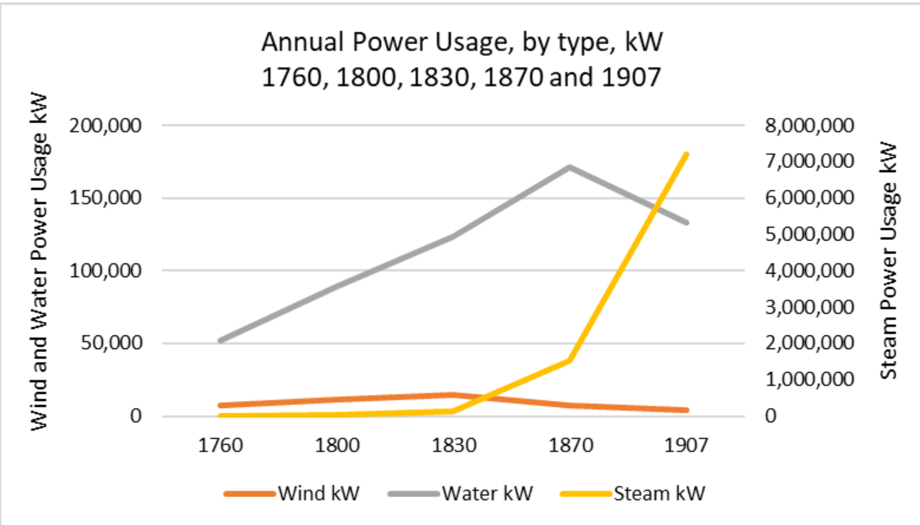


Figure 4.17 Estimates of wind, water and steam power usage in Britain, kW. (Hills, 2008 185)

An analysis of British industry electrification in the early 20th century (1907, 1912 and 1924) (Byatt, 1979), suggests that the DDC, which included a high proportion of textile manufacturers, may have been slow to transition to electricity (Figure 4.18). The textile industry maintained a higher percentage of self-supply of electricity (58% in 1924), compared to other industries (42%) (Figure 4.19) (ibid 74-76). This may be explained by the comparative maturity of the textile industry relative to some of the newer industries in the census data, with existing capital in mechanical power generation and distribution in place.

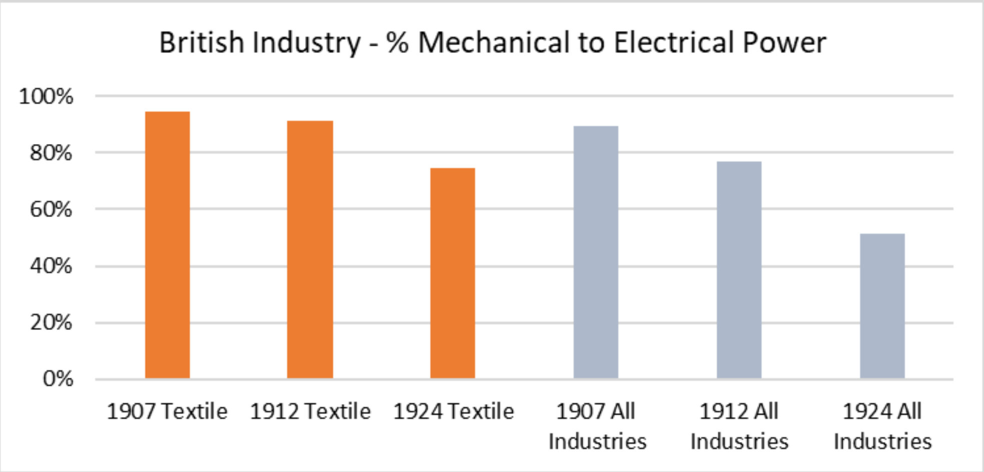


Figure 4.18 British textile industry's transition from mechanical to electrical power compared to other industries (Byatt, 1979 74-76)

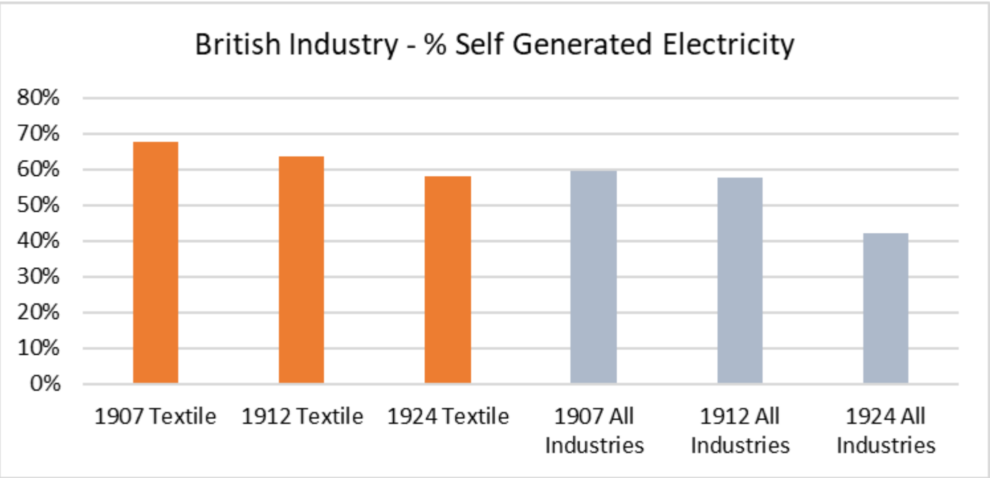


Figure 4.19 British textile industry's electricity self-generation compared to other industries (Byatt, 1979 74-76)

By 1913 the average power of electric generators installed was ten times larger (from 0.1 MW to 1 MW) than in 1895, due to the development of high-speed steam turbines (Hannah, 1979). The additional power demands could not be met by HEP sites that tended to be non-standard, with variability of flows and geographical challenges making sites' output difficult to predict, and the hydraulic structures (dams, reservoirs and powerhouses) being capital intensive (Reynolds, 2006 6). The larger HEP site developments also raised sensitive social and political issues: land rights, water rights, people displacement, fish protection, navigation rights and urban water supply demands (ibid). A few large-scale HEP projects were considered in the UK during this time, including harnessing the tidal waters of Britain (Gardner, 2008) and the Severn estuary (Hannah, 1979) (Section 1.3.1.7). Despite HEP being a limited resource in the UK, an article in *The Derby Daily Telegraph* in 1929 entitled 'New Electric Power scheme opposed: Miners afraid of decrease in coal output', suggests that the coal mining industry did see HEP as a threat. The article discussed the Miners Association opposing a bill before parliament, for the generation of electricity by water, to protect their jobs. Miners were aware that less HEP was being generated in Britain compared to the continent, but feared future extensive development might impact the coal mining industry (*The Derby Daily Telegraph*, 1929 9 March).

One of the most influential engineers of the day was Sebastian Ziani de Ferranti, who originated the idea of developing the larger coal fired power stations by rivers, building the Deptford station by the Thames, and gaining access to cheap river borne coal and cooling water (Hannah, 1979 11). In his presidential address to the Institute of Electrical Engineers in 1910, he explained a future vision that would be "all-electric", converting the country's coal reserves into electricity, generated in 100 large stations around the country (cited in Hannah, 1979 34). Due to the poor state of the electricity supply industry (too many small power units and too much variety in practise), state intervention in the electricity supply industry became a major political issue and, following changes of UK government and conflicting views of the future of the industry, in 1925 the Weir Committee was set up (Hannah, 1979 90). The UK was lagging behind countries like the United States and Germany, who had centralised generation, controlled by a small number of generating systems (Byatt, 1979 213, Hannah, 1979 93). In proposals for future development, consumption per head of electricity was viewed as a measure of success and compared with the international price of electricity. Interestingly, UK engineers believed comparisons with countries who had the advantage of cheap HEP sources should be discounted from the review (Hannah, 1979 93), rather than pursuing a policy of utilising more HEP.

The transition to a centralised, nationalised, electricity network required the setting up of the Central Electricity Board (CEB); existing power companies were allowed to continue to operate, but future power station planning, and the development of the national high voltage network, fell under the authority of the CEB (Hannah, 1979 93). This state-run network, operating alongside private electricity generators, may offer lessons for the current Net Zero transition. Full grid trading was agreed in The Electricity (Supply) Act 1926, with the CEB directing operations. Despite most of England starting to trade between regions in 1933-4, South Scotland didn't participate formally until 1937, as they had several large-scale hydroelectric schemes under development (ibid 121).

Post WWI, Scotland saw the potential and economic importance of the region's natural resources, with H. F. Campbell, asserting that 'the future of the Highlands depends largely on afforestation and the development of waterpower' (cited in Gardner, 2008 40). Having seen successful private (aluminium factories) large scale HEP developments in Scotland (Kinlochleven [1909] and Lochaber [1929] (Sample, Duncan et al., 2015)), Tom Johnston, as Secretary of State for Scotland in 1941, triggered a review to investigate the possibilities of further developing hydropower in Scotland (Gardner, 2008, Hannah, 1979 336). This ultimately led to the creation of the North of Scotland Hydro-Electric Board in 1943 (Hannah, 1982), which, after World War II, delivered the Scottish government's policy of electrification of the Highlands (Sample, Duncan et al., 2015). Despite Scotland's hydrological advantage, HEP still required low interest rates (due to the large capital costs) and high coal pricing for it to be competitive. The late 1950s stabilisation in coal prices, and improvements in steam technology challenged the economics of HEP (Hannah, 1982 153).

4.3.2.2 Post-nationalisation, 1948

Figure 4.20 shows the growth in electricity supplied by public companies between 1920 and 1988, from 3,976 GWh/year up to 27,871 GWh/year (BEIS, 2019). It also highlights the dominance of coal during this period, with HEP varying from 0.25% in the 1920s, c.3.25% in the 1930s-40s, c.2% in the 1950s-60s to c.1.25% in the 1970s-80s. Although only a small percentage, large HEP projects, primarily in Scotland, increased generation from 12 GWh/year (1920) to 3,297 GWh/year (1989). The introduction of nuclear electric power generation in the late 1950s can also be seen.

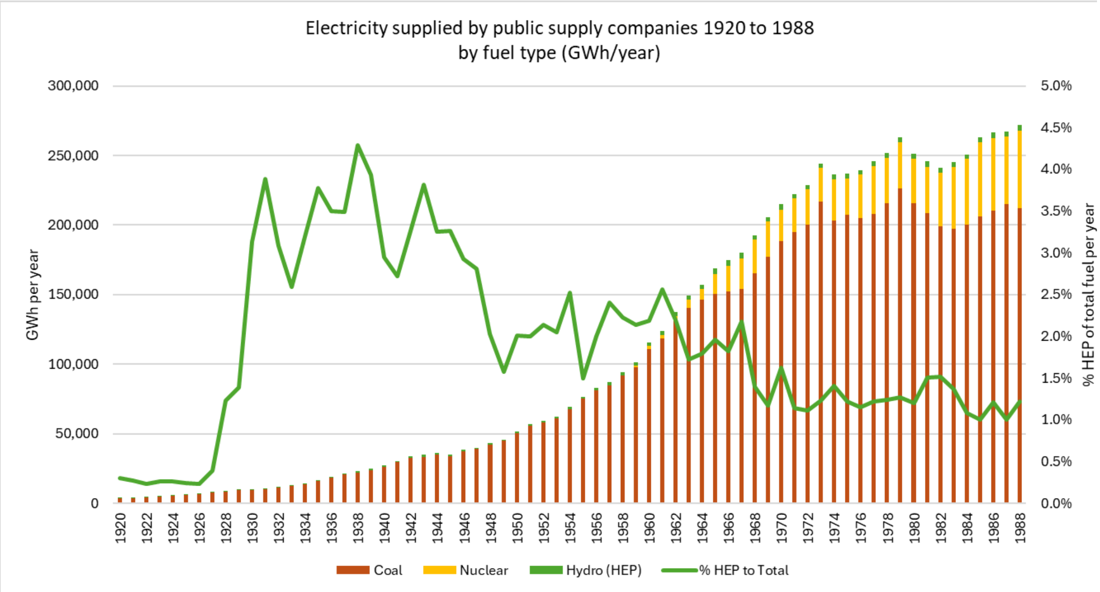


Figure 4.20 Electricity supplied in the UK by public supply companies 1920 to 1988 (BEIS, 2019).

Note: This data does not include locally generated power, including small HEP in the 1920s-50s.

As demand for electricity grew and the industry nationalised, larger coal fired power stations were built in strategic locations with access to coal and cooling water, such as the East Midlands coal fields and River Trent (Figure 4.21) (Rawstron, 1964). The post-nationalisation development focussed on supply operational efficiencies, rather than the pre-1948 local market demand, and enabled the closure of the early, large, power stations that caused heavy pollution problems in densely populated areas, (e.g. London) (Pedroche, 2013 167). Whilst coal was still the primary fuel, by 1962 ten stations had introduced oil-firing, and four nuclear power stations were operating (Rawstron, 1964).

A pumped-storage plant (using large scale HEP technology) had been inaugurated at Blaenau Ffestiniog, North Wales and the Scottish Highlands had a number of HEP stations (Figure 4.21) (ibid).

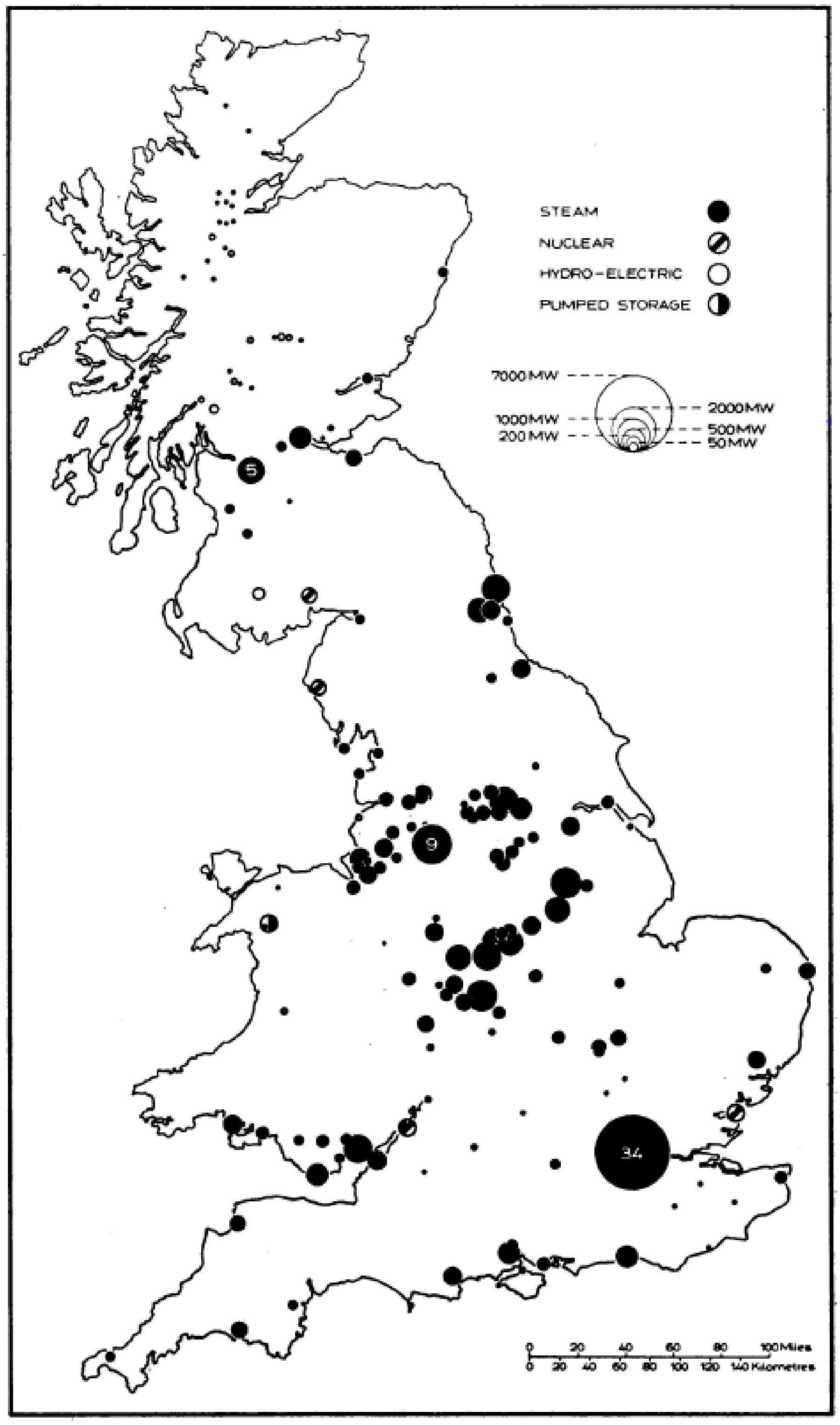


Figure 4.21 Installed capacity of power stations (over 10 MW) 1962, showing a cluster in the Trent catchment (Rawstron, 1964 305).

In order for the nationalised electricity board to sell electricity from its newly built power stations, tariffs, pricing structures (including exclusivity) and incentives were used, offering favourable terms for large users, such as ICI, who would accept interruptible supplies (Hannah, 1982 210). This may have been the situation at Richard, Johnson & Nephew (RJ&N) Wireworks, Ambergate, who were incentivised to accept switching off supply from the national grid, at very short notice and for a specific time-period (demand reduction), as part of an exclusive supply (no self-generation), agreement (S Charlton [ex-RJ&N], personal communication, 7 February 2015). This may also have been part of RJ&N's decision to remove their HEP turbines in the 1960s.

In assessing the reason for the decrease in water power usage by 1977, the National Association of Water Power Users group reported that, during an era when fossil fuel had been cheap and plentiful, many owners of turbines and water wheels had found that the power they could produce themselves was more expensive than fuel or power from other sources (ArkSoc NAoWPU, March 1977 1). The tendency to shut down small HEP was accelerated, with the Central Electricity Generating Board discouraging private power plants (Hannah, 1982 93, Slee, Whitfield et al., 2011).

4.3.3 Hydroelectric power potential in the UK (to 1989)

Section 1.3.1.8, discusses the disruption to the energy industry, with a number of challenges, such as the 1970s oil crises, leading to the setting up of the Department for Energy in 1974 (Lees and Eyre, 2021) and a search for UK owned, non-fossil fuel powered sources of electricity.

The Centre for Alternative Energy (CAT) aimed to plan a transition away from coal, oil and gas, which were rapidly exhausting, and to focus on the earth's energy 'capital' such as 'renewable energy', supported by energy conservation and improved energy efficiencies (Todd and Alty, 1978). Despite HEP being the only form of renewable energy available in any quantity in the UK at the time, run-of-river HEP wasn't included in CAT's future plans, as it would have required changes to existing water use legislation (ibid). This may be related to the 1973 Water Act that introduced water charges for mill owners, which were particularly high in Wales where CAT was based. Large water storage HEP schemes were included in the strategy, although CAT (1977-8) did raise concerns that, in addition to the capital cost of high-head reservoir HEP schemes, they damage countryside landscapes via the dams themselves, the flooding of valleys and diverting streams from their natural courses (ibid). The 1978 revised report concluded that the UK government would not move from its ‘more-of-the-same’ pathway, unless it was forced to change by dramatic events, such as another oil crisis or nuclear power accident (ibid).

Two further ‘official’ HEP studies for England and Wales were carried out for the UK government during this period, one by E E Francis (Department of Energy, 1978) and the other by the Watt Committee (1985), a critical friend of the government.

Francis’s 1978 report investigated small scale (up to 10 MW) run-of-river HEP opportunities in England and Wales and offers a snapshot of the HEP industry during the 1970s. HEP turbine technology developments had allowed larger (e.g. 100 MW) turbines to be built and connected to the national grid, competing with fossil-fuelled plants in Scotland. Economic modelling for 1978 was carried out on existing water authority reservoirs, but it was acknowledged that they ‘have statutory functions to supply water and to treat and dispose of wastewater’, so projects related to these responsibilities would always be prioritised over HEP developments (ibid 320). In terms of HEP resource size, Francis defined three categories, gross river potential (natural upper limit of a river), exploitable technical potential (technically usable over time, including man-made physical constraints) and exploitable economic potential (the fraction of technical potential that is economically feasible) (ibid 321). The gross river potential shouldn’t change dramatically over time, the technical potential changes with man-made river developments (e.g. dams, weirs, abstraction of water), and the economic potential changes radically and rapidly, due to the varying economics (energy pricing, costs and subsidies) versus competing energy sources (ibid).

The Watt Committee (1985) raised concerns that hundreds of unexploited HEP opportunity sites existed across the country (Wilson, 1985). Many HEP potential studies had been completed across different regions, with different scopes and criteria. The Watt Committee aimed to review these recent studies, under the gross, technical and economic categories defined by Francis (1978), to calculate UK HEP potential (ibid). Despite a considerable number of published and unpublished studies being reviewed, the Watt Committee declared there was ‘room for considerable error and the judgements made are inevitably subjective’ (ibid 2). The Watt Committee also identified a number of obstacles inhibiting HEP development, including the electricity authorities producing low cost, convenient electricity and not interested in small-scale developments (Corney and Baker, 1985). Some of the key obstacles to HEP highlighted in 1985, included, the water authorities not being incentivised to explore and develop HEP, grant systems focussed on innovative solutions rather than conventional technologies, and the formidable complex statutory requirements, legislation, and administration burden (ibid): these are relevant to challenges faced today.

All three reports include statements regarding the inaccuracies of their assessments and predictions, due to the difficulty in evaluating the large volume of individual HEP opportunity sites. The assessments are also complicated and restricted by the filtering of sites using changeable, ‘current’, economic criteria. Table 4.3 summarises the three reports’ findings.

Table 4.3 Summary of UK Hydro potential 1970s-80s studies

Centre for Alternative Technology 1977	
1977 assessment of UK installed HEP	1,300 MW generating 3,000 GWh/year
2025 projection (economic potential)	2,500 MW generating 6,000 GWh/year (inc. 1,000 MW in Scotland)
Francis 1978 (England and Wales)	
Gross potential opportunity	10,000 GWh/year
Technical potential opportunity (1/16th of Gross)	150 MW generating 600 GWh/year
Economic potential opportunity (nothing <50 kW)	130 MW generating 500 GWh/year
Watt Committee 1985 – Technical potential opportunity	
Scotland	generating 1,700 GWh/year
England and Wales (England = Water authority assessment x 4)	generating 716 GWh/year
UK	generating 2,416 GWh/year

4.4 Water: Supply and demand

1878-1989 was a period of change for the Derbyshire Derwent catchment (DDC) waterways, both physically and in their management. The upper Derwent Valley reservoirs, pumped water storage reservoirs, river gauging weirs, flood weirs and diversion weirs, were built during this period by the water undertakings and corporations, causing the catchment to become completely regulated by large structures.

A number of reservoirs had already been built during the 19th century, such as the Rivelin, Kinder and Fernilee reservoirs in the Peak District, to supply the growing cities of Sheffield, Manchester and Stockport (Edwards, Swinnerton et al., 1974), before the corporations of Derby, Leicester and Sheffield tried to build new reservoirs in the Derwent and Ashop valleys to store and supply their areas during 1898-1899 (Hallam, 2000). A contemporary Trent catchment report noted 'Water undertakers are scrambling over the hillsides, over-reaching each other to tap water supplies for domestic and industrial use before the other fellow gets or contaminates them' (Spicer, 1937 4). A combination of opposing and conflicting bills, and the objections from Nottingham Corporation and Derbyshire County Council, led to a joint bill, the *Derwent Valley Water Act*, 1899, which originally included plans for six reservoirs to be built in stages, starting with the Howden (1901 start) and Derwent (1902 start) dams (Bevan, 2004, Hallam, 2000). The planned Ronksley, Bamford, Haglee and Ashopton dams were never built, partly due to the Derwent Valley Board buying Derwent Hall from the Duke of Norfolk, allowing the larger Ladybower reservoir to be built (ibid). The Derwent Valley Board, created by the Act, was also obliged to construct and maintain aqueducts within the County of Derbyshire, to supply Derby, Leicester, Nottingham and Sheffield corporations and local authorities (Hallam, 2000) (DRO LS/628.1), and a tunnel was excavated under the Ladybower Gorge to take water to the Rivelin Reservoir, to supply Sheffield (Figure 4.22) (Bevan, 2004, STWA, 1978).

Two pumped water storage reservoirs were also approved and built in the DDC during the 20th century, Ogston Reservoir on the River Amber and Carsington Water on Henmore Brook (in the Dove catchment), both connected to the River Derwent north of Ambergate (TRA, 1973).

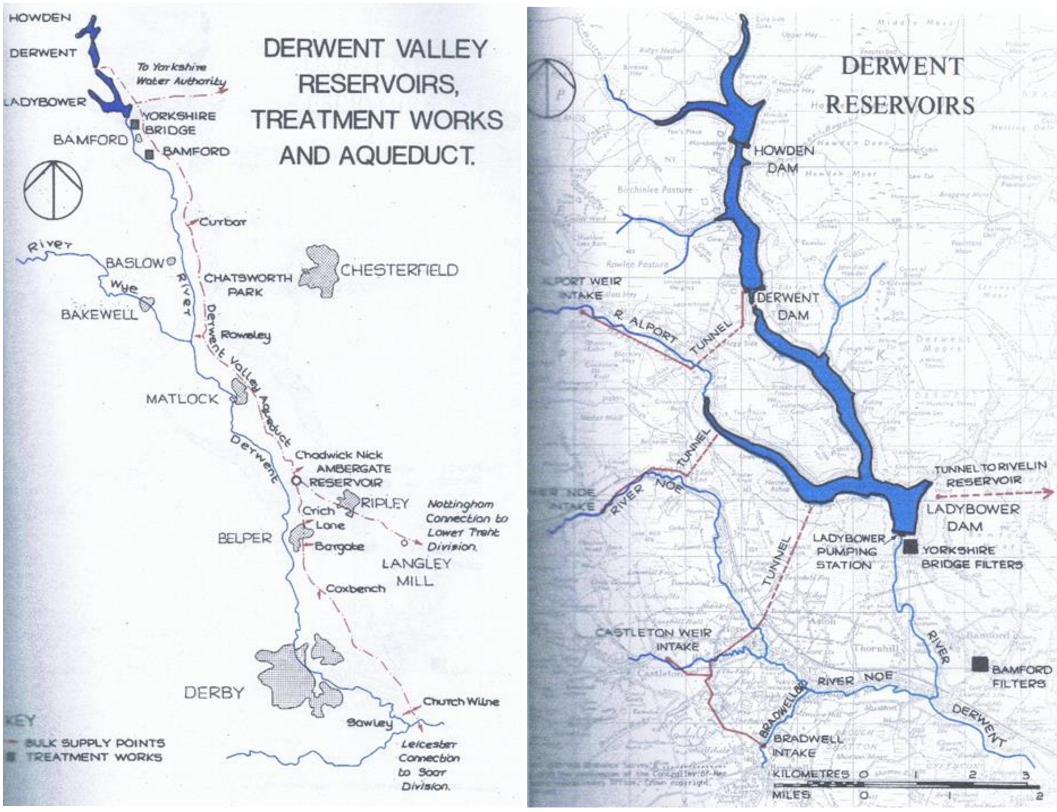


Figure 4.22 Derwent valley reservoirs, treatment works and aqueduct (STWA, 1978)

In 1971, national discussions took place to investigate the reorganisation of the country’s water and sewage services, proposing to set up 10 all-purpose Regional Water Authorities in England and Wales (TRA, 1972). The Water Act of 1973 dissolved the Derwent Valley Water Board, passing its responsibilities to the newly formed Severn Trent Water Authority in 1974, combining the Trent and Severn water catchments (TRA, 1973).

4.4.1 The Derwent Valley Act (1899, 1901, 1920, 1927, 1944)

The Derwent Valley Water Board (DVWB) was incorporated as a Statutory Water Undertaking as part of the *Derwent Valley Water Act* (1899) (DRO LS/628.1), with representatives from the four city corporations (Derby, Leicester, Nottingham and Sheffield) and Derbyshire County Council (DVWB, 1971). Revisions of the first Act accommodated changes to plans that required additional clauses, such as the 1901 revision a clause enabling compulsory purchase of specific mills and / or, their water rights if required (DRO LS/363.61 clause 16), and the 1920 revision allowing the abandonment of the smaller reservoirs and the building of the Ladybower dam (Hallam, 2000). The 1944 revision gave the Board powers to divert the waters of the River Noe into the Ladybower, impacting many water-powered mills (Eyre, 1988 94, Street, 1950).

4.4.1.1 Compensation flows

The 1899 Act and its revisions of 1901, 1920, 1927 and 1944, all included the volumes of water that could be abstracted to supply the different corporations, reducing the volume of water in the River Derwent available for other water users, including the industrial watermill owners. The Acts therefore included a clause requiring a minimum compensation flow to be released into the Derwent, at a minimum specified daily rate, which was based on six years of rainfall measurement in the catchment area. The Act required a ‘regular uniform and continuous flow’ throughout the day into the Derwent, equivalent to $^{1}/_{3}$rd of the annual available rainfall, which would be referred to as ‘compensation water’ (DRO LS/628.1 clause 52). The Act stated that the quantity of compensation water ‘shall be accepted and taken as full compensation to the several owners lessees and occupiers of mills works ….’ (ibid 29). The Board would be liable to make compensation for any loss, damage or injury sustained by any millowner impacted by failure to deliver the required compensation flow (ibid clause 53). There seems to be no consideration of the river’s ecology in the calculations of compensation flow.

The 1899 Act also included clauses protecting some of the major landowners affected by the reservoirs and aqueduct, including the Duke of Norfolk who owned Derwent Hall (ibid clauses 71-73). The Duke’s conditions include a clause offering the option of varying the compensation flow during the day, with the required flow from the Derwent Dam being allocated $^{2}/_{3}$rds during the daytime 8am to 8pm and 1/3rd during the night, 8pm to 8am or any variation as requested by the Duke of Norfolk (ibid clause 73 (5)).

Similarly, clauses 74 – 76 include specific provisions to protect the Fine Cotton Spinners and Doublers Association's (FCS&DA) Bamford Mills, requiring a minimum compensation flow of 18 mgd (0.95 m3/s); other owners with mills and factories on the Derwent, including the ESCC, RJ&N, Tempest & Son, Walter Evans and Co, Pegg & Co and Marcus Astle Ltd, were also offered protections regarding future water supplies. (ibid clause 75).

The later diversion of the River Noe into the Ladybower Reservoir did raise objections from the mill owners in the Derwent Valley. The diversion would impact many of the mills in the Hope Valley directly and reduce the flow to all mills on the Derwent below the Noe-Derwent confluence (Eyre, 1988). *The Derwent Valley Water Act* 1944 (DRO LS/363.63) included additional clauses relating to the mills that were still dependant on the use of water for their power supply, following a petition led by ESCC (PA HL/PO/6/33/94, 1944). Clause 21 included the 'protection' of the FCS&DA [Edale Mill on the River Noe], that the DVWB would be required to serve a compulsory purchase within 6 months of the passing of the Act. The owner of Hope and Brough Mills on the Noe received a payment of £8,000, based on accepting the new agreed compensation flow as a result of the DVWB having the 'power to take waters' (DRO LS/363.63 clause 22)(Eyre, 1988).

Clause 51(i) defined the compensation flow, now flowing from the Ladybower Reservoir, requiring the DVWB to discharge in a steady flow (at least 16,666,000 gallons [0.88 m3/s]), twenty-four hours of every day, into the Derwent. If the DVWB discharge was less than an allowable (e.g. drought) minimum flow, a payment would have to be made to the ESCC, on behalf of the scheduled companies (Table 4.4), based on every million gallons, or part thereof, lost, a sum based on 'the market price of three tons of coal delivered at Masson Mills, Matlock Bath' (one of ESCC's sites), with a minimum allowance of 14,965,000 gallons per day (0.79 m3/s) (ibid 36).

Table 4.4 The millowners on the River Derwent, 1944 (DRO LS/363.63 43)

Derwent Valley Water Act 1944	
The SCHEDULE referred to in the foregoing Act.	
Millowners on the River Derwent	
Owners	**Mills or Works**
Fine Cotton Spinners' and Doublers' Association	Bamford Mills
English Sewing Cotton Company Limited	Masson Mills Matlock Bath
	Belper Mills
	Milford Mills
Richard Johnson and Nephew Limited	Alderwasley Mills, Ambergate
Walter Evans and Company Limited	Darley Abbey Mills
Bleachers' Association Limited	Peckwash Mill Little Eaton
James Greaves Mudford, trading as J H Mudford & Son	Calver Mill

The River Noe diversion severely impacted the two corn mills owned by Marmaduke Hallam Eyre, who used the compensation money to install electric power to the site and attach a dynamo to one of his waterwheels, to add electric lighting in 1924 (Eyre, 1988 51). The Edale Mill, upstream of Brough and Hope, had already shutdown (DVWB compulsory purchase), but the Eyres were able to utilise the stored energy in the Edale Mill dam during a dry winter to match the power demand of their Brough and Hope corn mills. The Edale dam was filled overnight and released in the morning to arrive at Brough Mill at lunchtime, when their natural water levels were receding (ibid 86).

A 1968 correspondence between the DVWB and the Trent River Authority (who were introducing licencing and charges for water use, following the implementation of the 1963 Water Resources Act), records that the DVWB requested a 10% reduction in compensation flows to the minimal allowance levels previously agreed in the 1944 DVW Act (UoN RH/WR/S/5/10). Whilst no documents have been discovered confirming the change, a reduction in flow can be seen on the Yorkshire Bridge gauge flow chart from 1933 (Figure 2.15). It should also be noted, from

Section 2.3.3, that the compensation flow from Ladybower Reservoir is only one component of the total River Derwent flow, especially for the lower section.

Up to 1944, the Derwent Valley Water Acts (1899-1944) emphasise the importance of the water-powered industries downstream of the reservoirs and the need to continue to supply this fuel for the factories. The potential fine for non-supply was linked to the price of coal, highlighting the sites' alternative source of power, should the HEP not be available. Despite the compensation flows being agreed with the millowners, it appears that the reduction in flow did impact the Derwent mills, with the Belper Mills article (Section 4.2.2.2) mentioning the change in the water availability between 1910 (West Mill turbine installation) and the 1940s, reducing turbine HEP capacity from 400 kW to 250 kW (Copeland, 1991 573). One observation in the 1960s, relating to the quantity of small-scale HEP generation on the Wye and the Derwent, highlighted 'the Wye more than the Derwent, because of the great storage [Derwent Valley] reservoirs restricting flow to the latter', with Bamford Mill only producing a little power from the Derwent, and, at certain times of the year, only a third of its power needs (Edwards, Swinnerton et al., 1974 188).

4.4.2 Meerbrook Sough water supplies

The Meerbrook Sough, is an underground tunnel, originally constructed to drain the lead mines of the Wirksworth valley (Section 1.3.2.1). Long after the lead mining operations ended, the waters have continued to flow, along the five miles of tunnels discharging into the River Derwent at Homesford (Figure 4.23), between Cromford and Whatstandwell (Endfield and Van Lieshout, 2018, Oakman, 1979 Part 2, 53, Rieuwerts, 1966).

The boroughs of Ilkeston and Heanor bought the rights of the Meerbrook Sough Company in the late 19th century, and the Ilkeston and Heanor Water Board (I&HWB), constituted by Act of Parliament in 1901, was given powers to abstract up to 3 million gallons per day (0.13 m^3/s). Under different ownership, currently Severn Trent Water (STW) the site has developed to play a key role in supplying the hard water for the blending of water supplies across the wider Derwent Valley network, increasing abstraction levels up to 10 million gpd (0.44 m^3/s) in 1967 (South Derbyshire Water Board, 1970).

No information has been discovered showing whether there was any consideration of impact from the loss of water from the Derwent on the water-powered mill owners, or if the water board considered installing HEP, utilising the man-made sough water flow, in the design of the reconstructed water treatment works. No HEP is being harnessed by STW today from the Meerbrook tail at Homesford.

Figure 4.23 Meerbrook sough tail, main flow diverted to the right, supplying the STW Homesford water treatment works (Photograph: Author, 2021)

4.4.3 Ogston and Carsington (water [only] pumped storage reservoirs)

In 1954, plans for Ogston Reservoir, on the River Amber, were approved, aiming to supply water, at a rate of 1 million gallons per day (0.05 m^3/s), to the new National Coal Board's coal carbonisation plant, being constructed at Wingerworth (DRO D3040/LW/1/24, 1954). The report of the meeting references a compensation flow of 1 million gallons per day being required, based on an assessment of a 3.7 million gallons a day yield (0.19 m^3/s). Unlike the Derwent Valley Act, there is no reference to the impact the reservoir and compensation flow had on the water powered mills on the Amber and Derwent (below the Amber confluence). Ogston Reservoir was completed in late 1959, storing a maximum of 6.18 million m^3 and supplying water to North East Derbyshire District (Hughes, Kelham et al., 2004).

By the mid-1960s, sites were being investigated to improve water storage and security, using pumped water from the River Derwent, and the existing Ogston Reservoir was selected for the 'pumped storage reservoir scheme' (UoN RE/Pr/26). There was concern that, as RJ&N wireworks at Ambergate were no longer using the weir for power purposes, the river level required for the proposed upstream Derwent abstraction to the Ogston Reservoir, might not be maintained (UoN RH/WR/S/5/8 23 January 1969). One interesting design element of the proposed abstraction from the Derwent to the Ogston Reservoir, was the request from the Trent River Authority's Pollution Control and Fisheries Officer to install an electric fish barrier at the abstraction point, in preference to a small mesh screen, despite the 'fishing quality at this point is not of the best', to protect the mixed population of coarse fish and trout (UoN RH/WR/S/5/8 23 September 1970).

In order to further strengthen the water authority's water storage capacity and flexibility, the Trent River Authority confirmed the selection of Carsington as its site to meet the water needs suggested by earlier studies, requiring balancing between the Rivers Dove and Derwent, using a pumped storage reservoir connected to both water courses (TRA, 1973). Work started on construction in 1979 but, following delays in 1984 due to a partial collapse of the dam, a new dam was rebuilt in 1989, with the reservoir officially opening in 1992 (Figure 4.24).

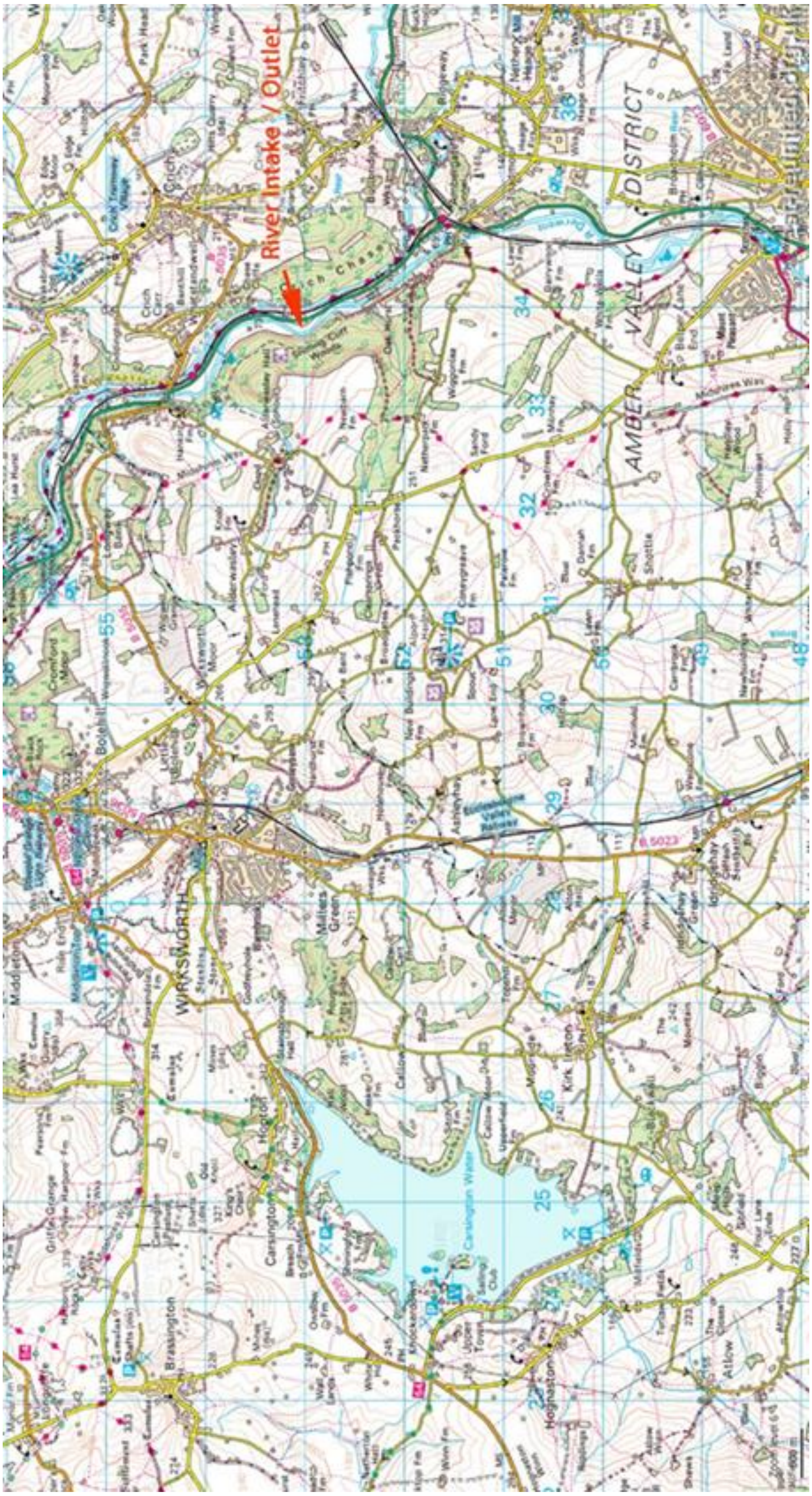


Figure 4.24 Carsington Water and the pumped abstraction point near Ambergate on the River Derwent (Digimap OS map)

Although the first ‘Pumped [Energy] Storage Hydropower’ system had been built in Wales in 1961, Ffestiniog Power Station (Bowers, 1982 172), there is no evidence that the North Derbyshire Water Board considered building either HEP generation or HEP energy recovery into the design of the Ambergate Pumping Station (Carsington and Ogston water storage reservoir feed) in the 1980s, as had been done at their Ladybower Reservoir.

One, more controversial, proposal was considered, building a ‘Superdam’ across the Derwent immediately downstream of the current Derwent Dam wall and 94 ft higher (200 ft in total), merging the Derwent and Howden dams and adding 8,000 million gallons (36,400 m^3) of water into the storage system (DRO D3040/LW/1/24/4 1977 317). The proposal came from a preservation society trying to block the construction of the Carsington Reservoir, but was opposed at the Planning Committee by The Peak Park Planning board in 1977 (STWA, 1977). Proposals to increase the volume of water stored at Ogston by raising the dam wall by 15ft were also made, but dismissed by Derbyshire County Council’s planning officer (DRO D3040/LW/1/24/4 1977). STW plans to improve water security today include a ‘superdam’ proposal similar to the 1970s idea, but have been blocked by current conservation groups.

4.4.4 Water use and charges

The Rivers Board Act of 1948, and the licensing regime of the Water Resources Act 1963, had the effect of restricting small-scale use of waterpower and stifled development of small-scale HEP generation (Brown, 2011 181). The 1963 Water Resources Act created River Authorities along with a Water Resources Board, replacing the River Boards and taking responsibility for conservation, re-distribution and augmentation of water resources for their area. The Act allowed charges to be made for water usage to fund improvement activities (UoN RH/W/2/2, 1967-68).

In response to the introduction of abstraction charges for the use of water to drive turbines, the National Association of Water Power Users (NAoWPU) submitted an Early Day Motion, via supportive MPs (14th January 1975). Motion 166, the need to encourage power generation by water turbines declared:

> 'That this house is concerned that the charges made in some areas, for the abstraction of water for use in power and electricity generating turbines, is both preventing new turbines from being installed and causing existing turbines to be taken out of use; finds it hard to understand how this use, where all water is returned to the watercourse, can be described as abstraction; and urges the Government to take steps to ensure that the licensing system encourages an increased use of water turbines' (ArkSoc NAoWPU 1975 np)

Inconsistent charges for different regions impacted on HEP generation geographically. It would appear that Wales was particularly challenged, with one small HEP installation in the Welsh National Water Development Authority seeing water charges increase from £100 to nearly £15,000 per annum overnight, with no right to appeal. These charges were reduced, slightly, after a bitter battle in the media, with the NAoWPU (Section 4.7.1) eventually succeeding in amending legislation (Brown, 2011, Daily Post, 1981, Watts, 2000, Weekly News, 1980 8 May, Weekly News, 1981).

Different regions were able to develop their individual charging schemes based on a classification system of water users. The Association of River Authorities' guidance on water charges recommended that the four criteria to be considered should be (UoN RH/W/2/1 1968 4-5):

a) The characteristics of the source of supply.
b) The season of the year when the water is abstracted.
c) The purpose for which the water will be used.
    a. The amount not returned.
    b. High abstraction rate.
    c. A deterioration in the water quality, impacting on subsequent abstractions.
d) The method of disposal of the water after it has been used.

The Trent River Authority's engineer, Marshall Nixon, appears to have acknowledged the minimal impact waterpower had, creating Class 5: Milling, describing it in his proposal:

> 'Finally, referring to Class 5 in respect of Milling, it is not suggested that any measurable quantity of water is consumed in the production of power

at a mill. If it is agreed that water used at a mill involves legally an abstraction of water, then clearly a nominal charge should be levied since the mill requires a certain quantity of water to be available in the stream. The ration of 1/1000 to Class 1[1], that is a reflected 0.1% loss, is without doubt purely a nominal rate of charge and reflects the effect on the resources in that certain quantities of water have to be retained in the streams in the mill reaches' (UoN RH/W/2/1 11).

Direct Cooled power stations, such as Derby power station, incurred losses of 72% due to water evaporation (UoN RH/W/2/1). Taking selected (large users and power generators) entries from the 1969-1974 records of the Trent Rivers Authority, shows that the power stations were taking, and evaporating, the same amount as half of the water being abstracted for the public water supply in the whole Trent Rivers Authority area (Table 4.1). The records also highlight the insignificance, volume and value, of the Milling Power water abstractions (UoN RH/W/2/3).

Table 4.5 Trent River Authority – 1969-74 water abstraction data (ibid)

Class		Abstract Licences	Est. Abstract 1,000 gallons (% of Total)	1969/70 £	1970/71 £	1971/72 £	1972/73 £	1973/74 £
1	Electricity Cooling Evaporation	18	13,771,611 (25%)	98,728	98,982	94,668	127,154	142,890
2	Water Public Supply	151	26,180,438 (48%)	187,692	188,175	179,972	241,733	271,647
4	Electricity Cooling Circulated	24	4,701,392 (8.7%)	33,687	33,774	32,302	43,387	48,756
5	Milling Power Production	38	172,974 (0.3%)	1,245	1,248	1,194	1,603	1,802

Whilst the abstraction costs for the DDC appear to have been relatively low, the new abstraction licencing process allowed the river authority to introduce conditions, such as agreed abstraction quantities and flow rates, which continue to impact on the development and use of HEP today.

[1] Class 1 being the cooling water evaporation from the coal fired power stations and irrigation water for the agricultural sector with significant losses (UoN RH/W/2/2, 1968)

4.5 Waterways: Environmental impacts

Waterpower and the quality of the waterways, including the fisheries, do not appear to have been high on the priorities for the Derby Corporation or the Derwent Valley Water Board during the first half of the 20th century. Prioritising the growth of cities and industries led to the waterways, completely regulated by large structures (Petts, 1990), being used as a supply of drinking water and a carrier of domestic and trade effluent. Changes also took place to reduce the impact of floods and droughts on cities such as Derby. The annual reports of the newly formed water authorities responsible for the Trent catchment (Trent River Board [TRB], 1953-1965; Trent Rivers Authority [TRA], 1966-1973; Severn Trent Water Authority [STWA], 1974-1982), record the changes and development of the Derbyshire Derwent catchment (DDC), during an under-researched period, the mid-20th century.

Historically, industrial expansion had been encouraged, for the good of the country, with little regard for the impact on water resources and, during the 1930s, local authorities were building cities with ‘no provision for the treatment of the waste products of such colonisations’ (Spicer, 1937 4). The legal profession was busy during this period, with competitors fighting over water supplies or locating ‘polluting’ agencies above them in the watershed, sometimes prohibiting industrial development (ibid). Later, work to reduce the impact of pollution on the River Derwent was delivering improvements, with Severn Trent Water Authority biologists carrying out studies in the 1980s into the reintroduction of salmon into the River Trent (DCAC, 1986).

By 1978, internationally, there were concerns about the impacts of fossil fuels and nuclear fuels on the environment, and small scale HEP compared favourably, as ‘an indigenous secure renewable energy source having minimal impact on the environment’ (Francis, 1978 318).

4.5.1 20th century dams and weirs in the Derbyshire Derwent catchment

In addition to the water storage reservoirs of Howden, Derwent and Ladybower (Section 4.4.1) and the pumped storage reservoirs of Carsington and Ogston (Section 4.4.3), several 20th century weirs were constructed on the River Derwent, to support water supplies, flood control and land reclamation (Figure 4.25). Of the new weirs and dams, only the Ambergate wireworks (replacement weir and continuation of HEP) and Ladybower Reservoir (new) generated HEP before 1989. The site walk-over of the Derwent and weir timeline development (Section 2.2.5), highlights that none of the 20th century dams or weirs incorporated fish passage in their design, including the Whatstandwell river gauge, built for the Carsington Reservoir project in the 1992.

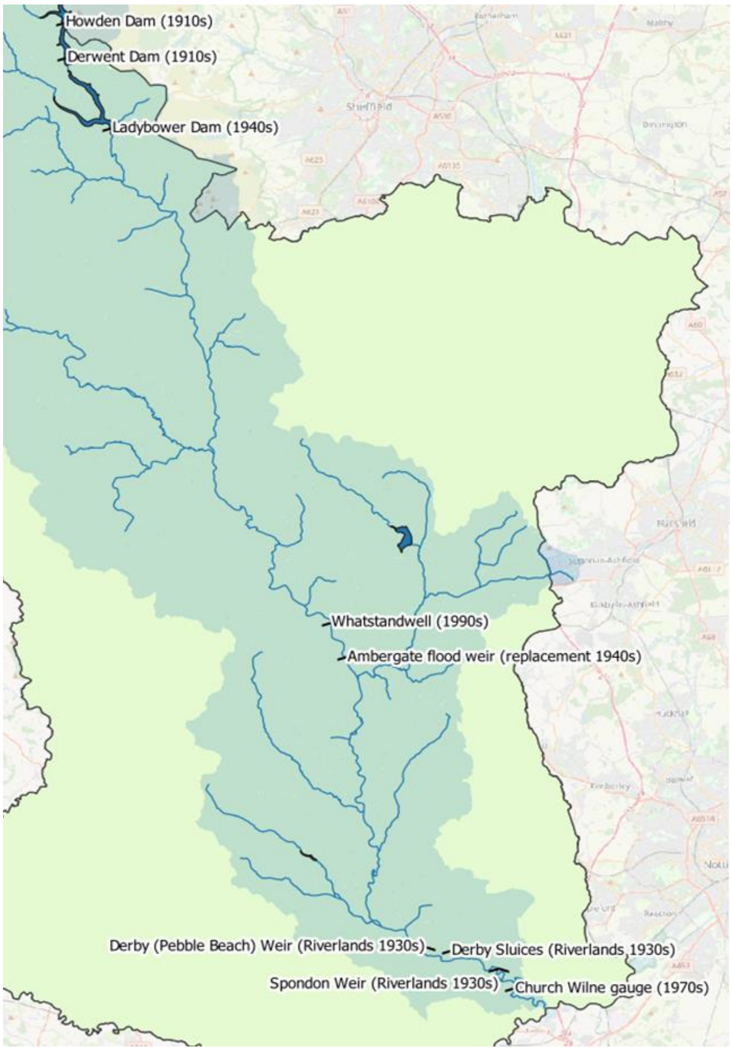


Figure 4.25 20th century dams and weirs built in the DDC

4.5.1.1 River gauging weirs

As part of the river management systems, gauging weirs were constructed in the DDC, none of which incorporated HEP generation in their design and with conflicting observations on their fish pass-ability.

Following the removal of the Church Wilne mill weir (date unknown), the first obstacle faced by migrating fish from the Trent is the Church Wilne river gauge (1973) (Figure 4.25, Figure 4.26), monitoring flows for the nearby water abstraction point (NERC, 2008 75). In 1985, a Severn Trent Water study, looking at returning salmon into the River Derwent, classified the weir as ‘D’ (passable at all flows) (Cowx and O'Grady, 1995). Tim Jacklin, the Conservation Officer of the Wild Trout Trust, clarified the classification, in that strong swimming salmon may be able to pass the obstacle, but less capable swimming species and fish like the barbel, that are capable but don’t in practise cross it (behavioural barrier), are impacted by the weir (T Jacklin, personal communication, 23 September 2021).

Figure 4.26 Church Wilne river gauge weir (Photograph: Author, 2022)

Two other 20th century gauging weirs on the River Derwent, were associated with the new reservoirs, the Yorkshire Bridge measuring weir (28001) was constructed in 1905 (National River Flow Archive, 2024), linked to the upper Derwent Valley reservoirs and the Whatstandwell gauging weir to measure flows before the Carsington Reservoir abstraction point. The Whatstandwell gauge, constructed in

1992, will be discussed further in Section 5.5.3, including the retrospective (2014) addition of a fish pass. The research walk-over survey also identified gauges installed on the main tributaries, (e.g. Rivers Wye and Amber) and on existing weirs (e.g. Derby's St Mary's Bridge) to assist in river management (NERC, 2008).

4.5.1.2 Flood management weirs

Richard, Johnson & Nephew (RJ&N), Ambergate, replaced their historic weir in 1949 (Figure 4.27), as part of a post WWII modernisation project at the site, that, in addition to creating a head for the HEP turbines, would 'eliminate flooding' on the site, with three controllable gates (Derby Evening Telegraph, 1949a)(UoN RE/DP/576). In 1954, a similar replacement weir, with five moveable 'flood sluices', was designed for the weir at Peckwash Mill, to reduce the impact of floods on Duffield (Derby Evening Telegraph, 1935) (UoN RH/Pk/7/2 drg.735). As a result of Peckwash Mill having stopped HEP generation during WWII, the weir was viewed as redundant and partially removed, saving the cost of the new weir, but effectively stopping its use for HEP generation at any point in the future.

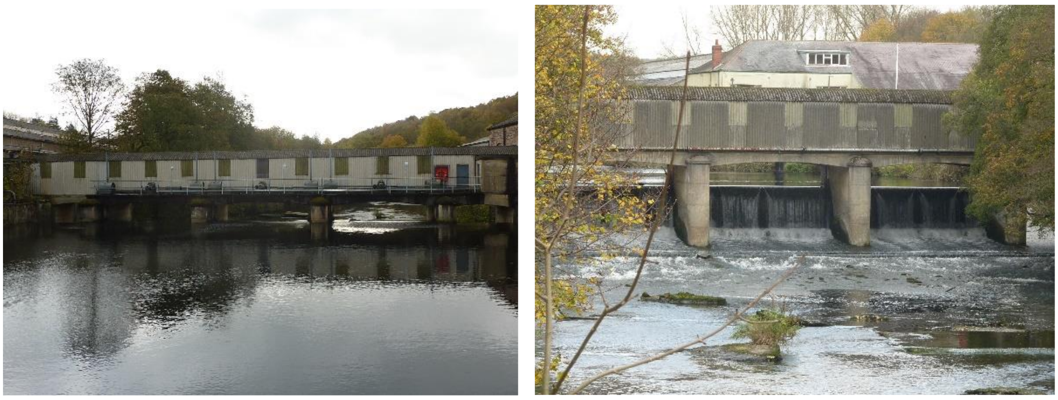


Figure 4.27 RJ&N new weir, Ambergate (Author, 2011)

Several 'industrial revolution' weirs were removed in the 1960s, such as Matlock Dale weir that powered a paint works and the St Mary's Bridge weir, Derby (Figure 4.28) that diverted water to Sorocold's water pump (1692) and powered Cotchett's (1704) and Lombe's (1717) silk mills (Section 3.2.1). The Derby weir was not maintained and, due to the risk of damage downstream during a flood if it failed, it was removed (*Derby Evening Telegraph*, 1968 11 July).

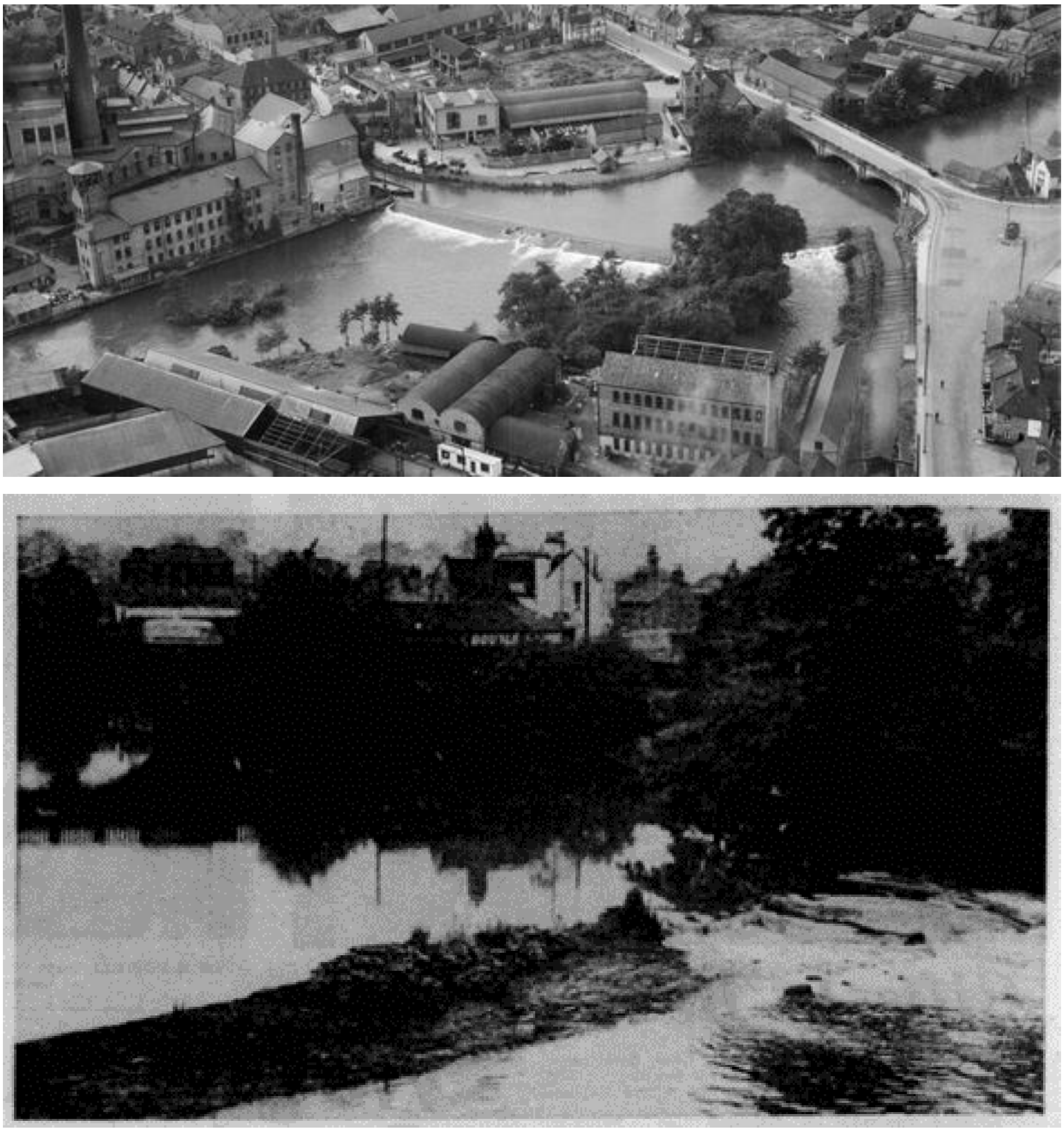


Figure 4.28 St Mary's weir Derby 1946 (Source: Historic England Archive, EAW002467) and 1968 (Derby Evening Telegraph, 1968)

The Derby Riverlands Scheme

The Derby Riverlands Project (1929-1934), proposed in 1919, changed the course of the River Derwent south of Derby, introducing three additional weirs (Farnsworth, 1919, The Engineer, 1920 12 November). The project was linked to flood protection for the city, but a key factor in its design and implementation was land reclamation, for the future development of industry in the city and roadway development. Edward Raynes, chair of the Borough Development Committee, believed ‘the greatest hindrance to industrial development of Derby had for many generations been the constant menace of flooding', launching the 'battle for reclaiming Riverlands' in 1919 (Derby Evening Telegraph, 1948 18 February). There appears to have been little, if any, consideration of HEP generation or river ecology in the project.

Following an extensive survey of the low-lying land by the River Derwent to the east of Derby, A W Farnsworth produced the '*Reclamation of Derwent River Valley Lands*' report (1919). Farnsworth's study started at the weir in Belper, and went to the Trent confluence at Sawley. It included interviews with weir attendants, who were generally old men who had studied and controlled the flow of the stream for many years (Farnsworth, 1919 4). Information regarding floods was captured, including marks on walls of high flood events, and the systematic record of all floods, as kept at Strutt's Mill at Belper [operated by the ESCC at the time of the survey] (ibid). The proposal aimed to free up over four km^2 of 'swampland', subject to flooding, to be developed on the east of the city, to include new roadways and land development for Derby Corporation to receive annual income (Farnsworth, 1919). The 'improvements' proposed included cutting off three large meanders in the River Derwent, but, to maintain river levels, three weirs were required, to effectively compensate for the natural fall in the river between the beginning and end of each bend, preventing scouring of the riverbanks and allowing land drains after the weirs to be maintained (Figure 4.29) (The Engineer, 1920 472). Ten years later a second engineer's report on the scheme, accommodating a much larger flood volume, and including three bypass roads to accommodate the new volume of traffic, was produced by Binney (The Derbyshire Advertiser, 1929 2 August). It was approved and included in the 1929 Derby Corporation Act, with specific information relating to river and weir levels (Derby Evening Telegraph, 1942 5 August, Derby Evening Telegraph, 1948). The impacts of the river modifications were captured by Historic England's aerial images (Figure 4.30). The development of the east of Derby facilitated by the Riverlands scheme is obvious, with the Pebble Beach weir as a reference, (Figure 4.30). In 1932 the completed scheme was tested by a great flood, which inundated the City of Derby (2.1 metre in the Corn Market), but did not extend to the Riverlands (Derby Evening Telegraph, 1948 18 February).

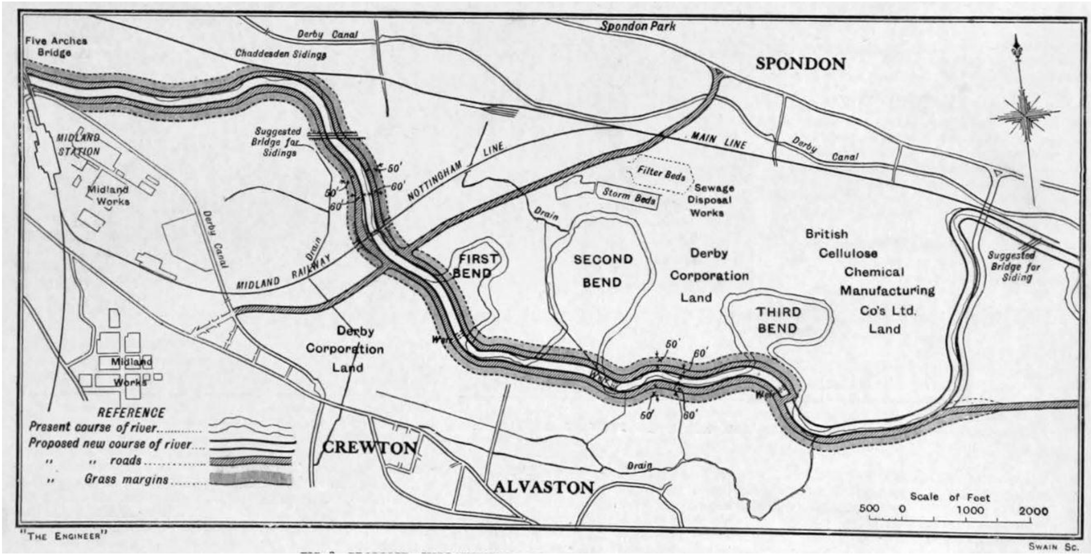


Figure 4.29 The original design of the Riverlands scheme (The Engineer, 1920)

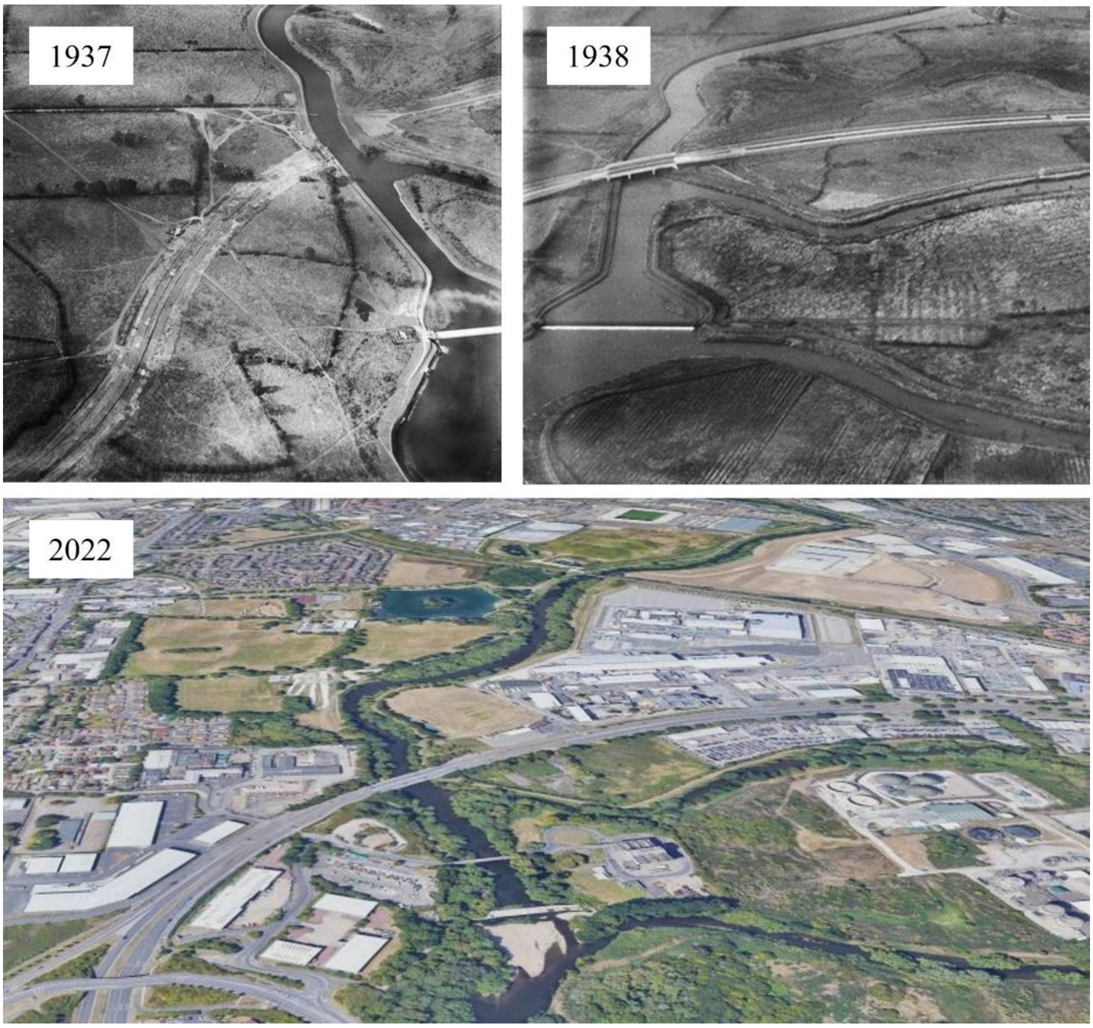


Figure 4.30 'Pebble Beach' weir, 1937, 1938 (Source: Historic England Archive, EPW055797, EPW060253) and 2022 (Google Earth 13/08/2022, Camera 495m 52°54'09"N 1°25'26"W 42m)

4.5.2 Pollution

The industrial weirs were identified as the primary reason for reductions in the salmon numbers during the 1860s inquiry, but just a few years later it became apparent that it was the pollution of the waterways that effectively halted salmon migration in the Trent catchment, including the DDC (Section 3.5.4). Evidence, below, shows that the pollution didn't improve significantly until the 1970s, suggesting that the lower River Derwent was unable to sustainably support certain fish, such as salmon, for approximately 100 years. River pollution reports mention the discolouration of streams and smell, but it is the 'destruction of fish' that appears to be the measure of how bad pollution discharges were.

Towards the end of the 19th century incidents of the destruction of fish by the discharge of poisonous liquid from the Ambergate Wire Works, and the pollution of Oakerthorpe Brook by discharge of sewage from the Alfreton Urban Sanitary Authority, were reported (The Field, 1889 27 July). The 1899 meeting of the Trent Board of Conservators, reporting on the disappearance of salmon and poor state of the fisheries in general, referenced 'thousands upon thousands of fish killed by sewage of Nottingham going into the Trent', but Major Pochin observed that 'the dirtiest stream he had ever seen was the Derwent below Derby' (The Field, 1899 25 March). Derbyshire fishing guides from the turn of the century referenced 'pollutions from mills and manufactories', and the River Wye affected by drainage, contamination and sewage, as well as new sewage works being planned or built in Matlock and Belper (Gallichan, 1905 21).

A Trent Fishery Board report described the Trent as 'a common sewer' in 1927, with signs of improvement between 1927 and 1937 (Spicer, 1937 3). The report was a first attempt to understand the river ecology issues and Spicer suggested the only reason the Derwent below Derby supported any fish life, was due to the large artificial silk factory [British Celanese] working to reduce its own impacts (ibid 5). Spicer produced the first Trent catchment map (Figure 4.31), showing the quality status of each waterway, with each section receiving a classification based on biological and chemical assessment. The map includes the sewage discharges (in gallons per day in dry weather) in the catchment, with principal industries noted in the DDC waterways (Figure 4.31) (ibid).

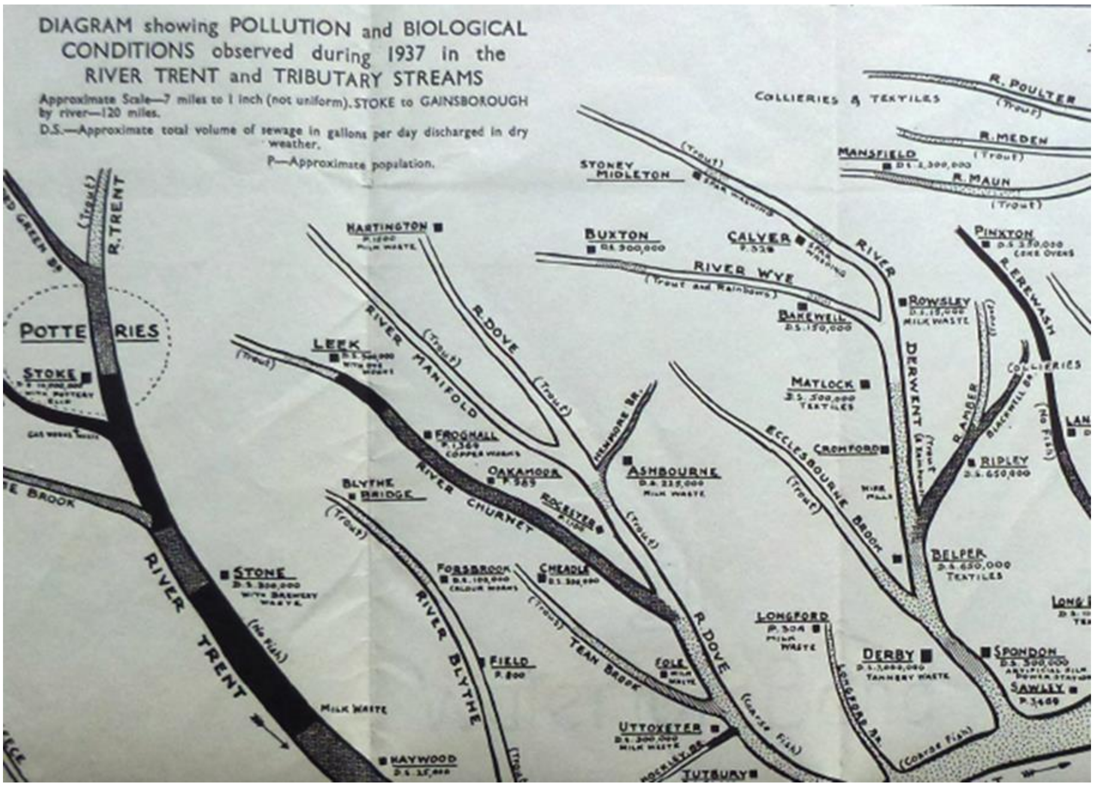


Figure 4.31 The first Trent catchment map identifying biological status (Spicer, 1937)

Table 4.6 DDC waterways pollution discharges in 1937 (Spicer, 1937)

Location	River	Gallons/day	m^3/s	Industries
Buxton	Wye	900,000	0.047	
Bakewell	Wye	150,000	0.008	
Rowsley	Wye	15,000	0.001	Milk waste
Matlock	Derwent	500,000	0.026	Textiles
Ripley	Amber	650,000	0.034	
Ambergate	Derwent			
Belper	Derwent	650,000	0.034	Textiles
Spondon	Derwent	300,000	0.016	Artificial silk and Power station
Derby	Derwent	7,000,000	0.368	Tannery waste

In 1952 a legal action was brought, by Lord Harrington and the Pride of Derby Angling Association, against four defendants discharging into the Derwent; British Celanese (cellulose, acetate and other organic wastes), the Derby Corporation (up to six million gallons of effluent per day), the British Electricity Authority (Spondon power station discharging heated water) and the Midland Tar Distillers (Sheail, 1998

125). Regarding the power station, the counsel suggested that, in clear water, there was a killing point (temperature) for cold-blooded animals, that was more severe in polluted waters. Their appeal to the judgment was resolved with an agreement with the Electricity Authority of a maximum temperature that could be discharged without harming the fish (Sheail, 1998).

An appeal regarding the Derby Sewage works became of national interest, as the Corporation claimed they had met the original requirements of the Derby Corporation 1901 Act and the issue related to local population growth, and if they were required to stop discharging it could cause flooding and other issues in the City (ibid). They also claimed that the technology wasn't available to deal with the quantity of sewage, hence the interest across the country. The appeal was rejected, supporting the original decision and setting a precedent nationally (ibid). British Celanese pursued a previously failed attempt to have their discharge treated at the Derby Corporation sewage disposal works, using the Public Health (Drainage of Trade Premises) Act of 1937, which required local authorities to treat all wastes, domestic and industrial, in a single location where possible. Ultimately, new Derby sewage works were built in 1958, incorporating the trade waste, but with a fee for the agreed 42 million gallons per day (2.2 m^3/s) of British Celanese waste (ibid). An immediate improvement in river quality was recorded in 1959, following the new sewage works becoming operational (TRB, 1959).

In the second half of the 20th century, a number of industries, e.g. coke oven plant, tar distilling plant and dye-works, closed their operations, leading to waterway improvements. Rivers were also improved through the introduction of on-site treatment works at troublesome sites, such as Stevenson's Dyers and F H Drabble & Sons (bleaching, dyeing, finishing, and mercerising), often after repeated fines (TRB, 1953, 1964, 1965) . Eventually sites were allowed access to upgraded local authority schemes, e.g. the Ambergate Wire Works, which stopped the discharge of a small quantity of cyanide into the Derwent by 1958, using a pre-treatment waste system on site before the local authority sewerage scheme came on-line in 1968 (TRA, 1968). Buxton sewage works improved the Wye fishery, whilst the Derby remedial pollution prevention works helped improve a portion of the Derwent between Borrowash and Wilne mills, that had been fishless in 1951, but with a good stock of roach in the waters by 1965 (TRB, 1965). The textile mills in the DDC were also able to divert waste to newly developed local authority sewerage works. The 1960s Belper sewerage works received 200,000 gpd (10.5 litre/s) of untreated dye waste from the Milford Works (ESCC), effluent previously discharged directly into the Derwent, and, by 1969, 250,000 gpd (13.2 litre/s) waste from the Belper works (ESCC) (TRA, 1968, TRA, 1969).

4.5.3 Fisheries

Early 20th century fishing guides of Derbyshire focussed on the waterways upstream of the polluted rivers, such as the Lathkill, dammed into a series of ponds, with a trout hatchery 'and all the accessories of a model fishery', and the private ponds stocked with rainbow and Loch Leven trout (Gallichan, 1905 20). They also reference 'close-seasons', including sections of the river with no fishing allowed on Sundays, such as the Wye between Bakewell and Rowsley (ibid 79).

The Trent Fishery Board's report (1937) stated that the fisheries were in their worst state around 1925, with no records of salmon takes at all in the catchment. By 1937, annual salmon takes of 100 to 160 across the whole Trent catchment were recorded, reflecting some improvements being made (Spicer, 1937). Their biologists' quality assessment of the catchment, one of the first in the country, did identify waterways in the Derbyshire Derwent catchment (DDC) given a grade A classification (over 95% dissolved oxygen): the Ecclesbourne Brook (trout), upstream of Matlock (trout and rainbow), the upper Derwent beyond Wye confluence, (trout), and the Wye (trout and rainbow). Parts of the Amber and Blackwell Brook were classified as E (40 to 50% dissolved oxygen), with fish unable to survive, but with some plant life. The Derwent below Belper and below Derby was classified D, with fish life possible but surviving precariously. For any migratory fish travelling from the Humber, one stretch of the Trent near Nottingham was also classified as D, but from the saltwater Humber waters to Newark the map shows coarse fish and salmon (ibid).

4.5.3.1 Reintroduction of salmon into the Derbyshire Derwent catchment (A study by the Derbyshire County Angling Club)

Severn Trent Water Authority biologists carried out studies, in 1982 and 1985, into the reintroduction of salmon into the Trent River, at the request of the Trent District Anglers' Consultative Association (Cowx and O'Grady, 1995, DCAC, 1986). Their study of the river conditions determined that the Trent was suitable as a migratory route, apart from low flow periods, when heat pollution from the power station cooling towers raised the water temperature above ambient (DCAC, 1986). They identified the Dove and Derwent as tributaries that could support juveniles, but considered the Derwent an uneconomic proposition due to the obstructive weirs and sluices (ibid). The DCAC report investigated the cost of bypassing or removing the weirs on the River Derwent, but did not include the eight weirs on the River Trent that migrating salmon would have to pass to reach the Derwent. Weirs were considered as fixed barriers, with no mention of the sluices or floodgates offering an open gap for fish passage.

The angling club's report saw no benefit from the barriers (weirs) in the river and could see no reason why fish passes of various forms, could not be built to circumnavigate them (ibid 14). They observed that many of the weirs had provided power to mills that were no longer operating, and referenced a recent announcement of the closure of the Belper and Milford sites (ibid). In their opinion, they were now obsolete and could be heavily modified or removed (ibid). At this time local HEP generation could not be connected to the national grid, so, whilst the anglers may have been correct about the power supply argument at that point in time, they gave no consideration to future site owners self-generating HEP, the role the weirs played in flood management or their heritage value, including the Belper Weirs, wall and sluices that had been given Grade II* listing in 1966. The report was incorrect in identifying some DDC weirs under the category of 'no longer used for their original purpose', including Milford (which has continued to generate HEP and was a listed structure), Ambergate Wire Works (that is a flood control weir and used by STWA to set the river levels for abstraction to Ogston and Carsington), and Cromford (Masson, which is still generating HEP and was listed).

4.5.4 Flooding

Despite the modifications made to the DDC waterways to reduce the impact of flooding the catchment repeatedly had to respond to major flood events. Changes appear to have been made directly as a response to major floods, such as the Derby Riverlands project (Section 4.5.1.2), first designed after the 22 February 1919 flood event. Somewhat optimistically, Farnsworth forecast that the development of the reservoirs by the Derwent Valley Water Board would considerably reduce the maximum flood level, and prevent any recurrence of the occasional extraordinary floods (Farnsworth, 1919 4). At this time only the Howden and Derwent reservoirs had been completed. The DVWB design engineers had originally stated the design of the reservoirs would allow the storage of wet weather flood waters (The Engineer, 1920). In 1965, the DVWB tried to empty the Derwent Valley reservoirs to capture some of the flood waters of the upper valley, but on the 8 December they were full, with the spillway at Ladybower discharging 150 m^3/s (TRA, 1966). Describing the major 1965 floods as similar to the 1931 floods (a one in 50-year event),

> ‘Considerable damage, suffering and inconvenience was caused by the flood at both Matlock and Derby. The flooding followed the familiar pattern of riparian development which was carried out at the time of the Industrial Revolution. The natural washlands on both banks of the river were used for development resulting in higher flood levels caused by the reduction of cross-sectional area of flood flow. At Matlock the main square and almost the whole of the centre of the town was flooded. At Derby flooding was more extensive’ (ibid 45-46).

One of the earliest river gauges installed in the DDC, with continuous flow data publicly available from October 1935, is the St Mary’s Bridge gauge on the Derwent, Derby. Plotting the flow data (mean value) from the UK National River Flow Archive from 1936 to 1990, Figure 4.32, identifies high-flow flood events (i.e. above the 150 m^3/s level that causes flooding of properties, such as the Belper Mill basement today), compared to the mean flow between 1935 to 2021 of 17.6 m^3/s.

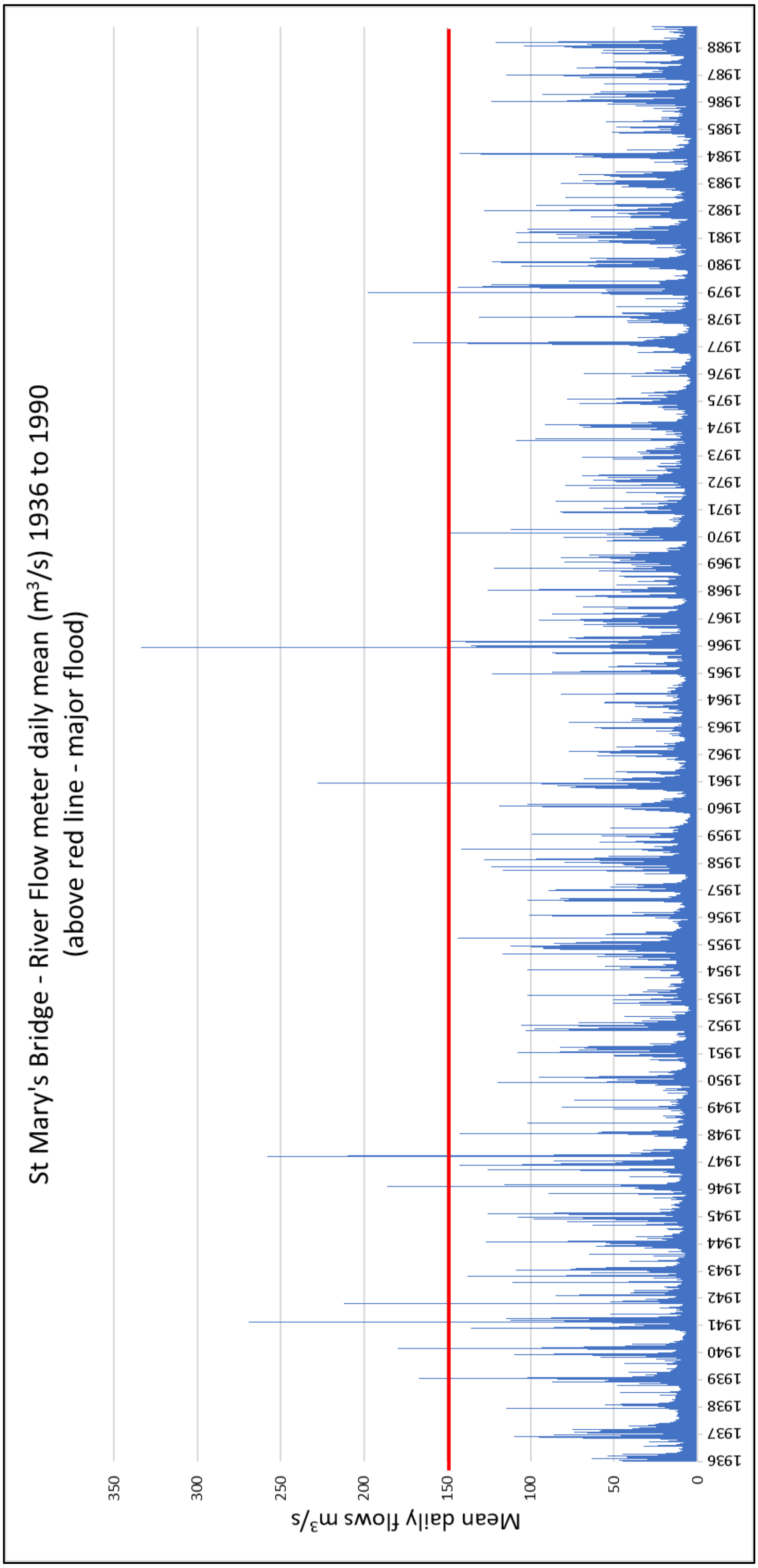


Figure 4.32 Derwent in Derby, daily mean flow identifying flood events.

4.6 Policy and regulation

During the 20th century UK government policy and regulation, such as The Electricity (Supply) Act 1926 impacted significantly on the use of HEP, largely negatively. Governments and local authorities were faced with new priorities, opportunities and challenges, that led to decisions with the unintended consequence of halting HEP usage, e.g. the need to improve waterways leading to abstracted water charges, even for watermill owners. Keen to utilise UK resources (i.e. coal), the energy transition to electricity led to policies marginalising small electricity generators, including HEP (Hannah, 1979, Kennedy, 2020). In this case, the government was also lobbied by the large and established coal industry, both by the workforce, in the form of unions, and by the owners of mines, particularly in Scotland (Hannah, 1979 139, The Derby Daily Telegraph, 1929). However, the successful roll out of gas central heating during the 1960s and 70s, despite barriers from the powerful coal lobby, is an example of an energy transition that may offer lessons to learn in the current low carbon transition, including the unlocking of HEP potential.

4.6.1 Gas central heating

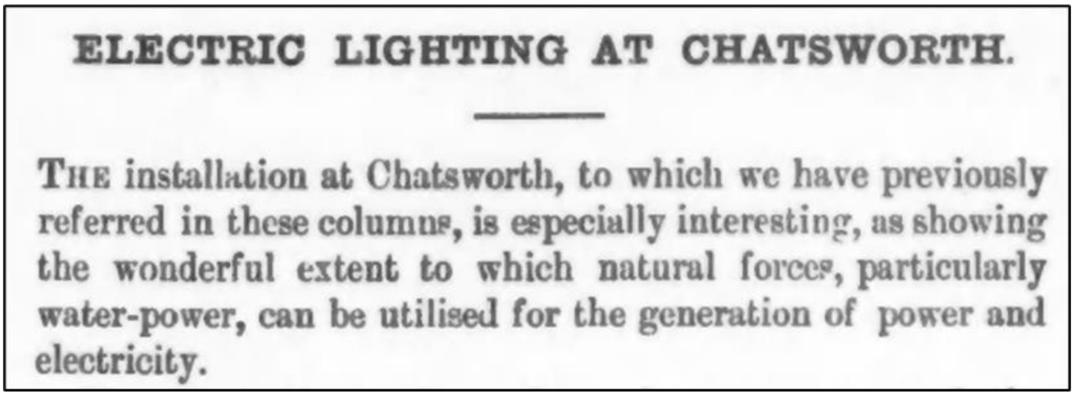
Gas central heating became the dominant form of domestic heating in the UK during the 1960s and 70s, following a rapid transition from coal-fires (Hanmer and Abram, 2017). Technical improvements, including small-bore hot water pipework and small, silent pumps, had encouraged the development of central heating in the early 1960s, before the discovery of North Sea Gas (ibid). One of the first challenges faced by central heating was to persuade heating installers to utilise the new technology, but the coal industry, which was producing gas from coal at that time, funded the training. The early marketing of the new heating systems highlighted the convenience of automated heating compared to the loading and stoking of a coal fire (ibid). The early roll out of central heating, promoted by the coal industry, was a sales-led process, but the national conversion from town gas (produced from coal or oil) to North Sea gas (methane), between 1967 to 1977, was a ‘centrally coordinated and state-led transition’ (Arapostathis, Carlsson-Hyslop et al., 2013 41).

Key elements of the state-led transition were the Clean Air Act of 1956 introducing ‘smokeless areas’, the 1967 fuel policy white paper outlining the country transitioning from two fuels (coal and oil) to a four fuel (coal, oil, natural gas and nuclear) system, and the Gas Act of 1972 creating the British Gas Corporation to build a gas supply network across the country (ibid). This one example highlights many of the key issues with a major energy transition, such as reskilling and accommodating existing fuel interests, but also what can be achieved by a state-led transition.

4.7 People: individuals, businesses, communities, society

It is impossible to discuss the early use of waterpower to produce electricity (electric lighting), without mentioning Sir William Armstrong at Cragside (1878) (Section 4.2.1). But the Derbyshire Derwent catchment also had early adopters and influencers, such as the 8th Duke of Devonshire introducing electric lighting (Section 4.2.1.1) to Chatsworth House (1891), G H Strutt in introducing HEP to his Milford mills (1907), persuading the ESCC to commit to future investment in Derbyshire (Section 4.2.2.2), and RJ&N (Ambergate) introducing electric lighting for Oakhurst House and probably their wireworks between 1876 (turbines purchased) and 1895 (first reported) (Section 4.2.1.1). The Duke organised a press day, including London reporters, to show off his 1891 project. They received a detailed tour, guided by the engineers responsible for the project, Messrs Drake and Gorman, who were quoted as saying:

> ‘it will be well if Englishmen will mark what cheap forces surround them if they will only bring their brains into play to use them’ (The Derbyshire Times, 1893 16 December).


ELECTRIC LIGHTING AT CHATSWORTH.

THE installation at Chatsworth, to which we have previously referred in these columns, is especially interesting, as showing the wonderful extent to which natural forces, particularly water-power, can be utilised for the generation of power and electricity.

Figure 4.33 Introduction to the detailed Chatsworth lighting article in the industry journal (The Electrical Review, 1893 29 December)

4.7.1 The National Association of Water Power Users (NAoWPU)

Whilst prominent individuals promoted its use, throughout the 20th century waterpower users collaborated to lobby against threats to their source of power: for example, The Derwent Valley Water Board acknowledged the ‘millowners of the Derwent Valley’ (Section 4.4.1.1) as a group, with compensation agreements organised by the lead organisation, the ESCC (DRO LS/363.63, 1944 36). When faced with the threat of charges for water as part of the 1963 Water Act, The National Association of Water Power Users (NAoWPU) was formed.

The NAoWPU seems to have been an effective representative association, with over 90 members by the end of 1974, covering 62 sites, running 92 water turbines or wheels, and with approximately 3,500 kW capacity installed. Nine sites were in the Severn Trent Water Authority region, including six in the DDC (ArkSoc NAoWPU, 1975 1 January):

- Messrs E Caudwell (Rowsley) Ltd, Flour Mill
- Mr P H Fielden, The Carbolite Co. Ltd, Bamford Mill, Bamford
- Messrs Fernehough’s Limited, Bakewell, Derbyshire
- Mr R C Tattersall, English Sewing Limited, Thread Division, Belper [representing Masson, Belper and Milford mills]
- Mr D Westmorland, Messrs S & J Johnson (East) Ltd, Ladygrove Mills, Two Dales
- C Charlton Esq, The Arkwright Society, Tawney House, Matlock.

In addition to existing waterpower users, potential users and ‘those interested and willing to promote the free use of water for power purposes’ were also invited to join the association, growing to over 200 members by 1979 (ArkSoc NAoWPU, 1979 30 April). The NAoWPU produced a memorandum for the government’s Sub-Committee on Energy Conservation (1975), raising concerns about the unexpected levying of a charge per gallon of water used. It challenged the assumption that the power is generated for free, with a need for constant attention and renewal of the sluices, grids (e.g. leaf build up) and sluice gates (ibid). It also pointed out that most sites had been impacted by improved land drainage, reducing run off into rivers, with nearly all the turbines being closed during a dry summer or heavy/prolonged frost in the winter. The memorandum stated that a:

> ‘great many hydro-plants, small and medium sized, have gone out of service in recent years. It is very difficult to ascertain just how many, since former operators now have no interest in our problems and are unlikely to contact us’ (ArkSoc NAoWPU, 1975 np).

In addition to directly lobbying the government, the NAoWPU also supported the Watt Committee on Energy in 1985, sharing practical information on the challenges faced in operating and installing new HEP. In the investigation into institutional barriers to HEP development, the Committee concluded that the legislation facing a HEP developer in England and Wales could be considered ‘formidable’. In addition to legislation faced for any development such as planning, the HEP developer also faced legislation concerning abstraction, pollution prevention, land drainage, impounding and fisheries (Reed, Hinton et al., 1985).

4.8 Lessons to learn

Due to technical development and early adopters, the late 19th century and early 20th century was a period of optimism for water turbine manufacturers, such as Gilkes of Kendal, as many waterpower sites transitioned from mechanical drive to electric lighting and power, self-generating hydroelectric power (HEP). Unfortunately, for the turbine industry and watermill owners, the limitations of waterpower (e.g. a finite resource per site and variability of flow) drove local authorities and private enterprises to develop electrical supply systems using the more reliable and scalable coal fired power stations. As local electricity networks grew, self-generating HEP sites had the opportunity to purchase the far more convenient electricity.

Locations in the UK with suitable topography and hydrology, such as the Scottish Highlands, were able to develop larger scale HEP, delivering electricity to more rural communities that were not being reached by the coal fired power station network. During the 20th century a series of state led interventions had the unintended consequence of impacting on the remaining small HEP generators across the UK. Whilst other nations continued to develop and harness HEP, known in Germany as white gold, the UK exploited its coal reserves to develop a national electricity network. As a nationalised industry the Central Electricity Generating Board (1958) needed industries across the UK to purchase their electricity, produced by their new super-power stations, many located in the Trent catchment. During the 1960s and 1970s more small HEP generators, not allowed to export surplus power to the grid, received financial incentives to switch to purchasing electricity from the national grid. It would appear that by the 1960s the remaining waterpower sites no longer had the support of the government, with a new Water Act introducing, temporarily, water charges for sites producing ‘milling power’. Lobbying by a newly formed waterpower body helped stop these charges but, by the time the Act was improved, more sites had invested in connection to the grid and removed their turbines.

The original DVWB Act (1899) allowed variable compensation flows for a specific downstream user. This original flexibility in compensation flows, whilst maintaining the daily level, could be of interest to today’s HEP generators, who could generate higher-value renewable electricity to meet the 4pm to 7pm peak demand period, with variable, time of day, compensation releases. On the River Noe, timed releases from an upstream dam enabled corn mills downstream to operate later in the day at times of low water. Could the Ladybower, Ogston and Carsington reservoirs release water to optimise HEP generation to meet peak demand?

With the waterways in such a poor ecological state by the early 20th century, it would appear that river management developments took place with little regard for the health of the river. The 19th century pollution problems were added to by the new 'thermal' pollution of the coal-fired power stations, such as the Spondon Power Station (Derby). Pollution legislation did make a change in the second half of the 20th century with industries having to reduce polluting effluent and local authorities building treatment works to accommodate the domestic waste from the growing populations and trade effluent. These improvements encouraged the water authorities, conservationists and anglers to investigate the reintroduction of species, such as the salmon, into the Trent catchment. Today, the rivers appear to be suffering from a decline in quality again, with new forms of pollution from a growing population and the potential of thermal pollution due to climate change. The 1978 HEP potential study focussed on the water utility assets but the author noted the water utility undertakings had other priorities, clean drinking water and managing pollution. Today, Severn Trent Water have similar responsibilities and priorities, impacting on their ability to develop HEP utilising their infrastructure (H Perry [STW], personal communication, 24 March 2023).

The transition from domestic coal fires to gas (natural) central heating systems, despite the challenges faced due to the potential impact on the powerful coal industry (owners and unions), is a clear example of what can be achieved with appropriate state intervention. Despite HEP's limitations it faced opposition from the gas lighting industry as electric lighting developed, and from the coal mining industry as large HEP developed in Scotland. Today we see the low-carbon transition to domestic heating systems powered by renewable electricity (e.g. air source heat pumps) from gas central heating, as a major challenge, and slow compared to other nations. Again, the UK government is supporting the North Sea oil and gas industries and we are relying on the fossil fuel industry (e.g. gas boiler manufacturers) to retrain heating engineers and market the new technology to consumers, as we did in the 1970s, ultimately it required state intervention to facilitate the change.

During the 20th century different fuels (e.g. coal, oil, gas nuclear) have been used to produce electricity with availability, supplies and prices fluctuating. Despite several energy security reviews, particularly during the 1970s, identifying waterpower as a potential source of home-grown energy using existing infrastructure and infrastructure, successive governments have chosen to continue focussing on large scale power solutions, e.g. nuclear power. The UK government's transition to Net Zero is currently focussed on identifying large scale power solutions, but sites, such as Milford, Belper and Masson in the Derwent Valley, continued to operate successfully into the 1980s, harnessing the available local fuel of the waterways as part of a mixed, hybrid, power management system, and continue to generate HEP today. The DDC has a number of sites with nearly 250 years of experience of harnessing the power of the river, that could share their best practise and successes, promoting the repowering of historic waterpower sites and offering a route to sustainable development, as the late 19th century early adopters (influencers) did.

Chapter 5 Waterpower: Renewable Energy (1989 – 2023)

5.1 Introduction

Chapter 5 begins in 1989, when Margaret Thatcher's Conservative government recognised HEP as the only significant renewable energy available, at that time, to mitigate carbon dioxide emissions and address concerns over global warming and environmental change (Lees and Eyre, 2021 1, Mahony and Hulme, 2016). In 1989, HEP was generating 4.8 TWh of electricity, with just 23 GWh from wind and a negligible quantity of solar (Lees and Eyre, 2021). In addition to the economic value of producing electricity, HEP now had the added value of displacing some fossil-fuel based power generation, helping to mitigate climate change.

The period 1989 to 2023, saw a rise and fall in HEP installation rates, similar to 1878-1989 (Chapter 4), but in a third of the time, reflecting changes in government support, river regulation and stakeholder priorities. From 1989, government intervention triggered a revival in small, run-of-river, HEP development across the DDC. For example, Chatsworth House, faced with rising electricity bills, and having the option to export and sell any surplus generation to the National Grid (Devonshire and Rogers, 1999, Strange, 2001) following the 1983 Electricity Act, repowered their Emperor Fountain HEP, shut down in 1939. This small HEP revival was relatively short-lived and effectively paused after 2015 (Figure 1.1).The pausing of development followed a reduction in government support and HEP developers being required to deal with growing planning complexity and changing environmental regulation (Bracken, Bulkeley et al., 2014), primarily the delivery of the Water Framework Directive (WFD) by the Environment Agency (EA). The key factors influencing the mini-boom in HEP deployment (1990-2015) and its subsequent pausing (2015-2019), will be investigated in this chapter.

This chapter also discusses a new form of HEP developer, community energy (CE) groups. Successful and unsuccessful CE HEP case studies are investigated, including the author's personal experiences with the Ambergate Hydro CE project in the DDC. UK government acknowledged the development of CE and the challenges it faced, developing a *Community Energy Strategy* report (DECC, 2014a). This chapter also draws on a work placement with Severn Trent Water (STW), funded by Midlands4Cities, which has given insights into the HEP opportunities (generation and energy storage) within the DDC's water utilities infrastructure, and the additional challenges faced in installing HEP in a highly regulated industry, compared to traditional HEP developments.

In 2001, the Derwent Valley Mills, was inscribed by UNESCO as a World Heritage Site, along with New Lanark Mills (Scotland) and Saltaire (Bradford) (World Heritage UK, 2021). The 24 km corridor of historic industrial textile mills, at the heart of the DDC, has a core story of using waterpower to mass produce cotton thread, and promotes HEP generation in its current management plan (2020-2025), identifying its waterpower infrastructure as a key attribute, noting:

> 'the successful harnessing of relatively large amounts of natural energy to deliver the mechanical power needed to drive newly devised machines housed in mills producing goods at an unprecedented rate' (DVMWHS, 2020 29)

The renewable energy cause-and-effect diagram (Figure 5.1) identified two different, but related, effects between 1989 and 2023: HEP reinstatements, upgrades and new projects initiated by changes between the 1980s and 2010s, then a pause in projects from 2015 onwards. The key influencing factors identified in Chapter 1, form the main structure of this chapter, capturing the changes and issues, mostly national, including those that have paused the repowering of HEP in the DDC, for now.

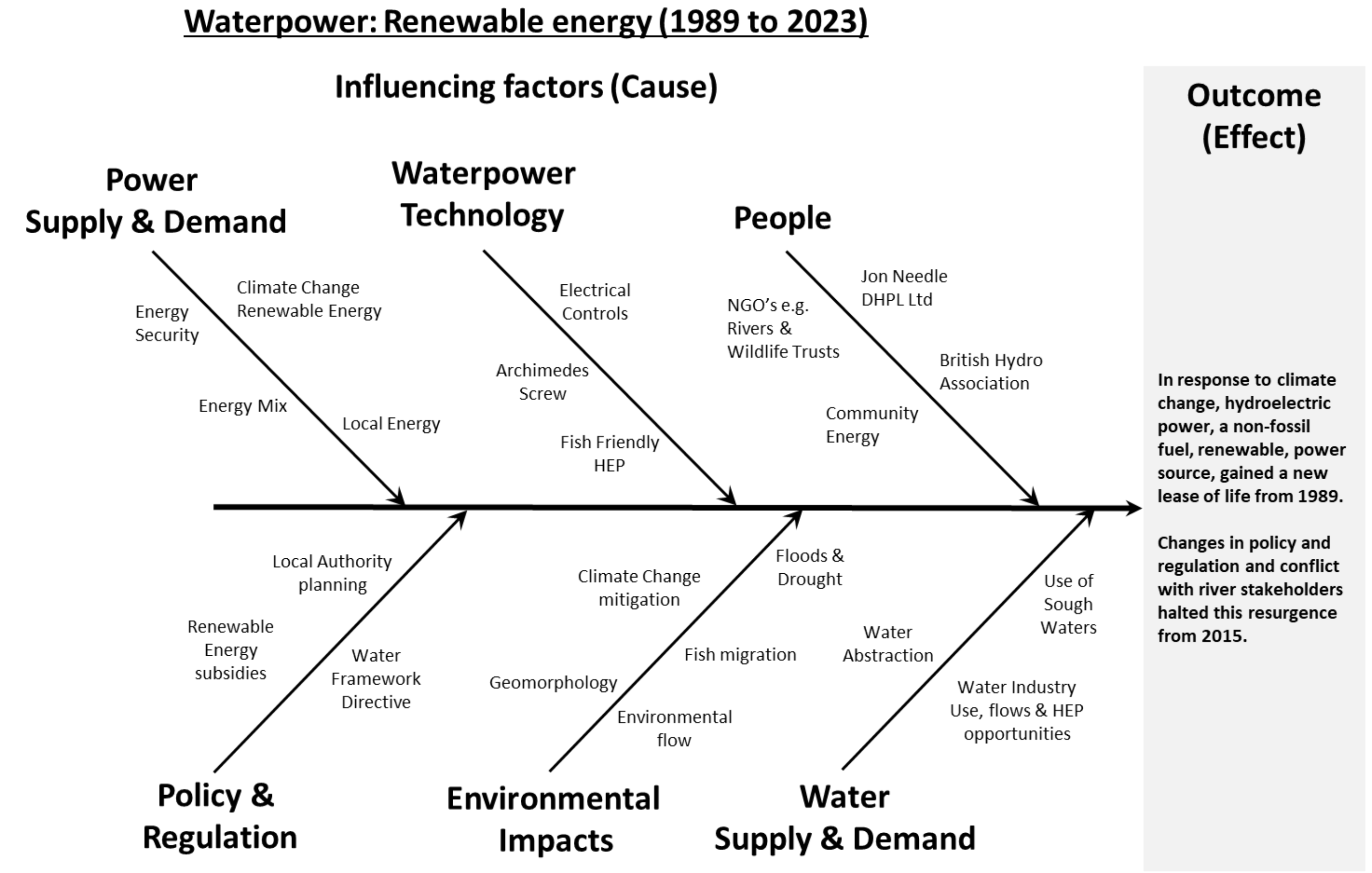


Figure 5.1 Factors influencing the use of waterpower between 1989 and 2023

5.2 Waterpower: Renewable energy

Whilst this section includes references to technological developments in the harnessing of waterpower, such as the use of the Archimedes Screw, the main focus is to identify the key drivers that initiated the reinstatement of HEP in the late 20th century and the growth in deployment up to 2015. Section 3.2.4 discussed the importance of the control of the water and waterwheels in the development of waterpower; this period has seen the automation of these controls and operations to improve efficiencies, improving HEP's economic viability. However, HEP also faces challenges of abstraction licencing conditions that may impact its feasibility, such as adding a fish pass (capital cost and water loss) or requiring finer intake screening (restricting flow to the turbine) (EA, 2016).

The period of renewable energy introduced a new form of HEP developer, community energy (CE) groups, often volunteers, motivated by wanting to benefit their local community and environment through generating clean energy (Willis and Willis, 2012). Community Energy England, founded in 2014, described 2018 as a year of uncertainty and challenge, being the toughest year yet for community energy, with new generation capacity falling steeply in comparison to previous years, following the changes to Feed-in-Tariffs combined with the restrictive planning environment (Bridge, Proctor et al., 2019 3).

Whilst the British Hydro Association views HEP as a proven and reliable form of renewable energy generation with an operational life of 80+ years (Gilmartin, 2023), the UK government, a critical stakeholder, downplays the potential role of HEP describing it as a mature technology, with generation tending to fluctuate from year-on-year in line with rainfall (DESNZ, 2023 Chapter 6, 6). The UK government appears to be repeating mistakes from the 1970s, highlighted then by Lord Wilson:

> 'By all means let us spend millions of pounds investigating potential sources of power, many of which cannot be available in less than 10 to 20 years; but, in the meantime, let us invest some capital in schemes which we know will yield valuable power' (PA HC Deb 1 February 1978).

5.2.1 Waterpower development

5.2.1.1 Archimedean Screw

Archimedean Screw HEP technology was introduced into the UK by MannPower in 2004, as a viable HEP option for the Georgian, Howsham Watermill, located at a Site of Special Scientific Interest (SSSI) in Yorkshire, benefitting from the turbine's 'fish-friendly' characteristics (The Yorkshire Post, 2016). The use of the fish friendly Archimedean Screw was quickly adopted as a technology to generate HEP in the UK during the early 2000s 'boom' period. One of MannPower's most visible projects was the installation of a 10 kW screw at Cragside House, a site owned by the National Trust, 'returning hydropower to the place of its birth' in 2014 (MannPower, 2015) (Figure 5.2). The first community energy hydropower project in the UK, Torrs Hydro at New Mills, Derbyshire, installed a 63 kW Archimedean Screw using the weir that originally powered the Torr Mill in 2008 (Brumhead, 2015). Most of the HEP turbines currently in use in the DDC are based on original Francis/Kaplan type turbine technology (Harton, Chandler et al., 2012), but when replacing a turbine at the former Borrowash Mill site in the DDC, Derwent Hydro Power Limited (DHPL) selected the Archimedean Screw technology, installing a 50 kW unit (J Needle, personal communication, 4 October 2021).

Figure 5.2 Archimedes screws generating HEP at Cragside (Northumberland), New Mills (Derbyshire) and Borrowash (Derbyshire) (Photographs: Author 2020-2023)

5.2.1.2 HEP generation infrastructure

HEP is being generated in the DDC in 2023 by old (e.g. 1950s), refurbished and new water turbines, and operators strive to continuously improve the wider HEP generation system, to increase the electricity generated. An important development for waterpower in the late 18th century was the introduction of the governor to control the speed of the waterwheel. Similarly, today, the monitoring of river flows and levels, sluices and turbines, allow HEP generation to be optimised automatically, and, more recently, remotely (Paish, 2002). This remote monitoring and automation of the wider HEP generation equipment, has encouraged the reinstatement of historic HEP self-generation sites, such as Chatsworth House. B Garstang (Estate manager, personal communication, 1 September 2021) believes that the house switched from HEP self-generation to a local grid supply in 1936, due to the inconvenience, impracticality and cost of manually monitoring and controlling the distant reservoir and sluices (482 ft, 147 m) above the turbine (Clearline, 1989) (Section 4.2.1.1). In 1989, the 'astronomical' cost of electricity initiated the interest in reinstating HEP at Chatsworth (Chatsworth, 1989), but it had to be economically viable to install and operate replacement HEP turbines. The designers of Chatsworth's HEP control equipment developed new technology to accommodate the 'unpredictable nature' of fuel supply, compared to conventional fossil-fuel plant, to 'maximise yield and provide efficient operation' (Payne, 1989). The Thamesmead Engineering equipment installed was the first solid-state electronic speed and load governing control device, with no mechanical components, in the world (ibid).

Additional improvements have been introduced at existing and new HEP sites in the DDC, to reduce the cost of operation and improve generation outputs, such as self-cleaning screens (Figure 5.3). The self-cleaning screen technology, which operates 24 hours a day and automatically adapts to flow conditions (e.g. cycling more frequently during the autumn leaf drop), has become critical, as the EA licencing conditions have changed requiring finer spacing on intake screens to protect specific fish (EA, 2013 16) such as eels and salmonid smolts.

Figure 5.3 Screen cleaning in the DDC. (Photographs: Author, 2020-2023) Derby, new HEP installation rake system (2012) Belper, Rake and chain self-cleaning screens (2015)

5.2.2 Renewable energy subsidies

One of the most impactful factors on HEP deployment in the UK in the last 35 years, was the government subsidies to encourage electricity generation using low carbon fuels. The Energy Act 1983 had already enabled small HEP generators to sell electricity through the national distribution networks but, despite needing to increase renewable energy generation, HEP progress was slow, as it wasn't economically competitive with nuclear and fossil fuel power sources (Paish, 2002). In response the government used economic instruments to address the need (Needle, 2020), introducing three renewable generation-linked subsidy schemes, each scheme being more successful than its predecessor (Table 5.1), (ibid 30).

Table 5.1 UK renewable energy subsidies 1990-2019

Subsidy scheme	Years	Total HEP added MW	Annual HEP added MW/year
Non-Fossil Fuel Obligation (NFFO)	1990 to 2002	95.4	8.0
Renewables Obligation (RO)	2002 to 2017	158.5	10.6
Feed-in-Tariff (FiT)	2010 to 2019	222.6	24.7

In order to protect the state-owned nuclear industry from falling oil prices and gas discoveries during privatisation, a levy was introduced, as part of the 1989 Electricity Act, to ensure that nuclear-generated electricity was purchased by the new privatised regional electricity companies (Patterson, 2021). The levy on fossil-fuel generation aimed to deliver a billion pound subsidy to existing nuclear plants but, not wanting to call it a ‘nuclear levy’, it was called the Non-Fossil Fuel Obligation (NFFO) (ibid).

Initially the NFFO only related to nuclear fuel but, to encourage the market for renewables, a portion of the obligation was allocated exclusively to renewable sources (Walker, 1997). The premium set price paid for nuclear and renewable electricity, by the electricity companies, was then recovered by the ‘Fossil Fuel Levy’ added to the cost charged to all electricity consumers (ibid). Prices were set for each round of the NFFO, for each technology, with HEP reducing from 6p/kWh for NFFO2 (1991) to 4.08 p/kWh by NFFO5 (1998) (ibid). Each regional electricity company invested in renewable projects during the NFFO funding rounds, focussing on different technologies, e.g. Norweb Generation (owned by Norweb) invested in small HEP between 1990 and 1994 (ibid). These investments included the HEP turbines at Belper Mills (EA, 1996 65) in 1989, which hadn’t run since Tootal (formerly ESCC) relocated to Scotland in 1986 (Derby Daily Telegraph, 1986 11 April). Norweb/Hyder Industrial used NFFO support to enable the UK’s largest run-of-river scheme on the River Trent, at Beeston, Nottinghamshire (historic navigation weir), gaining planning permission in 1995 and commissioning the two 0.8 MW turbines in January 2000 (AMEC, 2010, International Water Power, 1999).

A geographical analysis of renewable generators, contracted under the NFFO, shows the UK distribution of HEP in 1997 (Figure 5.4). The concentration of sites on the west reflects the higher rainfalls and topography, but the locations, predominantly, were based on historic water mill sites, with weirs that had been converted to generate electricity in the past (Walker, 1997 69).

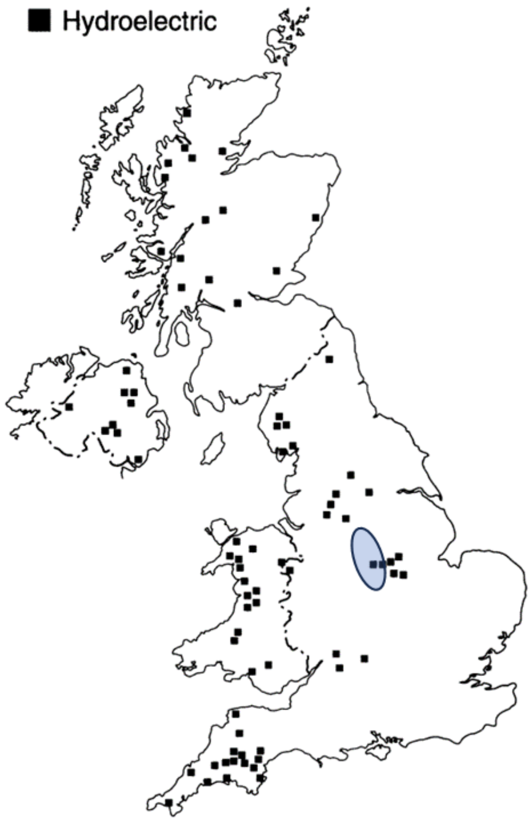


Figure 5.4 Locations of HEP projects contracted under NFFO (1997)
(DDC in blue) (Walker, 1997 70)

In 2002, the UK Government aimed to increase the supply of renewables from 3% to 10% by 2010, with an aspirational target of 20% by 2020 (Hain, Ault et al., 2005 1200), (actually achieving 42.7% by 2020 (DESNZ, 2023 32)). To facilitate this the Renewables Obligation (RO) policy was introduced on the 1 April 2002, providing a guaranteed market. Renewable energy generated was effectively traded using Renewable Obligation Certificates (ROCs), issued by Ofgem, to certify that 1 MW had been generated by a renewable source (Hain, Ault et al., 2005). The value of ROCs was set by the market, but the scheme included restrictions on the size of generators (> 0.5 MWh/month) (ibid), and the challenges of economies of scale worked against small HEP generators.

In April 2010, Feed-in-Tariffs (FiTs) became available under the Energy Act (2008), providing economic support for small-scale technologies (Watkin, Kemp et al., 2012). FiTs were so effective in stimulating small-scale renewable installations, especially solar photovoltaics (PV), that the UK government launched a consultation to review the technology support levels in November 2011 (Willis and Willis, 2012). The impact of renewable subsidies, particularly FiTs, can be seen in the UK government renewable energy deployment statistics (DESNZ, 2023). Figure 5.5 shows the main growth being in the newer wind and solar PV technologies and Figure 5.6 shows the growth in small HEP. Bearing in mind the period of design and build of a typical small HEP scheme (two to five years), the impact of the introduction of the Renewable Obligation in 2002 and Feed in Tariffs in 2010 can also be seen on Figure 5.6.

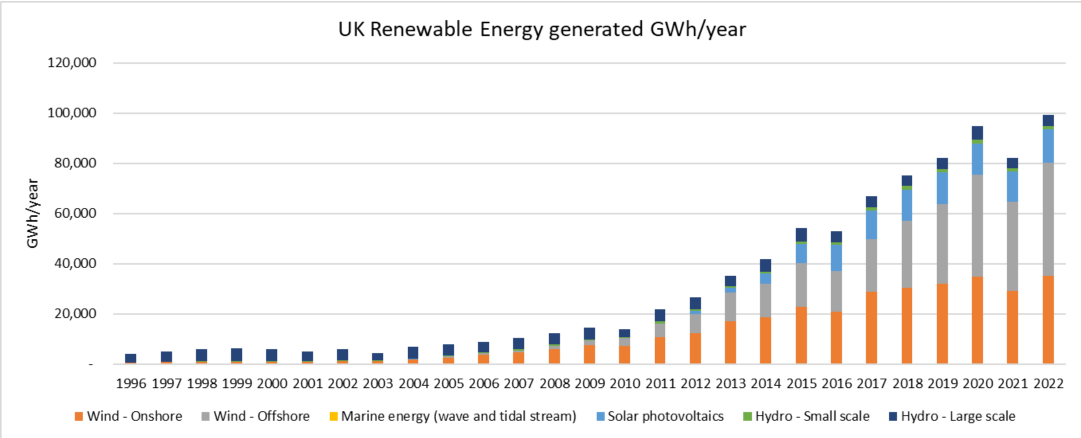


Figure 5.5 Electricity generated from renewables (All) (DUKES, 2020 6.4)

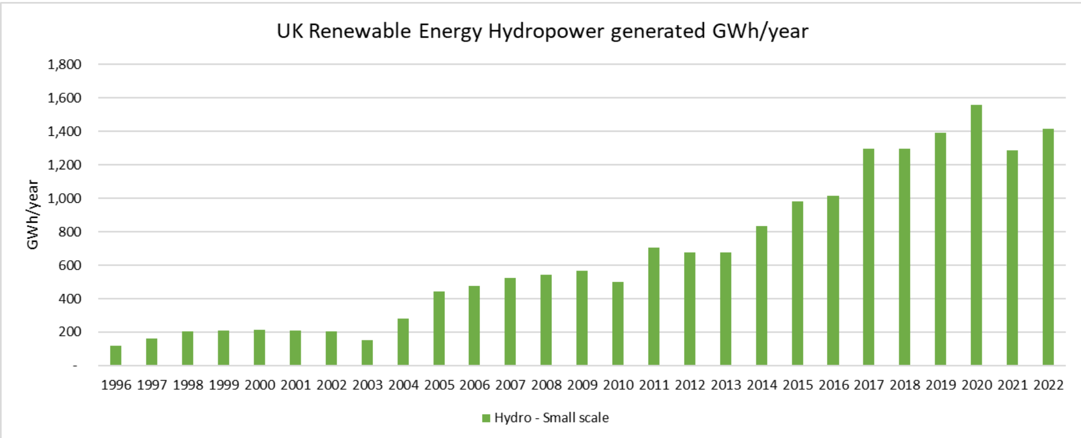


Figure 5.6 Electricity generated from renewable (small HEP) (DUKES, 2020 6.4)

Early in 2012 the UK government made changes to the FiT scheme, partly due its popularity, but also due to new technologies, such as solar PV, becoming more cost effective (Needle, 2020 42). It introduced degression for new solar PV projects, dependant on deployment volumes (maximum annual capacity levels), and FiT reductions (quarterly) (DECC, 2012). The degression mechanism was then applied to non-solar PV renewable technologies (including HEP) in April 2014 (ibid 9); this added risk factors for new HEP projects, of not knowing when a project may be allowed (subject to other projects claiming the available capacity) and knowing that the subsidy would be reduced (by quarterly FiT reductions) if delays were incurred.

In 2015, it was announced that the FiT scheme would end in 2019 (DECC, 2015 12), creating a ‘cliff edge’ for potential projects (BHA, 2018). With HEP projects typically taking two to five years to deliver (Needle, 2020 113), the uncertainty around capacity availability and subsidy support immediately added economic risk and time pressures on projects (Johansson and O'Doherty, 2017), with HEP developers having little control over delays incurred through planning complexities, electricity grid connections and EA permitting. Figure 5.6 shows the impact of the reduction and removal of FiT support on the growth of HEP generation in the UK: it should be noted the annual outputs are dependent on rainfall, with a particularly wet year in 2020 recorded (DESNZ, 2023). One aspect of the HEP FiT tariff structure led to smaller turbines (100 kW) being installed than the opportunity available, in order to receive the higher rate of FiT payment (i.e. 15kW-100kW receiving 19.6 p/kWh, but a larger 100kW-2MW only receiving 12.1 p/kWh (DECC, 2012)). Future policy makers should be aware that this banding of FiT tariffs had the unintended consequence of reducing the installed capacity (Wilson, Day et al., 2022 21).

Focussing on large scale projects (similar to the post-war government), since 2014 the UK government’s main mechanism for supporting low-carbon electricity generation has been the Contracts for Difference (CfD) scheme (BEIS, 2020 149). Developers of large-scale projects, with high upfront costs and long lifetimes can bid in an auction for a guaranteed price for 15 years, protecting them from volatile wholesale prices (Energy UK, 2022). Only large wind and solar PV projects have increased in capacity (Figure 5.5) (DESNZ, 2023): the CfD auction excludes all small HEP projects in the UK, due to a minimum size criterion, causing the British Hydropower Association (BHA) to lobby the UK government to reduce the lower threshold for HEP from 5 MW to 1 MW, with the ability to combine projects (Gilmartin, 2023, Wilson, Day et al., 2022).

A survey of HEP developers in 2022 identified the main hurdles to new hydropower projects as, the lack of ongoing financial certainty in a post-FiT framework, difficulty in gaining consents, particularly from the EA, and obtaining grid connections (Wilson, Day et al., 2022). A leading HEP developer, Derwent Hydroelectric Power Limited (DHPL), based in the DDC, but operating 14 sites throughout England and Wales, created a model to revisit past projects in a post FiT environment and concluded:

> ‘the HEP sector faces significant decline without subsidy support. Developments will be sporadic and offer reduced financial returns. New HEP installations, however, are not expected to cease altogether’ (Needle, 2020 89).

The NFFO, originally introduced to support the nuclear industry, was improved by allocating a portion of spend for renewable technology. Similarly the FiT scheme was an improvement on the RO scheme, by supporting smaller renewable energy schemes, also offering different rates for different renewable technologies. There is an opportunity to learn from these previous support schemes and allocate a portion of each CfD auction for small HEP, reducing price volatility risk, offering a guaranteed return and some certainty in future project investment.

5.2.3 HEP in the DDC (1989 to 2023)

Figure 4.9 shows the few remaining HEP generating sites in the DDC by the 1980s, three of which were the ESCC turbines at Masson, Belper and Milford. Unfortunately, at a time of difficult trading conditions in the textile industry, a grant encouraging the relocation of manufacturing to a Scottish economic blackspot (Derby Daily Telegraph, 1986 11 April) and a need to consolidate its activities during a hostile takeover bid by Coats (Financial Times, 1991), Tootal (who took over ESCC in 1963) closed its manufacturing sites at Milford, Belper and Matlock Bath (Masson Mills) between 1986 and 1991, effectively shutting most of the remaining HEP generators in the DDC.

The government's NFFO programme enabled Norweb, who had developed an interest in small HEP (Walker, 1997), to restart the Belper Mills turbines c.1990, under the name Norgen (Belper) Ltd. A local entrepreneur, Jon Needle, with a belief in self-sufficiency, saw the former ESCC HEP assets in the DDC as an opportunity to generate renewable electricity, now with the option of exporting (selling) HEP, supported by generation-linked fiscal packages (Needle, 2020). In 1988 Derwent Hydroelectric Power Ltd (DHPL) was incorporated and started work on HEP reinstatements and new installations, including the refurbishment and operation at Milford (1990), Masson (1994) and Belper (1998), and installations at Borrowash Mill (1995) and Hamlyn Mill, River Amber (2006), in the DDC (ADVyCE DHPL, 2007). HEP generating sites in the DDC are primarily relatively small run-of-river type schemes, with 13 of the 17 sites generating HEP in December 2022 (Figure 5.7) located on historic watermill sites (Figure 2.17).

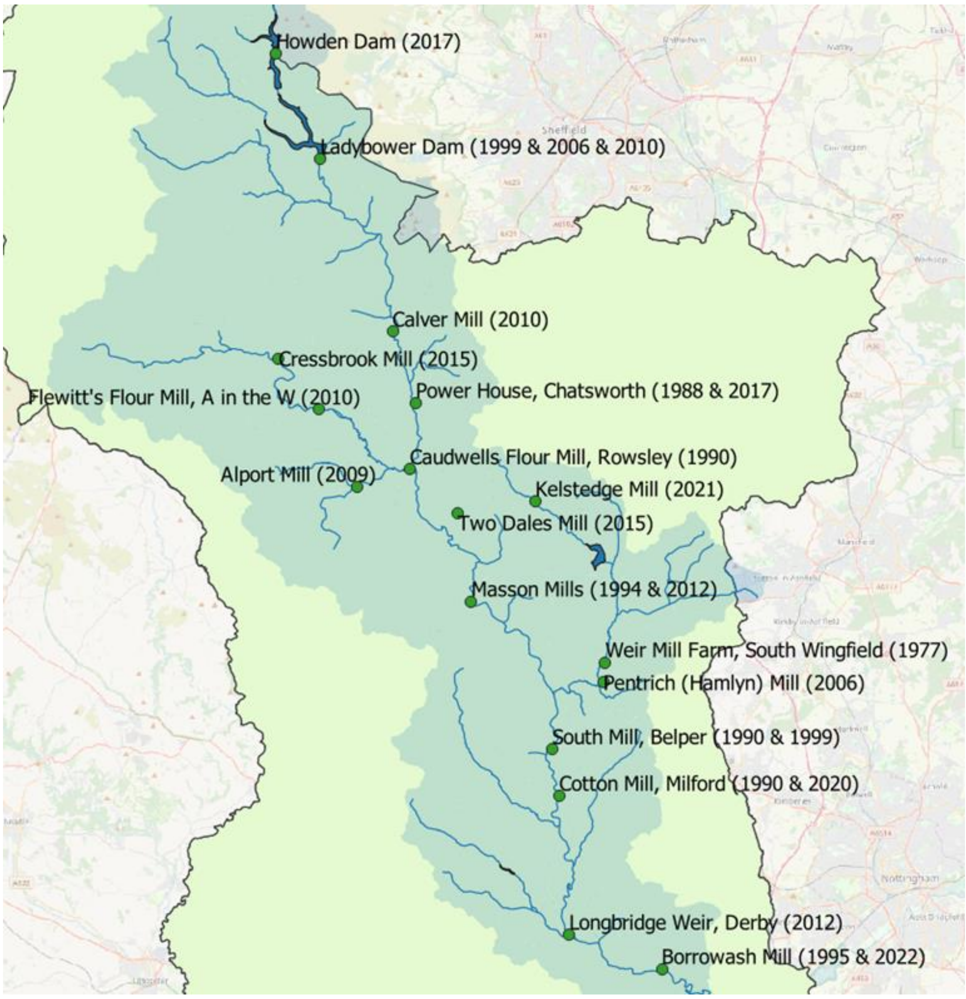


Figure 5.7 The DDC map showing current (December 2022) HEP generation, including the dates that turbines were reinstated, upgraded or installed.

5.2.3.1 HEP projects paused (post 2015) in the DDC

Feed-in-Tariffs encouraged more HEP development across the DDC but, as described in Section 5.2.2, the subsidy was scaled back in 2012 and the degression mechanism was introduced in 2015. With FiTs being phased out by 2019, projects initiated between 2010 and 2015 were placed under considerable time pressures and economic viability risk. This situation was repeated across the UK, with the government policies and national bodies (stakeholders) further impacting on HEP project development. Case studies of successful and unsuccessful HEP projects highlight the complexity and number of stakeholders, such as the EA, Local Authorities, English Heritage and Natural England, who are generally supportive but whose differing, wide ranging priorities have the unintended consequence of negatively impacting the feasibility of HEP, through the insistence on man-made constraints, requiring considerable, time, effort (sometimes duplicated) and cost (Alexander and Edgeworth, 2018, Armstrong and Bulkeley, 2014, Bomberg and McEwen, 2012, Bracken, Bulkeley et al., 2014, Slee, Whitfield et al., 2011, Watkin, Kemp et al., 2012).

The issues facing HEP development, and other renewable energy projects, were identified by the UK government in 2014. Rather than challenging the time and costs associated with pre-planning, the government introduced funds for community energy groups, in the form of Rural Community Energy Funds and Urban Community Energy Funds (DECC, 2014a 10). The *Community Energy Strategy* (2014) identified the indicative costs of an electricity project (pre-construction phase) (Figure 5.8) (ibid 51-54), but there is no reference to the time and effort involved, or any added-value of the pre-construction phase activity. The one renewable energy sector that did identify a need for specific support to 'navigate the regulatory process' was HEP, creating a working group with key stakeholders, including the EA, to look at issues such as joining up the various EA processes relating to small scale HEP (ibid 63). With no work carried out on a Hydro working party, following the government abandonment of the CE strategy in 2015, an opportunity still exists to set up a new taskforce to improve the processes, removing waste, saving time and reducing costs for all the stakeholders involved.

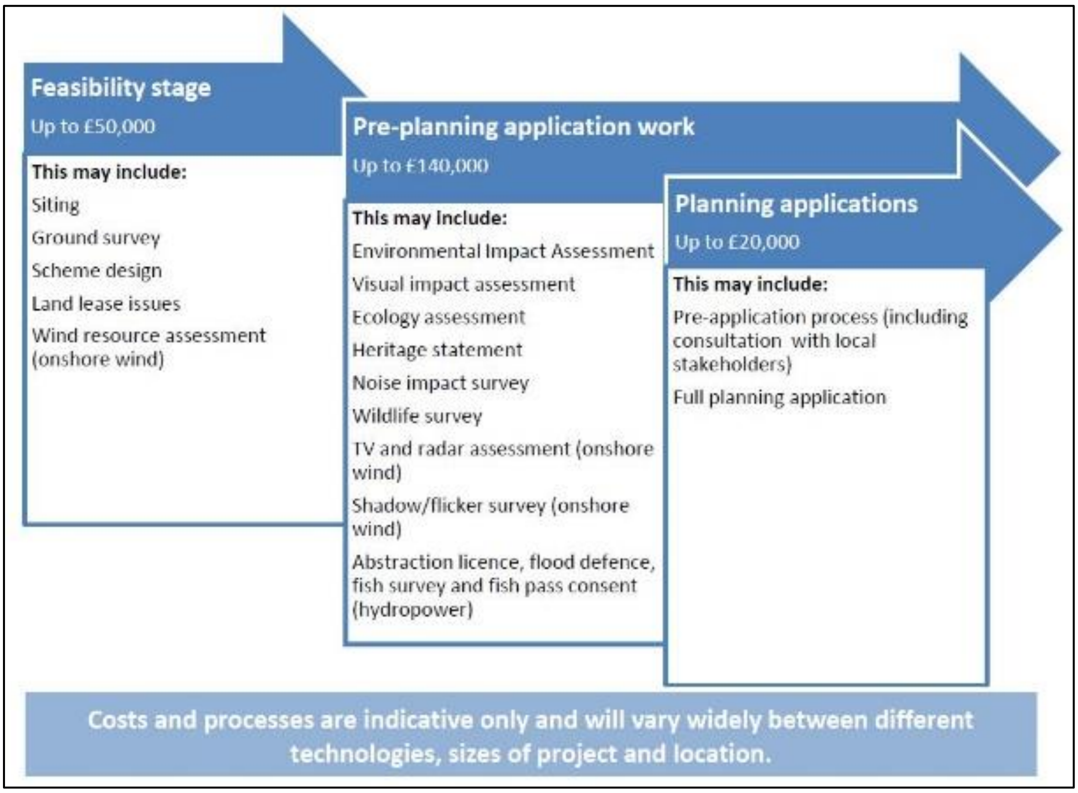


Figure 5.8 Community Energy Strategy - Indicative pre-construction project costs (DECC, 2014a 52)

In many cases the FiT subsidy was necessary just to recoup the indirect costs of associated activities, e.g. planning studies, consenting , fish pass facility and grid connections (BHA, 2018). Three potential HEP projects in the DDC (Darley Abbey, Chatsworth and Ambergate) failed to progress to installation during the FiT degression period, largely due to the removal of subsidy support, but each project also identifying different regulatory issues leading to delays and failure, due to the complexity and uniqueness of each HEP project

Darley Abbey had planned to refurbish and repurpose the West Mill of the complex, one of the DVMWHS key sites, into a sustainable wedding venue, by reintroducing the HEP that had powered the site up to the 1960s. The mill leat and turbine pit had been filled in, requiring exploratory excavations directly underneath the listed mill building, to assess the feasibility of the project. At the pre-planning stage, Derby City Council were very supportive of the wedding venue scheme but warned the developer that including the HEP in the plans could severely impact on the timescale of the planning permissions, due to the role the EA would take in any development proposal, despite this being a reinstatement with no depleted reach and a newly installed fish pass already on the weir. To ensure the wedding venue could be completed in a timely manner the 100 kW HEP plans were removed from the formal planning application submitted in 2014 (A Rose, personal communication, 14th January 2014).

The planning aspect was particularly challenging for a potential scheme (two existing weirs) at Chatsworth House, which was understood from the outset, being located in the Peak District National Park (PDNP). Delays to the Chatsworth project, which planned to install two Archimedes turbines (including fish passes) (Derbyshire Dales, 2015 NP/DDD/0515/0432), were added to by the repeated revision of the turbine house design and additional heritage assessments required by the Derbyshire Dales and PDNP planning officers (Chatsworth Settlement Trustees, 2015, B Garstang, personal communication, 1st September 2019). The rural setting of the Chatsworth weirs would make transmission of the HEP generated very difficult in this landscape, impacting significantly the financial viability of the project (ibid). Planning delays led to the project being caught in the FiT degression system and, facing high connection charges, led to its cancellation.

The Ambergate community hydro project, which I led (2012-2018), came within the jurisdiction of Amber Valley Borough Council (AVBC), and whilst the site was located in the DVMWHS, it was not one of the key heritage sites. It was an active industrial premises in 2012, when the owners were first approached about a community HEP reinstatement, on a site that shut down its self-generation in the 1960s. Following good practice at the time, contact was made with the planning department to see if planning permission would be required, as the project would be simply refitting a turbine into an existing turbine pit inside the factory, and replacing the existing inlet sluices and screens. Between 2012 and 2018 the AVBC planning office was never able to respond as to whether or not planning would be required, but the community energy team completed the planning related work, just in case. The Ambergate site had produced HEP using a weir built in the 1940s and an extended tailrace built in the early 19th century (Section 3.2.4.2), enabling more power to be generated, but this was subsequently interpreted by the EA as causing a depleted reach (ADVyCE – EA, 13 May 2014) (Section 5.5.2.1). Screens that had been used in the past to protect the turbines and prevent fish entering the intake channel would, under revised regulations, also have to be replaced with finer spacing, reducing the flow of water (reducing HEP potential) and efficiencies due to more frequent blockage (ibid). Unlike under the original Salmon Fisheries Act (Section 3.5.3.2) the HEP potential would be harmed by the reduced flow and at the cost of the HEP developer, rather than the 'conservator'. The project was put on hold in 2018.

These three DDC 'failed' projects confirm that, in addition to the physical complexity of developing HEP, other, man-made, factors such as planning and consenting, impact on the possibility of future HEP development and are discussed further in this chapter.

5.3 Electricity: Supply and demand

Figure 4.20 shows the growth in electricity supplied across the UK between 1920 and 1988, primarily generated using coal. Reviewing the UK government energy data since the electricity industry’s nationalisation (1948) to 2018, a number of generation changes can be seen (Figure 5.9). Demand for electricity continued to grow until 2005, but, critical to the volume of renewable electricity required, there has been an overall reduction in electricity usage since then (Figure 5.9), due to improved energy efficiencies as well as economic factors, including high electricity prices. The variation of percentage of electricity supplied from HEP (relative to the total) (Figure 5.9) relates to the variation in overall electricity supplied rather than a significant increase in HEP generation since 2010.

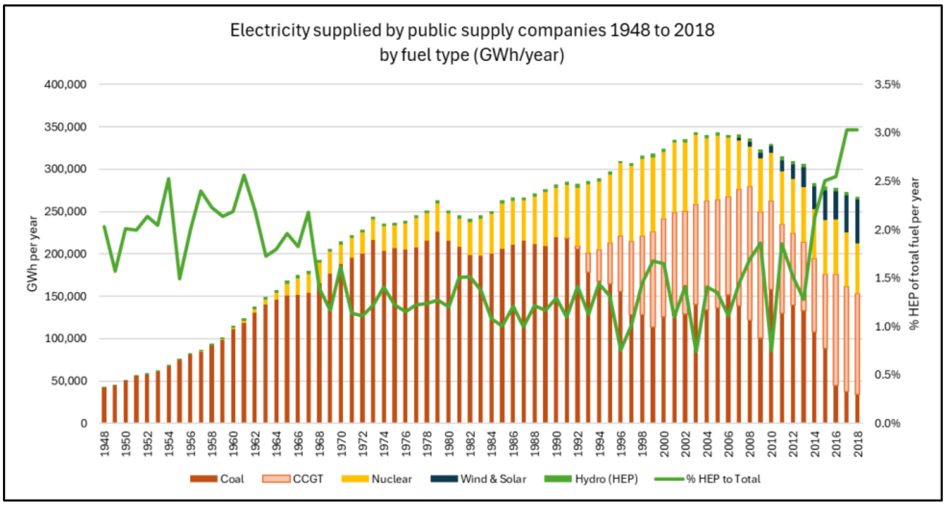


Figure 5.9 Electricity supplied in the UK by public supply companies 1948 to 2018 (BEIS, 2019)

Figure 5.9 also shows the continued growth of nuclear power, supplying approximately 25% of the UK’s energy needs through the 1990s. In efforts to decarbonise the UK’s National Grid, the first priority was to close down the coal-fired power stations. The privatisation of the electricity industry (1990) allowed a proven technology to facilitate the ‘dash for gas’, moving to combined cycle gas turbine (CCGT) generation, taking advantage of the lower fuel price with improved environmental performance (Winskel, 2002). The decline in coal use hasn’t been a steady fall, with other factors having an effect in recent years, such as unavailability of nuclear-generated electricity causing an unexpected spike in 2006 and varying fuel prices disrupting markets, in particular for gas (Figure 5.10) (DESNZ, 2023).

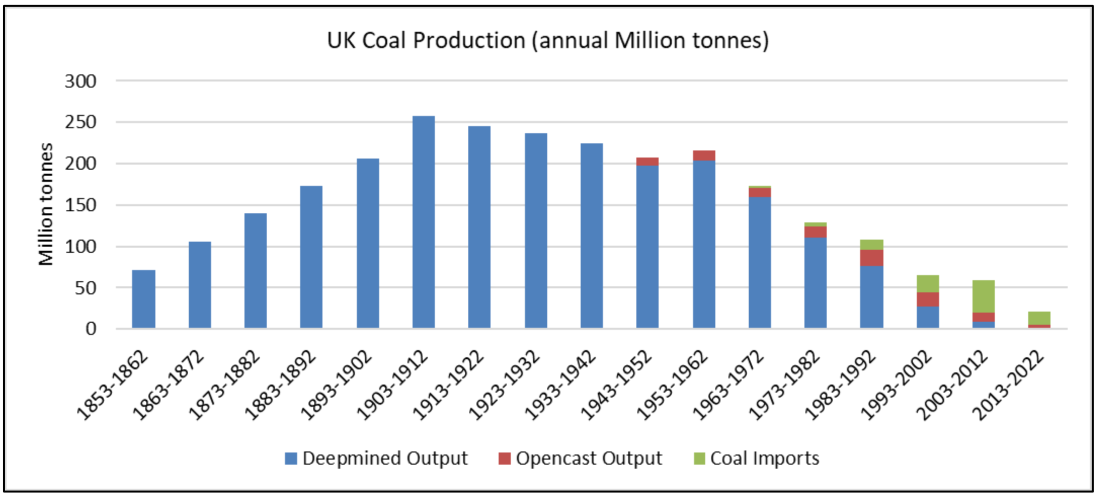


Figure 5.10 UK coal production 1853 to 2022

The largest electricity power station in the DDC, at Spondon (Section 4.3.1.2), was redeveloped for a third time in 1995, using CCGT technology, replacing the inefficient Spondon H combined heat and power station (Heath and Hunt, 2017). The CCGT Derwent Power Station was still relatively small, aimed at delivering steam and electricity to the Celanese industrial site and exporting any surplus electricity to the national grid (ibid). The power station continued to operate until the closure of the Celanese plant in 2012, with no local demand for the steam (ibid). The site was purchased in 2018 by Peel Environmental, with plans to refurbish the gas power station, claiming it would provide a flexible power source to support the growth in renewables that are largely intermittent and weather dependent (Robin Johnson, 2018). In Peel's planning application, which failed, they claimed the reuse of an existing site would be good for security of supply and would enable local power production (Lodge, 2020).

5.3.1 Renewable energy in the UK electricity supply

Large scale HEP development, in Scotland and North Wales (Figure 5.11), appears to have halted in the 1960s with the overall generation level of HEP produced by public companies remaining around 3,700 GWh/year (Figure 5.12). Despite this lack of growth, HEP remained the largest source of renewable energy in 1994 (Figure 5.13), but through the 2000s, solar PV, onshore wind, offshore wind and biogas, replaced HEP as the primary renewable energy source (Figure 5.14).

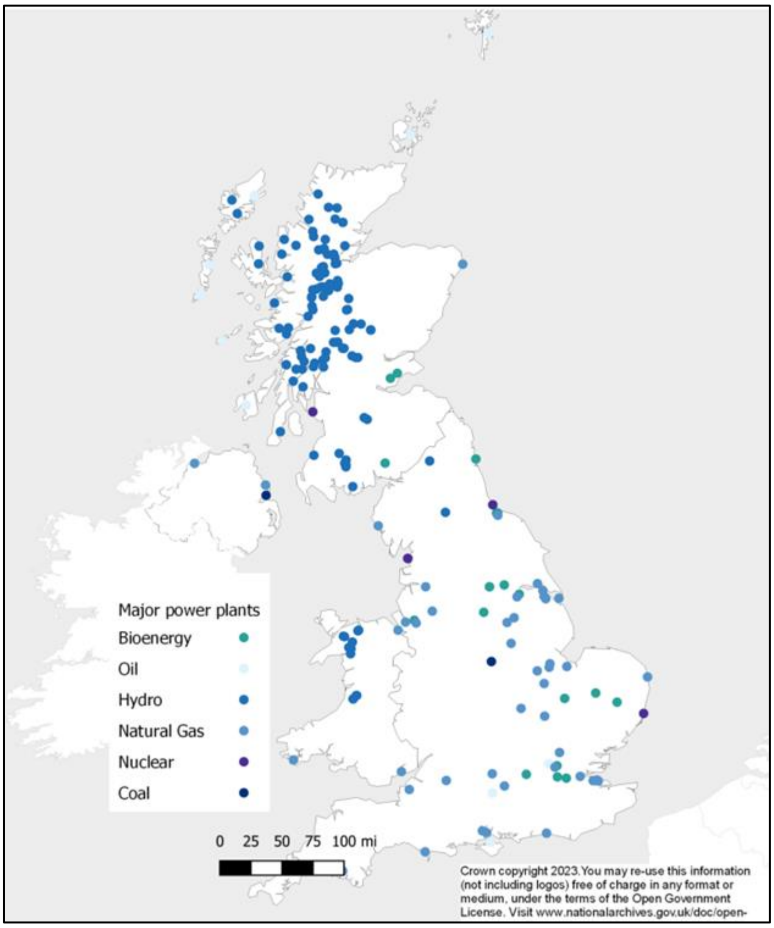


Figure 5.11 Map of UK major power producers, May 2023 (DESNZ, 2023)

Within the UK, Scotland has always been the main producer of HEP and in 2000 it accounted for 90% of Scotland's electricity (Sample, Duncan et al., 2015). In a pattern very similar to the early 20th century, when coal became the primary fuel to meet the growing demand for electricity, despite a slight increase in HEP generation, by 2012, a combination of growth in demand and a rapidly expanding wind sector meant HEP only produced 33% of Scotland's electricity needs (ibid).

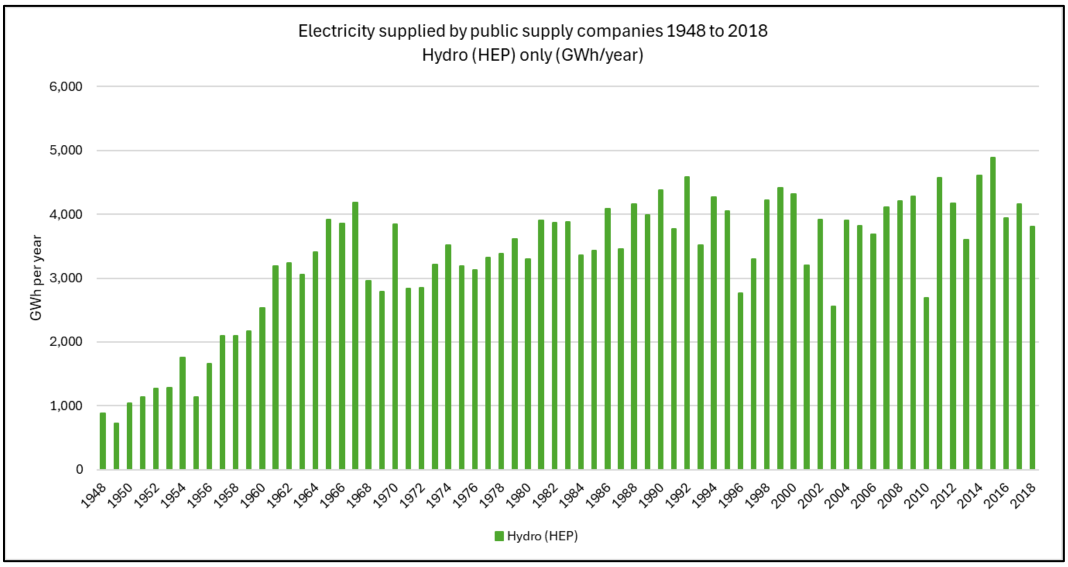


Figure 5.12 Hydro generated by electricity suppliers 1948 to 2019 (BEIS, 2019)

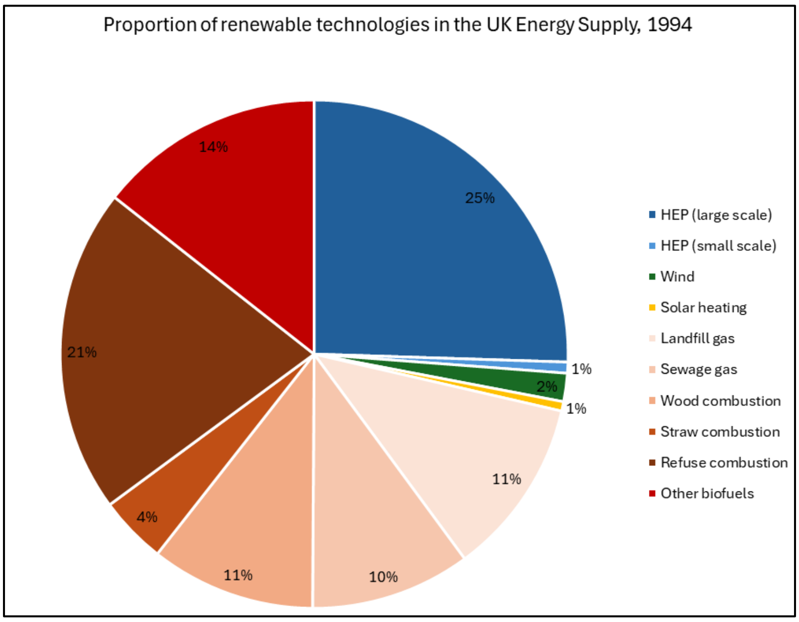


Figure 5.13 Proportion of renewables - UK energy supply (1994) (Walker, 1997 72)

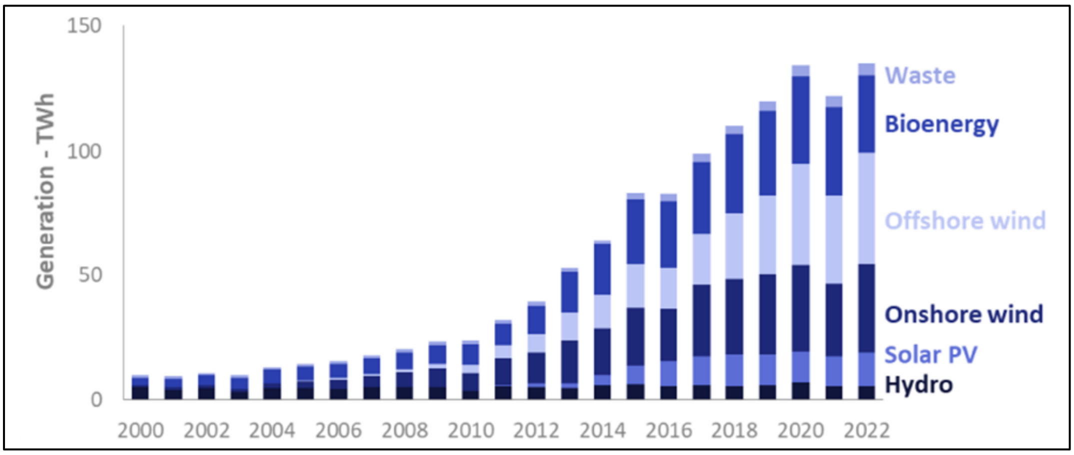


Figure 5.14 Trends in renewable energy generation by technology 2000 to 2022 (DESNZ, 2023 6)

5.3.2 HEP potential in the UK

Section 1.4.5 discusses the UK government's current view of HEP as insignificant in terms of overall future generation plans. Responding to a presentation of my research findings in June 2022, the Minister of State for Energy, Clean Growth and Climate Change stated that HEP accounts for approximately 2% of the total electricity generation (Hands, 2022). Regarding remaining resource, he states that it is 'less than 1% of total generation' and is subject to economic and environmental constraints (ibid); there is no reference to the total technical potential of HEP, or potential achievable with the removal of the government man-made constraints. No comprehensive technical HEP potential assessment has been completed for the UK, but, despite this, the government claimed the UK has 'a maximum remaining technical potential of around 1.5 GW for small-hydro, including existing weirs' (PA UIN 180362 14 April 2023).

The most recent national HEP potential study, commissioned by the British Hydropower Association (Wilson, Day et al., 2022) reviewed past studies and highlighted some of the issues relating to their accuracy. Since 1989 a variety of HEP assessments have been undertaken for different regions across the UK, with very different outcomes, as a result of the different scopes of HEP considered, methodologies used, and inclusion / non-inclusion of economic constraints. Each study has applied different economic (e.g. current electricity prices, with or without different subsidies) or environmental (e.g. WFD river quality) constraints. Each study, includes accuracy disclaimers, including the EA mapping of hydropower opportunities study in 2010, which is still used as a reference by the UK government (EA, 2010). This stated that individual site data may be inaccurate but assumed that overall any errors should be averaged out. It also states 'there is not a high level of confidence in the power generation calculation' (EA, 2015 1).

The 1989 Salford Energy Technology Support Unit (ETSU) study identified a future potential HEP of 322 MW, across the UK. Since then over 500 MW has been installed (Wilson, Day et al., 2022), with at least another 1 GW available (ibid), questioning the value of historic, constrained studies. A detailed study of Scottish additional potential in 2003 provided three totals, a technical potential of 1,000 MW, reduced to 500 MW by planning and 270 MW when current financial constraints (e.g. electricity prices) were added (ibid 8). A more robust study of Scotland's resource five years later identified a far higher 2,593 MW technical potential (in addition to the installed 1,354 MW), being reduced down to 657 MW when specific financial constraints were applied (ibid 8).

The EA's 2010 *Mapping Hydropower Opportunities and Sensitivities in England and Wales* report, investigated their 2010 dataset of barriers in the rivers. The barriers in the study were collated from the OS Master Map and included waterfalls, weirs, dams, barrages and locks (EA, 2010 5). The EA applied a different constraint, identifying only win-win opportunities at existing weirs in a WFD classified 'Heavily Modified Water Body' (HMWB) waterway, with a medium to high power potential (ibid 60). This led to HEP opportunities only being listed as 'win-win' if they gave the EA an opportunity to improve a waterway's WFD status by incorporating fish passage on a weir (as a condition of abstraction licencing) that, under normal circumstances, could not be removed to improve the river's WFD status (ibid 61). The study identified nearly 25,935 barriers totalling 1,178 MW of HEP potential, including 4,190 'win-win' sites with an estimated 526 MW of HEP potential (EA, 2010 61 64). An analysis of the EA dataset identified 52 'win-win' weirs within the DDC area (Figure 5.15). Figure 5.16 compares these with the DDC sites that have generated HEP either in the past or currently, revealing some overlapping of site findings.

Using previous study findings, and analysing a number of current renewable energy databases, the BHA (2022) found an installed HEP capacity of 2 GW across the UK. Using past study information, combined with current HEP developer plans and feedback, they declared a restricted additional deployment potential of 1 GW, based on economic constraints (Wilson, Day et al., 2022), rather than the much larger, but unassessed, technical potential. Since 2017 the UK's total installed electricity generation capacity has been above 100 GW, (HM Government, 2021)(BEIS, 2021), confirming HEP's current position of supplying approximately 2% of the UK's electricity demand.

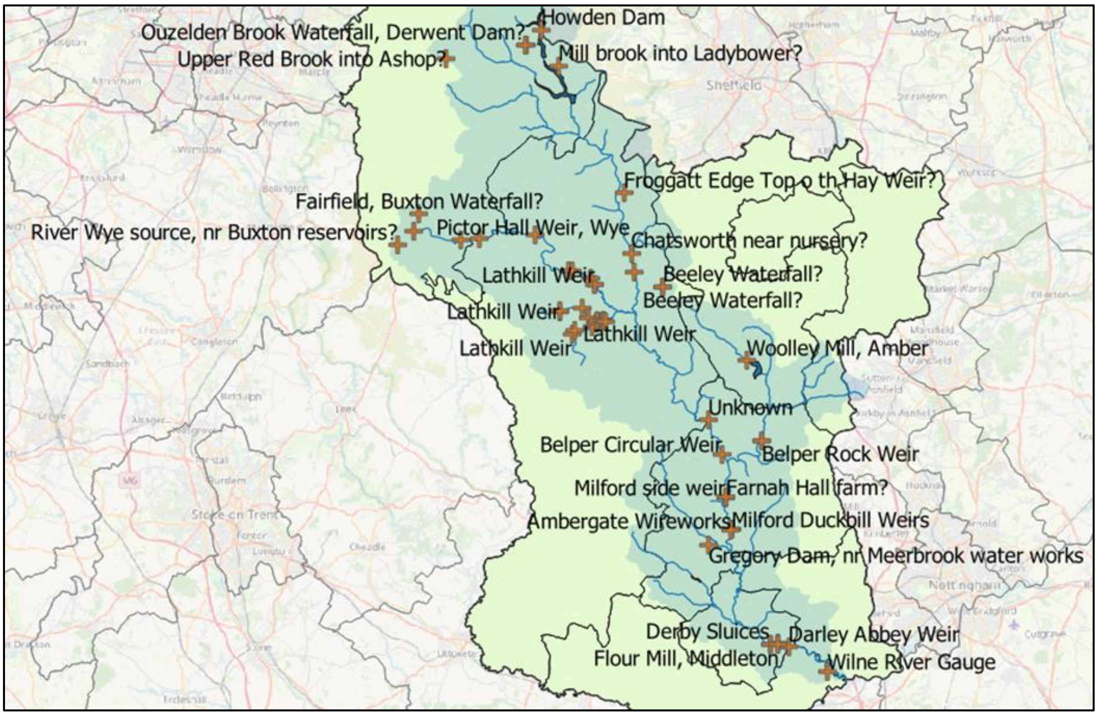


Figure 5.15 EA 'win-win' sites identified in the DDC

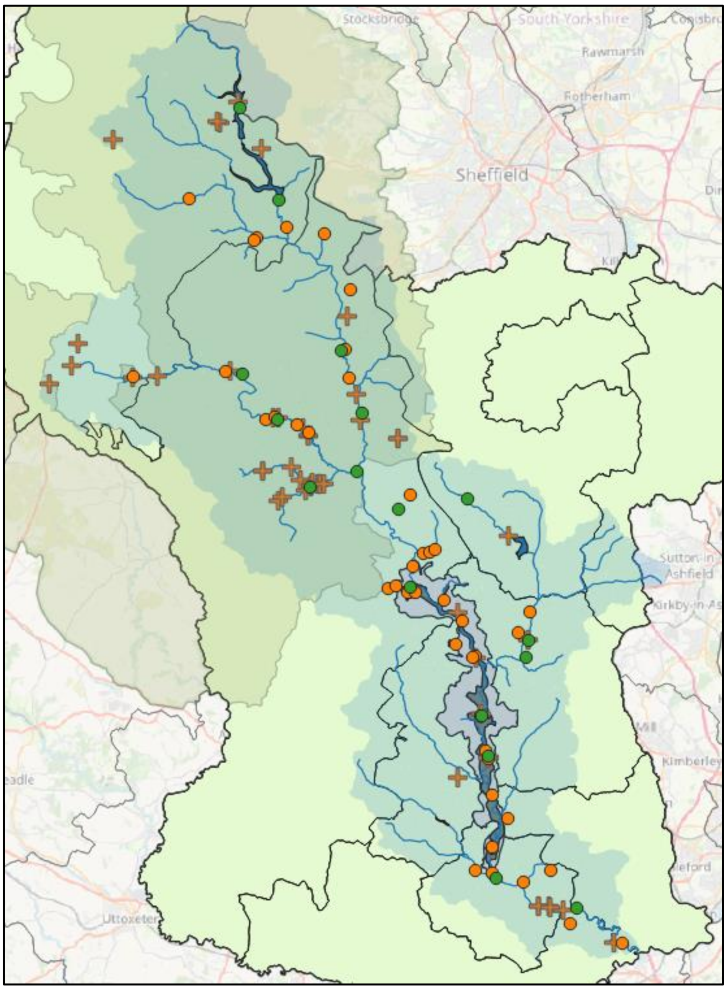


Figure 5.16 EA 'win-win' sites (brown cross), generating HEP sites, 2023 (green dot), former HEP generating sites (orange dot)

5.3.2.1 HEP Potential in Derbyshire

Whilst not all 164 former watermill sites identified in the DDC have the potential to install HEP today (e.g. St Mary's weir in Derby has been removed), opportunities may exist in those sites that generated HEP in the first half of the 20th century, if the infrastructure remains. In a local response to the global challenge of climate change (and encouraged by UK government fiscal support), HEP potential studies, covering different areas of Derbyshire, were carried out by the Friends of the Peak District (FotPD) (2010) and Transition Belper (2012).

The most comprehensive Derbyshire study (over 150 sites in the Peak District were surveyed) was carried out by the FotPD, whose aim was to encourage local residents, community services, local businesses and others, to consider harnessing waterpower, as part of a move towards more sustainable lifestyles, whilst protecting the special features of the National Park (Woods, Tickle et al., 2010). The small HEP potential assessment was based on all known watermill or waterpower sites, with information gathered from specialist publications, databases, map-based resources, community consultations and interviews with HEP experts; a similar approach to that used in this research project. The FotPD report identified small HEP as suitable for the National Park, as a form of renewable energy that wouldn't dominate or ruin landscapes, and offering a source of energy in rural communities with minimal industry (ibid). The report included the natural, cultural and policy constraints in their site assessments, which were particularly challenging as a national park, but didn't question these policy constraints or suggest the user group could also become a lobbying organisation (ibid 1).

With no readily available HEP potential study available for the DDC, which is the geographical focus of this research project, HEP potential studies for Derbyshire were reviewed. The three studies including assessments for Derbyshire were compared with the findings of the HEP potential calculated in Chapter 2 (Table 5.2).

Table 5.2 Summary of HEP potential studies for Derbyshire

	No. of sites	Capacity MW	No. of sites	Capacity MW
	East Midlands Councils (2011) (Technical potential) **(Land Use Consultants, Centre for Sustainable Energy et al., 2011)** Based on EA (2010) – *Based on FotPD (2010)*			
	EA win-win barriers		EA all barriers	
Amber Valley		1.39		3.20
Bolsover		0		0.05
Chesterfield		0.04		0.34
Derby		1.20		2.64
Derbyshire Dales		*0.74*		*0.74*
Erewash		0.64		2.91
High Peak		*0.66*		*0.66*
North East Derbys.		0.04		0.32
South Derbyshire		0.68		2.78
Derbyshire		**5.39**		**13.64**
	Derbyshire County Council, (2012) (Improvement and Scrutiny Committee, 2012)			
	2012 Installed		2012 Installed + Planned	
Derbyshire	17	**2.4**	22	**3.0**
	Derbyshire Spatial Strategy (2022) (Scene Connect, 2022)			
	2022 Installed		Future potential	
Derbyshire	14	**1.7**	14	**1.7**
	Research HEP potential assessment (2024) (Table 2.5)			
	2022 Installed		Future technical potential	
DDC	17	**2.2**	144	**5.5**
Derbyshire	25	**3.3**		
	Note: not including Severn Trent Water potential			

The 2011 East Midlands Council’s study used the findings from the EA (2010) study for its assessment of HEP potential, including the restricted win-win sites and the total technical potential, by local authority area. Where more detailed assessment information was available the findings were incorporated, therefore the Derbyshire Dales and High Peak potentials were identified from the comprehensive and more accurate Friends of the Peak District study (Woods, Tickle et al., 2010), previously mentioned.

The HEP potential studies (2012, 2022) developed for Derbyshire County Council (DCC), and used to support policy and action plan development (Scene Connect, 2022 13) have identified considerably lower levels of HEP potential, and existing installation, compared to the East Midlands (2011) study and these research findings, both based on site-by-site analysis. Neither of the DCC studies referenced the East Midlands study in the reports, or the EA (2010) potential by local authority used by the East Midlands report. The Derbyshire spatial study (2022) was completed by the consultants Scene Connect for DCC, using an adapted spatial assessment framework (DECC, 2010), although they didn't follow the recommendation of using the EA (2010) findings in their future potential assessment. Scene Connect filters out large HEP potential schemes, quoting (BEIS, 2013) guidance on HEP assessment methodology.

Harnessing the power of water for electricity generation is not restricted to run-of-river (e.g. former watermills) opportunities, with other technologies such as the large-scale reservoirs, tidal range and pumped storage, all able to play a key role in the UK's net zero plans. Whilst tidal power is not considered in this research project, Chapter 2 identified non-mill sites, including the drinking water infrastructure, country houses, sough water tails and weirs (pump and canal) as sites capable of generating HEP. Only the Peak Sub-region study (2009) mentions Severn Trent Water and United Utilities assets, both water companies in the Peak Sub-region, that were in the process of investigating future potential, considering impounding reservoirs, flows in water distribution networks, sewage treatment outfalls and run-of-river (reservoir inlets) (National Energy Foundation and Land Use Consultants, 2009 60-72).

5.3.2.2 HEP Potential in the water industry, including the DDC

The most significant non-mill HEP opportunities in the DDC, are within the water utility assets owned by Severn Trent Water (STW), which could offer larger scale and pumped storage HEP. Section 4.4.1.1 noted that the 'compensation flows', for the industrial watermill owners of the Derwent Valley, were based on 1/3rd of the annual available rainfall, with the remaining 2/3^{rds} available to the water company. The water 'lost' by the waterpower generation sites, due to drinking water abstraction in the upper Derwent, could potentially be utilised by STW for HEP generation (including energy recovery) within their network.

Research across the globe into HEP generation within the water industry focusses on three areas: raw water networks (storage (or service) reservoirs (SRVs)), water distribution networks (break pressure tanks (BPTs) and pressure reducing valves (PRVs)), and wastewater treatment plants (inlets and outlets to the wastewater treatment plants (WWTPs)) (Gallagher, Harris et al., 2015).

Storage (or Service) Reservoirs (SRVs)

Typically, reservoirs located in the uplands of a given water catchment have the greatest potential for electricity generation (Gallagher, Harris et al., 2015). Water industry reservoirs' primary purpose is to store water, but, by design, they create a head that could generate HEP, subject to the flows released by the reservoir, normally a controlled compensation flow, the intermittent over-spill flow and the abstraction flow (often to a water treatment site). The reservoirs of Howden, Derwent, Ladybower, Carsington and Ogston potentially offer the largest opportunity for HEP generation within STW's DDC assets, and potentially in the whole DDC. Today, HEP is being generated using compensation (250 kW, 2007) and overspill flows (250 kW, 2010) from the Ladybower Reservoir (Figure 5.17 left) and transfer flows from the Howden Reservoir to the Derwent Reservoir (300 kW, 2017) (Figure 5.17 right). The turbines at Ladybower have been upgraded several times since their original installation (1945 [Table 4.2]), with renewable energy subsidies facilitating their latest upgrade and the addition of the turbine at Howden. Figure 5.18 shows the HEP generated by the STW reservoir turbines.

A study, commissioned by STW in 2008 to look at HEP potential, ruled out two major opportunities, 700 kW and 900 kW, using the Howden, Derwent and Ladybower reservoirs, due to risks associated with the aged network (Dent, 2008).

Figure 5.17 Turbines installed at Ladybower Reservoir (left) (kind permission of Ladybower Reservoir facebook) and Howden Reservoir (right) (Photograph: Author, 2019).

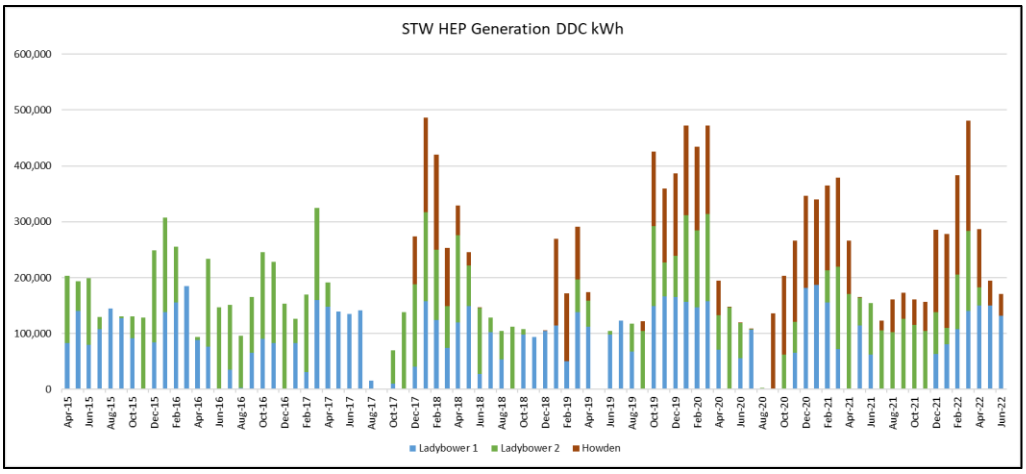


Figure 5.18 Monthly HEP generation from the STW HEP turbines in the DDC (Jackson, 2023)

Pumped Storage Hydro (PSH)

Section 3.3.1 discussed the valuable role of the mill pond and the recirculation of water using steam pumps, and in one case a windmill, to optimise the storage and use of power, historically. Until the development of responsive CCGT gas generation, the only energy storage option in the UK has been PSH, originally developed to help balance the national grid at off-peak and peak times, with a large nuclear baseload (Bailey, 2020).

Globally, PSH has been in use since the beginning of the 20th century and in 2020 contributed 90.3% of the world's energy storage (Hoffstaedt, Truijen et al., 2022). The development of the more flexible gas turbines in the 1990s not only replaced coal fired power stations in the UK, they also reduced the importance of PSH (Bailey, 2020). However, the combined cycle gas turbines (CCGT) are fossil fuel powered and will have to be phased out to meet Net Zero targets, which, combined with the expansion of renewable generation (particularly wind and solar) that has resulted in greater intermittent generation, increases the importance and value of PSH (BEIS, 2022).

Opportunities may exist within the current STW reservoir assets of the upper Derwent valley (Howden, Derwent and Ladybower), and also in the Carsington – River Derwent – Ogston network, which already have pumps in place that could generate, or recover, HEP, a technology known as Pump As Turbines (PAT). With a head of approximately 115m between Carsington Reservoir and the River Derwent, a HEP opportunity study, based on current abstraction licence volumes and an alternative, maximum flow based on current infrastructure, would determine the potential of repurposing the Carsington Reservoir as both a water and energy store. Ogston, with a 40m head to the Derwent abstraction station, may also offer a PSH opportunity. The *Derbyshire Spatial Study* (Scene Connect, 2022) only included battery storage capacity in their report, missing the potential available of PSH within the existing DDC reservoirs.

Water Distribution Network (BPTs and PRVs)

Break pressure tanks (BPTs), or newer Pressure Relief Valves (PRVs), are located in upland water pipelines to release excess pressure to the atmosphere. A HEP turbine can be used to recover energy (c.20 kW) prior to the break point, rather than a PRV, without impeding downstream pressure (Gallagher, Harris et al., 2015, McNabola, Coughlan et al., 2014). Figure 5.19 shows typical scenarios for the use of BPTs, and therefore HEP recovery opportunities (McNabola, Coughlan et al., 2014 295), and can be compared to the cross section of the gravity fed Derwent Valley aqueduct, Figure 5.20. Whilst there is evidence that the Derwent Valley Water Board, predecessor to STW, installed turbines to ‘recover’ electricity between the 1920s to 1950s (Table 4.2), there are no known turbines currently operating in the STW distribution network, including the Derwent Valley aqueduct (Figure 5.20) or underground reservoirs at Ambergate and Spondon (Jackson, 2023).

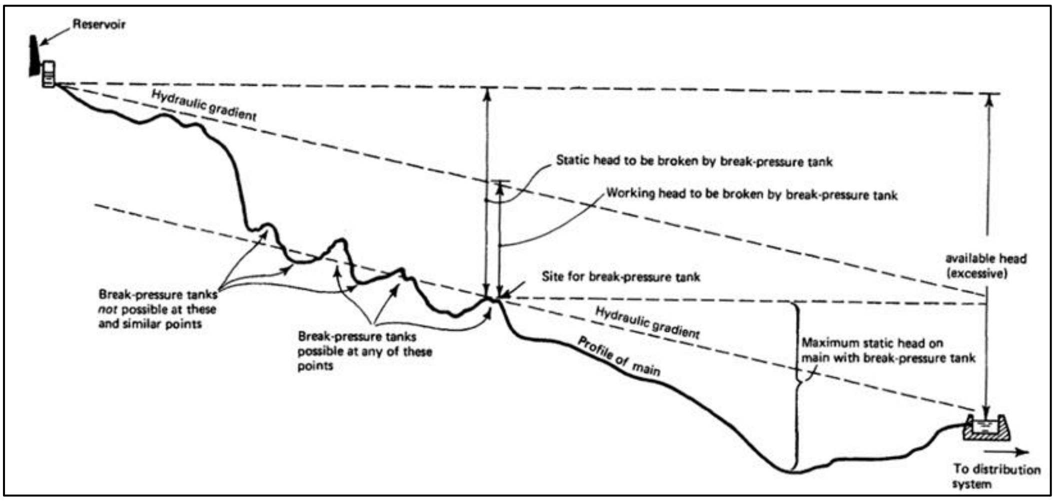


Figure 5.19 Typical scenario of break pressure tank in a water distribution network (McNabola, Coughlan et al., 2014)

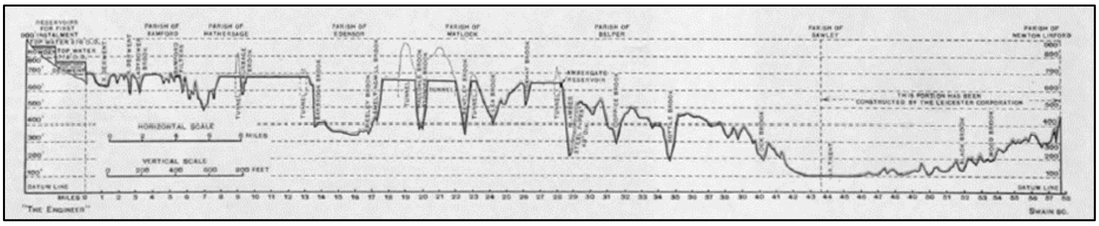


Figure 5.20 Profile of the STW Derwent Valley aqueduct. (The Engineer, 1912 59)

Wastewater Treatment Plant (WWTPs)

At the treatment end of the water utilities network, the flow of sewage effluent entering, or treated effluent exiting, a WWTP can also be considered for energy recovery using HEP (Gallagher, Harris et al., 2015)(Gallagher et al, 2015). STW carried out a HEP potential assessment across their WWTP assets in 2008, identifying 25 sites (including the 20 largest sites) for assessment. The report included two WWTP sites in the DDC and, applying their economic criteria for feasibility, found the Derby site had no HEP potential and the Buxton site had some potential, approximately 7.5 kW (Jackson, 2023).

Water utility HEP development

Following difficulties in developing HEP opportunities within their assets, the UK water industry carried out research (Black, Straker-Smith et al., 2015) into the barriers preventing renewable energy scheme development. A survey of the industry identified technical, regulatory and policy, stakeholder, financial and administrative barriers, impacting on the uptake of renewable energy (ibid). During the author's placement with STW it was apparent that a practical barrier to HEP development related to the water industry regulator, Ofwat, which approves capital programmes. Ofwat require the prioritisation of investment in the industry's primary activities of water supply and treatment (H Perry, 2023, personal communication 24th March 2023). This almost identical situation was described in Francis's first study of small HEP potential (Francis, 1978 320) in the water utility industry, before privatisation. If capital were to be approved for renewable energy investment by Ofwat, it must be the most cost effective (quick rate of return), putting potential long-term hydro projects behind technologies such as solar PV and onshore wind. The role of Ofwat may explain why the UK Water Industry trade body (Water UK)'s Net Zero 2030 Routemap only includes solar PV and onshore wind as future renewable energy options, despite the obvious HEP potential within the water industry's assets (Ricardo and Mott Macdonald, 2020 31)

5.4 Water: Supply and demand

5.4.1 Derbyshire Derwent catchment river flows

Concerned over the ecological impact of the Derwent Valley reservoir river diversion schemes, completed in 1951, the EA commissioned a study in 2001. Using a habitat modelling approach, the feasibility of changes in operations were studied and proposals were produced, including compensation control rules for both normal and dry years and seasonal variability (Maddock, Bickerton et al., 2001). Section 1.3.3.3 discusses environmental flows and the research being carried out aiming to modify flows, such as compensation flows, originally designed to protect species (Neachell and Petts, 2017), but now aiming to optimise flows to store water, improve river ecology and optimise HEP generation around peak demand periods (Kuriqi, Pinheiro et al., 2019, Song, Omalley et al., 2019, Zarri, Danner et al., 2019).

Maddock, Bickerton et al. (2001 420) stated 'the EA and STW are unclear as to the exact reason for the size of the historic flows in Jaggers Clough and the River Derwent […] Likely to have been allocated based on the requirements of abstractors/mill owners downstream'. This suggests the EA, STW or the authors didn't refer to the original Derwent Valley Act, which states why and how the Derwent compensation flow was calculated (Section 4.4.1.1). This 2001 study mentioned existing abstractors who would be impacted by the proposed changes to compensation flows, one negatively (ibid 437), but it doesn't indicate if the abstractor was a past or present HEP generator, missing the opportunity to find an optimal solution for all parties. The report also claimed there was no documented compensation flow for the River Noe, but the owner of Brough and Hope mills, Marmaduke Hallam Eyre, who had petitioned against the diversion of the river, accepted the £8,000 compensation with a guaranteed flow of 3,513,000 gallons per day (0.185 m^3/s), versus a typical 17 million gallons per day (winter) average (0.90 m^3/s) (Eyre, 1988 99).

Ladybower Drawdown

As part of their flood management responsibilities, STW can ‘drawdown’ Ladybower Reservoir, with a controlled release of additional water into the River Derwent, creating storage capacity to capture the additional volume of water resulting from a forecasted heavy rain or snow melt event. The drawdowns, coordinated by the EA and STW, release approximately 550 mega litres of water per day (6.37 m^3/s), increasing the river level at Chatsworth by approximately 20 cm (EA and STW, 2023). Drawdowns do not take place between February and July, to protect water supplies through spring and summer, but typically a drawdown will take place in autumn to create extra storage capacity for the expected heavier rainfalls (ibid).

Global research and practical trials (Section 1.3.3.3) suggest that variable (environmental) flows from the Derwent Valley reservoirs offer the flexibility to deliver dynamic releases of water, producing more HEP during peak demand periods (4pm to 7pm) and optimising water flows to suit river ecology and fish migration, in addition to their primary water storage function. This is an opportunity to produce more high value renewable energy, using existing HEP run-of-river sites on the River Derwent, during the highest period of energy demand, the winter, using releases from the reservoirs.

5.4.1.1 Sough water

An alternative, smaller, source of water for generating HEP, are the historic mine drainage soughs (Section 3.4.1.1). During the walk-over surveys (Section 2.2.5), HEP generation using sough water was discovered at a former corn mill, now a private residence. Harnessing the power of sough water should be less environmentally challenging, with no weirs involved. A study of sough water tails entering the Severn Trent catchment, includes details of the most significant running into the Derwent and its tributaries: Meerbrook Sough, Bradwell Sough, Hillcarr Sough, Magpie Mine Sough and Millclose Sough (Figure 5.21) (Oakman, 1979). This report could be used as a reference for a future HEP assessment incorporating active sough flows.

Redacted: Unable to trace author.

Available in the Derbyshire Local Studies Library.

Figure 5.21 Plan of soughs in the DDC (Oakman, 1979 Part 1 Figure 4)

5.5 Waterways: Environmental impacts

During the 20th century, the Derwent ceased to be considered a salmon river, as new weirs were built by the river authorities, as late as 1992, with no facility for fish passage, despite the Salmon and Fisheries Acts (1861 to 1975) requiring such facilities in new weirs built in waters frequented by salmon (Salmon and Freshwater Fisheries Act, 1975 Part 1 9). Responding to the new, EU, Water Framework Directive 2000 (WFD), opportunities to improve fish passage within the DDC were sought. Management of the DDC waterways during this research period (1989-2023) changed, evidenced by several retrospective fish pass installations, including a fish pass being added, at considerable cost, to an EA gauging weir, built in 1992 at Whatstandwell, in 2014 (post WFD) (Section 5.5.3).

The repowering and development of HEP sites since 1990 has taken place against a background of often competing, but sometimes complementary, policy discourses (Slee, Whitfield et al., 2011). The development of HEP can generate income, based on clean energy, rewarding landowners and local communities for their environmental stewardship (ibid 54). Alternatively, alterations to flow regimes such as depleted reaches, fish passage barriers, and loss of weir-pool habitat may adversely affect fish populations, which may in turn lead to downgrading of water body status under the Water Framework Directive (WFD) (Sample, Duncan et al., 2015). New HEP schemes have also frequently been opposed by influential stakeholder groups, such as the WWF, with preservationist agendas (Slee, Whitfield et al., 2011).

Climate change is expected to lead to an intensification of the global hydrological cycle, leading to changes in both the magnitude and seasonality of river flows, potentially affecting the water available for energy generation (Sample, Duncan et al., 2015 111)

5.5.1 River Derwent weirs

Other than the waterwheel or turbine, the most significant element of run-of-river waterpower is the weir. Section 3.2.4.1 identified the historic weirs in the Derwent and Section 4.5.1 discussed the dangers of weirs becoming a maintenance liability to their owners and being allowed to fail, as per the St Mary's weir Derby, eventually removed during the 1960s. There is a threat to HEP, for both existing and future generators, due to the physical condition of the historic weirs, gates and sluices that are critical to the creation of the head and diversion of water, to enable HEP generation in the DDC. This research has introduced the concept of the industrial mill owners' role as river stewards but there remains a gap in our knowledge, and an opportunity for future research, regarding some very important (power, heritage and local economy) weirs in the DDC, not only historic information about their original design (including flood management and fish passage) and build, but also their current ownership and condition, e.g. Belper weir (Grade II* 1335702) (Figure 5.22). Currently, many DDC weirs (some granted the 'protection' of being listed by Historic England) are not being used for their original purpose and are therefore a potential liability to their owners (Figure 5.23). Changes in land ownership have also meant that today's HEP developer may not own the weir and therefore has limited, if any, control over its maintenance, as recently evidenced by the failure of a historic weir (no heritage listing) in Rowsley on the River Wye, causing the listed Cauldwell Mill (Grade II* 1088147) to lose its HEP generation facility. Highlighting the value of small HEP generation to local communities, the financial impact of losing HEP generation at Caudwell led to the closure of the mill (several small businesses), café and visitors centre in 2023 (R Eastwood, personal communication 5 September 2023). Similarly, a local community set up the Calver Weir Restoration Project in 2004 (Calver Weir Restoration Project, 2004) in response to concerns about the condition of the listed Calver Weir (Grade II 1334720) on the River Derwent. With the support of the Heritage Lottery Fund, the £1.8 million project was completed in 2010 (Figure 5.24), incorporating an improved fish pass, although the project did not use the available Calver Mill wheelhouse to repower the site, which has a 125 kW potential (Woods, Tickle et al., 2010).

In addition to weirs being critical, functionally, they often are the most visible aspect of a HEP generation system, with turbines 'hidden' in former wheel pits or power houses. The weirs, if protected, offer the opportunity to visually tell the story to local communities and visitors of waterpower's heritage value and promote its future potential to generate renewable energy, to help mitigate climate change.

Figure 5.22 Belper circular and northside weirs.. The secondary 'Rock weir', right, with a hole (possible tunnel collapse) (Photographs: Author, 2023 2018)

Figure 5.23 Sluices in a state of disrepair on the River Derwent, Baslow (left) and Milford (right) (Photographs: Author, 2023 2020)

Figure 5.24 Calver weir restored 2004-2010

Both the concern over the impact of climate change on historic sites and the risks associated with weir modifications or removal as a result of the WFD, were addressed in research commissioned by English Heritage (now Historic England) focussed on the DVMWHS, aimed at better disaster planning and building in resilience for heritage (Howard, Coulthard et al., 2017). The study acknowledged the original purpose of the weirs, producing waterpower, but considered if the preservation of the historic weirs was incompatible with the WFD related 'green environmental agendas' (ibid 40). The report also noted concern over the antiquity of many of the weirs and the on-going cost of maintenance, and the changes in potentially contaminated sediment movement following the removal or major alteration of the weirs. The study appears to have treated weirs as fixed barriers, not incorporating the historic floodgates and sluices and their operation, their impact on historic sediment movement or the impact on river ecology. The study has not considered the win-win opportunities of reinstating the remaining historic floodgates and sluices to improve river management, or the wider benefits of reinstatement of the complete watermill landscapes (including HEP generation) by local communities, to deliver economic, environmental and social improvement.

5.5.2 River regulation

Prior to 1989, ten regional water authorities, including the Severn Trent Water Authority, were responsible for the supply and distribution of drinking water, sewerage, land drainage and flood risk management, fisheries, water quality management and pollution prevention in England and Wales (TRA, 1973). In 1989, the water authorities were privatised and a non-departmental public body, the National Rivers Authority, was appointed, with statutory duties including the environmental condition of the rivers and water abstractions. Prior to privatisation a gradual improvement had been reported in water quality over the previous 30 years, with over 90% of surface fresh water described as good or fair (Sheail, 1998 133). River pollution incidents relating to new rural farming practices were identified in the 1980s (Ward, Lowe et al., 1995) and there was evidence of a slowing down and even reversal in improvement trends in 1990 surveys, raising concerns about the future of the waterways (post 1998), requiring positive and concerted action by the new water companies (Sheail, 1998).

The Environment Act 1995 created the Environment Agency (EA) in 1996, covering England and Wales. The Agency took over the functions relating to waste regulation, water pollution and water resources, radioactive substances, and most aspects of integrated pollution control (Bell, McGillivray et al., 2017 24). The EA effectively replaced the National Rivers Authority, Her Majesty's Inspectorate of Pollution and the waste regulation authorities. It had responsibility to improve the quality of waterways and manage water abstraction resources, thereby indirectly regulating the HEP industry in England and Wales. In 2000, a select committee was created to report on criticisms of the EA from a wide group of stakeholders. The committee acknowledged the challenges for the EA, formed from 86 predecessor bodies and the large range of disparate functions, including conservation of salmon stocks (Bell and Gray, 2002 77). The adoption of the select committee's recommendation, to be a champion of both the environment and of sustainable development, highlighted the tensions within the organisation, with the latter involving the reconciliation of economic, social and environmental goals, whilst the former only concerns the environment (ibid).

HEP projects may require up to four permits from the EA (including abstraction licencing), planning permission from the Local Authority, and consultations with local communities and other river stakeholders (Armstrong and Bulkeley, 2014, EA, 2013). Receiving over 100 HEP submissions annually, following the introduction of FiTs in 2010, compared to typically less than 20 applications per year, the EA initiated a consultation in 2011 on their 2009 *Good practice guidelines for hydropower*, focussing on four key areas: the Environmental Site Audit checklist, minimum flows in depleted reaches, monitoring HEP abstracted flows and fish protection (EA, 2009). The consultation appears to have influenced EA decisions with variation of consent advice over time, such as depleted reaches, potentially a significant aspect of a historic watermill HEP reinstatement.

5.5.2.1 Depleted reach

Good waterpower practice of the past may not meet the requirements put in place by today's consenting authority, the EA, which impacts on the potential output or viability of historic watermill HEP reinstatements. Describing depleted reaches in their 2009 consultation, the EA stated:

> 'many old mill sites were built with either a moderate length of intake channel, a tailrace channel, or both (often partly culverted). This helped isolate the mill house from flood flows and preserve the driving head during high flow conditions (when the weir itself might be drowned out). Many of these mill races still exist and provide the majority of current opportunities for low head projects' (EA, 2009).

Extending the tail race utilised the natural fall of the river to create additional head, similar to raising the height of a weir, to create more power. The 2011 EA consultation neglected to include the additional benefit of renewable power available from an extended tailrace, resulting from the increased head, and therefore the impact on the economic feasibility of HEP development.

The Alderwasley (Ambergate) site timeline provides an example of the historic use of an extended tail race for more power and the negative impact of modern-day restrictions on water abstraction, because of an extended tailrace, and on the feasibility of a HEP 'repowering' project. Section 3.2.4.2 discusses an 1800s dispute between the Strutts (Belper) and Hurts (Alderwasley) following the raising of the Belper Mills weir, which raised river levels, impacting on the Hurts' lower iron forge upstream. The resultant compensation paid for the building of an extended tailrace from the upper forge (Judge, 1993), increasing the head and augmenting the power available to the upper forge site (wireworks). The Transition Belper study looking for the optimum site to reinstate as a community hydro project, identified the former Ambergate Wire Works, primarily due to the existing infrastructure, including tailrace (Harton, Chandler et al., 2012). Despite the tailrace having continuous flowing water for over 200 years, via partially open sluices and natural land drains, and associated ecology, the EA viewed it (Figure 5.25) as a problem and therefore restricted the volume of water to be available for HEP generation (ADVyCE EA 13

May 2014). The community energy group, ADVyCE, were given the option of accepting the reduced flow or returning the tail immediately to the river, losing head (power potential) and the impacts of high tailrace river levels impacting the economic feasibility. Modifying the tailrace would also incur additional capital costs, incur habitat loss and introduce heritage conservation risk, with changes to structures in the World Heritage Site.

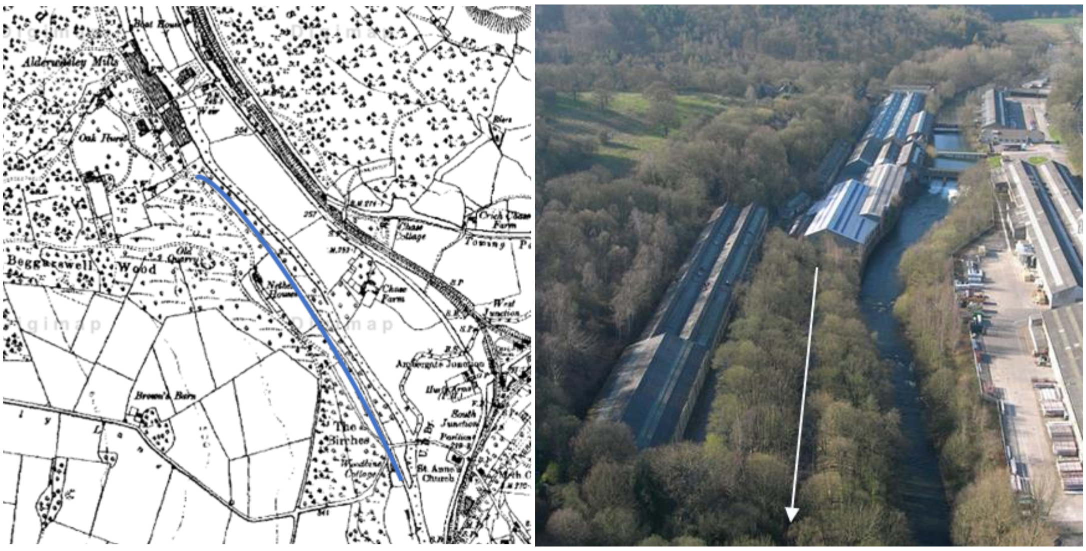


Figure 5.25 Ambergate Wire Works, extended tailrace (blue line on Digimap 1920s OS map), depleted reach or fish friendly watercourse?

A decade-by-decade review of the historic DDC OS maps, identified that several of the larger historic DDC watermills had repurposed historic watermill sites that had originally used natural meanders to create a head (i.e. power) (Section 3.4.1), potentially creating depleted reaches in the Derwent. More recent OS maps (post-1960) show that most of the extended leats and tailraces in the DDC, no longer generating HEP, have been filled and the land used for other purposes, such as house building (Milford Hopping Mill), car parking (Darley Abbey Mills) and public pathways (Darley Abbey park). Whilst loss of the historic depleted reaches in the DDC supports the river ecology it does mean several of the larger historic waterpower sites have a reduced HEP generation potential.

5.5.2.2 Water Framework Directive (WFD)

The WFD was a European Union response to the deterioration of water status and it aims to protect and ensure the good ecological and chemical status of all inland water bodies (Abazaj, Moen et al., 2016 410). Since its inception in 2000, policymakers in Europe have reviewed policy and regulation to try to address the competing interests of two key policies, renewable energy (EU Renewable Energy Directive, 2009) and environmental goals (the WFD) (ibid 415). Hydroelectric Power (HEP) is indirectly affected by the WFD, being identified as the third most common water use for designating ‘Heavily Modified Water Bodies’ (HMWBs) (Abazaj, Moen et al., 2016, Water Framework Directive, 2000 Article 2.9). HMWBs signify waterways with physical alteration and substantial changes in character resulting from human activity, that cannot be removed owing to high economic and social cost (ibid). Weirs are critical to run-of-river HEP schemes, but weirs have been constructed for many reasons, including irrigation, municipal water withdrawal, flood control, low-flow augmentation, recreation and navigation, all potentially having a significant impact on fish movement connectivity (Silva, Lucas et al., 2018). To improve a water body’s ecological status, a priority for the EA is either weir removal or creation of fish passage by weirs, to provide fish movement connectivity, particularly for migratory salmonids. The UKs *The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017* (WFD (UK), 2017) does not discuss climate change directly and it is not clear if the long-term effects of climate change, such as floods, drought and river/marine warming, would be captured in the ‘natural causes or force majeure’ clause, which accommodates a temporary deterioration and not breaching environmental objectives (ibid Part 5 18).

Accommodations to not harm waterpower generation, incorporated into the Salmon and Freshwater Fisheries Act 1975, which is still in force, have not been included into the WFD (UK), potentially causing conflict between the two pieces of legislation, but also providing an opportunity to update the WFD (UK), with amendments offering some protection for the climate change mitigation measure of HEP renewable energy generation.

5.5.3 Fish passes (Trent catchment)

The 1980s studies investigating the reintroduction of salmon into the Trent catchment identified weirs as barriers to fish movement to different degrees (Section 4.5.3.1). A review of past reports and weir assessments highlights some inconsistency in the 'pass-ability' ratings of weirs, and with the different views dependent on fish species. The 1985 Trent catchment study by the Severn Trent Water Authority (STWA) identified and catalogued 110 obstructions with an assessment of pass-ability for migratory salmonids being recorded (Cowx and O'Grady, 1995).

The findings were reused in a number of later reports and, for this research, have been compared to the list of weirs identified in the mill gazetteer (Section 2.2.3) (Table 5.3). The obstruction pass-ability has been updated with the current (2021) EA Weir working documents (R Taylor [EA], personal communication, 15th August 2022). Table 5.3 shows the River Derwent weirs (Wilne Mills closest to the Trent confluence), with the first barriers to fish passage, after the Wilne weir (planned to be removed), identified as the Milford Weirs, although there is no explanation as to why the Derby Riverlands weirs (1930s) have been reclassified as passable, from impassable, in the recent assessment.

The Whatstandwell gauging weir, installed as part of the Carsington pumped storage reservoir project, was built close to the abstraction point in 1992, without fish passage. The fish pass, installed retrospectively in 2014, claimed to open up 72 km of the river for all species of migratory fish, despite the weirs either side at Ambergate (3 km downstream) and Masson (6 km upstream) being classed as impassable (Whatstandwell online, 2014). In order for migratory salmonids to reach the Whatstandwell gauging weir, they would need to pass weirs downstream in the Derwent (Table 5.3) as well as the eight weirs in the Trent which currently prevent migration into the Trent catchment interior. The EA's Trent Gateway project is planning to invest up to £20 million to develop fish passage by these eight weirs in the Trent (Barlow, 2018). The first fish pass on the Trent at Colwick was completed in 2023-24 at a cost of £12m (with the EA stating a calculated £18.6m economic benefit), bypassing the Holme Sluices (owned by the EA), built in the 1950s as part of Nottingham's flood defences. This is to date, the largest fish pass project in the UK (EA, 2024).

Table 5.3 River Derwent weirs, fish passability

Location	Name	Dates Installed, Improved	STWA Trent Report 1985 (data reused by DCAC, 1986 & Cowx et al, 1995 & EA, 2004)	Fish Pass Installed IJ Research, 2022	EA, 2021	
	RIVER DERWENT				Passable	Comment
SK 16985 92454	Howden Dam	1912	no comment			
SK 17267 89832	Derwent Dam	1916	no comment			
SK 19952 85486	Ladybower Dam	1943	no comment			
SK 19802 85082	Yorkshire Bridge River Gauge	1905, 1936	no comment			
SK 19796 85034	Yorkshire Bridge waterfall	natural	no comment			
SK 20458 83369	Bamford Mills (Cotton)	1791	B			
SK 23202 80636	Corn Mill, Leadmill	ancient	D			Broken weir
SK 23346 80599	Corn Mill, Leadmill Bridge	Late 18th C.	D			
SK 241 792	Grindleford Fish Weirs 1, 2	?	D			
SK 24540 75305	Calver Mill (Cotton)	1786, 1799, 1840	A	2010 refurb.		Larinier
SK 25000 72491	Hodgkinson's Flour Mill, Baslow	?	A			
SK 25786 69471	Chatsworth (Upper Weir)	1772	A			
SK 25958 58946	Flour Mill (Lower Weir), Chatsworth	1761-2	A			
SK 29596 59082	Matlock Dale	?				Removed
SK 29554 57484	Masson Mills (Cotton)	1771	C			
SK 33111 54437	Whatstandwell River Gauge	1997	not built	2014 new		Larinier
SK 34163 52245	Wireworks & Forge, Ambergate	1945	A			
SK 34553 48157	Belper, Circular Weir (Cotton)	1796, 1809, 1844	A			
SK 34476 48123	Belper, Rock Weir (Cotton)	1796?	no comment			
SK 34858 45399	Hopping Mill, Foundry Weir, Milford	pre 1717, 1791	A			
SK 35072 45048	Upper Duckbill Weir, Milford	16th century, 1819	D (fish pass)			
SK 35055 45007	Lower Duckbill Weir, Milford	1819	no comment			
SK 35261 42307	Peckwash Mill, Little Eaton	15th century, 1780s	D			Broken weir
SK 35324 38543	Boars Head Mills, Darley Abbey	ancient, 1783, 1793	A	2013 new		Larinier
SK 35370 36688	St Mary's Bridge Weir	pre 1692				Removed
SK 35520 36369	Exeter Bridge Weir	?	no comment			Drowned out
SK 35650 36346	Longbridge Weir, Derby	1793-1797?	A	2012 new + HEP		Larinier, not all species
SK 38689 34239	Derby (Pebble Beach, Cut B) Weir	1934	A			
SK 39495 34147	Derby Sluices	1934	A			
SK 40448 33933	Spondon Weir	1934	A	2012		via loop
SK 41085 34464	Borrowash Mill, Weirs 1, 2, 3	1760s, 1780s	A (weirs 1 & 3)			River diverted
SK 44149 31647	Church Wilne River Gauge	1973	D			some species, removal planned
SK 44274 31656	Wilne Mills (Cotton)	18th Cent	C			

20th Century weirs

Category A: Impassable at all flows
Category B: Passable at high flows only
Category C: Passable at all flows with difficulty
Category D: Passable at all flows with no difficulty

The first community hydro scheme in England, Torrs Hydro at New Mills in Derbyshire, (Figure 5.2) (pre-FiT's) was able to integrate a fish pass into the design and build of their system, with the help of the EA funding the pass to support fish migration from the Mersey (Brumhead, 2015). However, a few years later a similar community hydro project in Sheffield, Jordan Dam Hydro, failed to proceed partly due to the increased fish pass requirements of the EA (Sheffield Renewables, 2013), which required two fish passes (upstream and downstream) alongside their fish-friendly archimedes turbine, to be funded by the community energy group, making the project unfeasible (ADVyCE Gilmartin, 2013).

The Ambergate Hydro project received a formal pre-application response from the EA in May 2015, which determined that a fish pass was not a requirement of the scheme, with impassable heritage weirs downstream, although a flow allowance for a future fish pass should be reserved (ADVyCE EA 13 May 2014). Following the announcement of FiT degressions in 2015, one last review of the project took place, requiring a second abstraction licence pre-application, in 2017. Following significant delays in reviewing this pre-application (22 May 2018) and with no discussions, the EA changed the conditions of approval, now including an EA approved fish pass (ADVyCE EA 23 July 2018). It was unlikely that a fish pass could be designed and approved by the EA prior to March 2019 (end of FiT scheme), and the estimated cost of £250,000 led to the project being paused (Transition Belper, 2019). Acknowledging that fish passage was not a requirement in their previous (2015) letter, the EA stated 'However as a result of improvements to fish passage in the downstream catchment, and anecdotal evidence of salmon accessing the weir at Ambergate during high flow conditions, the situation has now changed' (ADVyCE EA 23 July 2018). Between the 2015 and 2018 EA responses, no new fish passes were installed on the River Trent or River Derwent, and projects were ongoing to identify fish passage at the 'impassable' heritage weirs at Belper and Milford, immediately downstream of Ambergate, making the claims of fish passage improvements in the EA's 2018 response questionable.

There is a possibility that salmon may have migrated further up the Derwent following a series of flood events in the early 2000s, but it is not clear if an anecdotal sighting qualifies as 'waters frequented by salmon', as required in the SFFA 1975

(Salmon and Freshwater Fisheries Act, 1975 Part II 9). The decision by the EA, which was aware of the negative impact it would have on the HEP project, has left an operational weir on the river Derwent with HEP infrastructure in place but neither HEP generation nor fish passage.

The EA fish passage improvement programme in the Trent catchment, referred to above, and added to with the Colwick fish pass (2023-4), appears to have been focussed on weir assets owned by the Environment Agency. The Colwick fish pass is the eighth weir with no fish passage in the 'Trent gateway' project for fish migrating from the Humber, so it is not clear what the effectiveness of delivering fish passage only at EA owned assets, or EA designated HEP win-win weirs (e.g. Ambergate Hydro), will be on the overall repopulation of salmon in the Trent catchment.

The UK's WFD regulations allow for less stringent environmental objectives for a body of water where:

> 'a) that body of water is so affected by human activity or its natural condition is such that the achievement of the environmental objectives set would be infeasible or disproportionately expensive' (The Water Environment Regulations 2017 clause 17 (1)(a)).

It is not clear if the cancellation of community HEP projects, as a result of the requirement to install a fish pass at the community's cost, to meet WFD objectives, could be evidence of achieving the environmental objectives being infeasible or disproportionately expensive.

5.5.3.1 Weir Removals

The issue of poorly maintained weirs being removed has been discussed, but stable weirs in the DDC are being removed as part of the WFD UK improvement programme. As part of the River Ecclesbourne (a tributary in the DDC) restoration project, the EA and Wild Trout Trust removed the Snake Lane weir, Duffield in 2022 (Dam Removal Europe, 2022), under permitted development, to open up the river for fish migration. A second former mill weir (Postern Mill) on the Ecclesbourne has also been bypassed, with the reintroduction of a water channel (Derbyshire Wildlife

Trust, 2023, Jacklin, Stapley et al., 2021). Both projects are associated with weirs and locations related to historic watermill sites, but no published assessment of HEP potential loss for either project has been made available.

The *Plan for Water* (DEFRA, 2023) policy included plans to meet the demands of the WFD. The Plan included the creation of:

> ‘a new Water Restoration Fund to channel environmental fines and penalties into projects that improve the water environment, including redundant water modifications, for example, weirs, to restore natural processes’ (DEFRA, 2023 8).

The plan does not acknowledge the heritage value of ‘redundant’ weirs or the potential environmental and economic benefits of weir (and associated infrastructure) reinstatement, for both river stewardship and HEP generation opportunities. This appears to reflect the concerns, raised in 2000 (Section 5.5.2) of the EA having potentially conflicting goals of championing environmental improvement versus sustainable development. In 2023, The MP for Mid-Derbyshire, P Latham MP, did request that the EA carry out HEP assessments and local community engagement prior to any future weir removal (PA UIN 180362 14 April 2023). The DEFRA minister’s response did not acknowledge the potential value of weirs for generating renewable energy for climate change mitigation (PA UIN 180362 21 April 2023), continuing the narrative of classifying all historic weirs in the DDC, not already generating HEP, as ‘redundant’ and at risk.

There is a struggle over a future vision of what the water resource (a river) is for, i.e. who controls it and who decides (Armstrong and Bulkeley, 2014). The original angling fishing licences were introduced in the 1860s to help fish conservators, not the mill owners, to fund fish passes on existing weirs (Willis Bund, 1873). Similarly, the Water Restoration Fund, offers the opportunity to fund new fish passes, rather than removing weirs, as part of future HEP reinstatements on the EA’s lists of win-win opportunities; this could be facilitated through the EA working in partnership with environmentally motivated community energy initiatives.

5.5.4 Fisheries (Salmon)

There is no specific information relating to salmon stocks for the Trent catchment or River Derwent in the 2022 EA salmon stock report as they are not identified as principal salmon rivers, or as rivers designated as Special Areas of Conservation (Figure 5.26).

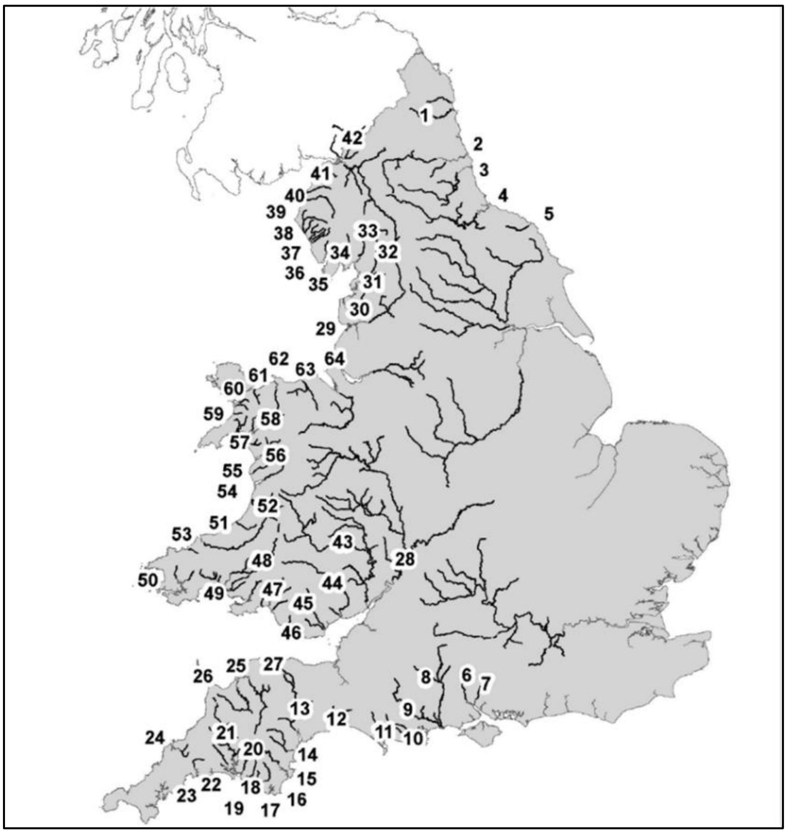


Figure 5.26 Map of England and Wales showing the Principal Salmon Rivers. The Trent catchment is not listed (EA, 2022 9).

The EA's 2021 salmon stock assessment report includes marine populations, with pre-fishery abundance (PFA) data showing declines in salmon stocks of 46% impacting the England and Wales fisheries since the 1970s, and a marked decline around 1990 when a general perception of a decrease in marine survival around the North Atlantic was identified (Crozier, 2017, EA, 2022 69, Nicola, Elvira et al., 2018). The EA assessment references 'above average temperatures' in rivers as one of the many causes influencing fish catches, with a voluntary agreement not to fish on the Hampshire Avon if the river temperature exceeds 19° C at 09:00. (EA, 2022 83). However, the 'threats to salmon' section of the report does not mention the warming of the oceans or rivers due to climate change.

The cause of the more recent (compared to the 1850s) 1970s reduction and 1990s major decline in salmon fisheries globally is not fully understood. The global decline in the abundance of Atlantic salmon stocks since the 1970s led to a science report being produced by the EA titled *Effect of climate change on salmon fisheries* in 2005, referencing global research in the field. Rivers experiencing warming would see the greatest declining growth rates, resulting in adverse consequences for abundance and survival, especially for trout, which have a lower thermal tolerance than salmon (Davidson and Hazlewood, 2005). One change recorded during the last 25 years, that appears to be affecting the complex salmon life-cycle, relates to global warming impacts on marine ecosystems (Figure 5.27), which are predicted to increase, with species responding by changing their spatial distributions (Dahms and Killen, 2023). A recent analysis of research into the impacts of climate change on different fish species and their responses to changing marine ectotherms, highlighted the need for more representative and standardised research to improve predictions in face of a changing climate (ibid). Warming of rivers and streams can particularly impact on species such as salmon but are not always obvious and lethal, as spawning only occurs within a limited temperature range, and recent climatic changes reduces the time available for successful spawning (Lightfoot, 2008).

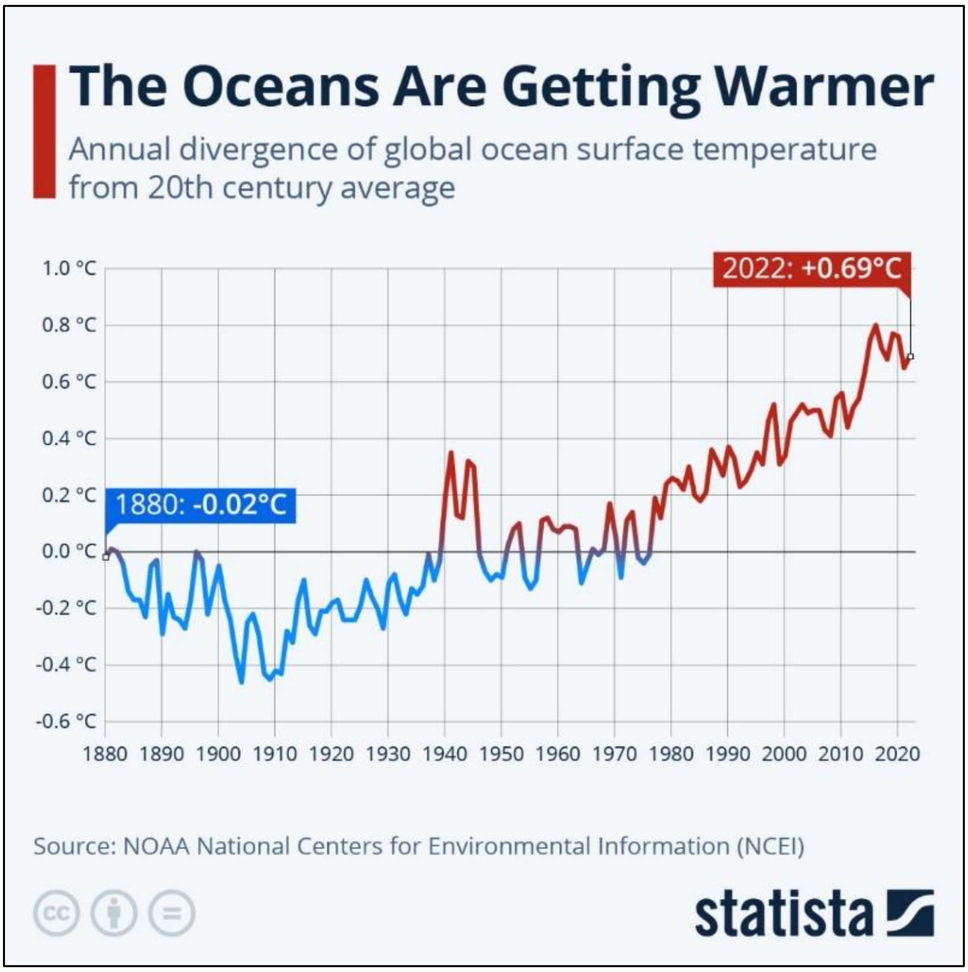


Figure 5.27 Ocean warming chart (World Economic Forum, 2023)

Whilst there is limited data available relating to historic salmon population change and river temperatures, research in Spain, investigating 65 years of salmon return data, has identified both local (rivers) and global (ocean) temperature as the primary cause of the decline in their salmon rivers (Nicola, Elvira et al., 2018). The popular British Wild Isles documentary series, presented by Sir David Attenborough, led episode 4, Freshwater, with the startling statistic that salmon numbers have dropped by 70% in the last 25 years (BBC, 2023). This headline statistic was based on the Atlantic Salmon Trust's findings that only 5% of salmon leaving Scottish Salmon rivers return, compared with 18% returning 52 years ago (Atlantic Salmon Trust, 2022). Despite listing a potential cause of the losses as being the global warming of the oceans, Attenborough also mentioned the river barriers and weirs as part of the problem. I queried this statement with the production team, questioning how 200 year-old weirs, which could be used to mitigate climate change, could be the cause of the recent decline and be targets for removal. In response the producer of Wild Isles stated, ‘finding the balance between climate concerns and conservation is imperative’ (C Howard. personal communication, 5th May 2023).

During the 19th century, salmon conservators focussed on either enabling fish passage or removing weirs to improve the Trent catchment’s fisheries, initially dismissing the threat of pollution. Recent dramatic declines in salmon populations (i.e. since the 1970s), now considered to be linked to reductions in marine survival (Nicola, Elvira et al., 2018), are thus unlikely to have been caused by the industrial weirs, built up to 200 years earlier. Yet today, despite the EA’s awareness of the impacts of climate change on salmon fisheries (Davidson and Hazlewood, 2005), the above examples (Section 5.5.3.1) indicate that the EA’s focus on improving salmon fisheries in the Trent catchment by removing or bypassing weirs, may represent history unhelpfully repeating itself.

5.6 Policy and Regulation

Two aspects of government policy that have impacted on the development of HEP in the last 30 years have already been discussed, namely renewable energy subsidies (Section 5.2.2) and Water Framework Directive (Section 5.5.2.2). However, one other theme running through the age of renewable energy, is the apparent lack of joined up government policy around the utilisation of water across the UK (the responsibility of DEFRA) to harness renewable energy (the responsibility of DESNZ). DEFRA's response to the question regarding weir removal included the criteria considered by the EA (PA UIN 180362 21 April 2023), but did not include renewable energy generation or climate change mitigation. DESNZ is the government department responsible for climate change mitigation, but it views HEP as insignificant (Section 5.3.2). This situation mirrors the 1970s, when the National Association of Water Power Users, lobbying for the waterpower industry against water charges (Section 4.4.4), were negotiating with two government departments with different priorities, the Department of Energy and the Department of the Environment. The Association failed to gain any interest from the Department of Energy, despite the energy SAVE IT campaign, they stated that the Department of the Environment 'had no interest in waterpower or energy saving and apparently no concern other than to maximise taxation' (ArkSoc NAoWPU, 1977).

5.6.1 Planning Policy

Until the early 1990s, 'energy projects' meant large-scale power stations (large HEP, fossil fuel powered or nuclear) with construction decisions taken at national level by the Secretary of State for Energy (Walker, 1997). With no national guidance, and many renewable energy projects including innovative technologies (e.g. onshore wind turbines), local planning departments struggled to cope (ibid).

The *Derbyshire Spatial Strategy* developed in 2022 for DCC produced maps for each renewable energy opportunity, highlighting the man-made constraints (Table 5.4) as defined by DECC (2010) (Scene Connect, 2022), potentially preventing renewable energy development.

Table 5.4 Level of constraints used in the *Derbyshire Spatial Strategy* (Scene Connect, 2022)

Red	More constrained	location is severely constrained … highly unlikely that the technology would be permissible, it is not impossible
Amber	Constrained	This location is constrained to a notable degree for this type of energy development. Development in this area would require in-depth engagement with the planning authority and regulators.
Green	Less constrained	This location has minimal constraints for this type of energy development. Site-specific analysis is required and engagement with the planning authorities and regulators should be conducted to confirm the suitability of the site.

The clearest visualisation of the impact of man-made constraints on potential renewable energy generation, are the three, onshore wind maps in Figure 5.28. Figure 5.29 is the hydro opportunities map for Derbyshire, with all of the waterways in the Peak District National Park and the Derwent Valley Mills World Heritage Site (Figure 5.30), classed as More constrained or Constrained. Derbyshire contains many environmentally and culturally sensitive locations, including six Special Areas of Conservation/Special Protection Areas, 88 Sites of Special Scientific Interest, 371 Conservation Areas, over 6,500 listed buildings, and 20,000 sites and features of archaeological and historic interest (Scene Connect, 2022).

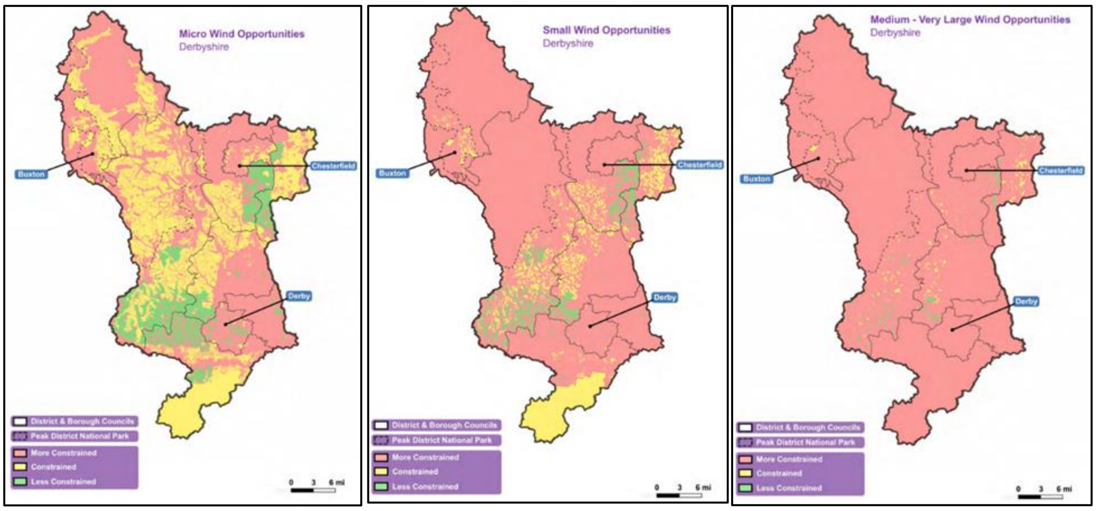


Figure 5.28 Onshore wind constraints - Micro, Small and Very Large wind opportunities (Scene Connect, 2022 96-98)

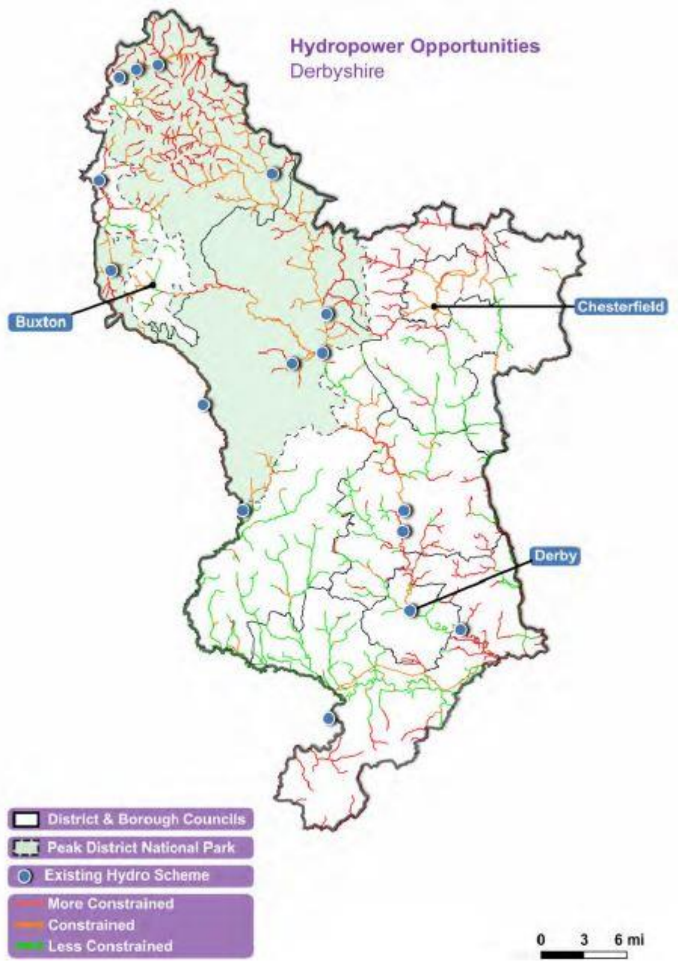


Figure 5.29 Hydro opportunities in Derbyshire, constrained waterways (Scene Connect, 2022 100)

Each stakeholder involved in the planning process, including Historic England, Environment Agency and Natural England, has different priorities and remits, and, whilst potentially being supportive of HEP generation, the combined agencies' focus on their respective priorities has the unintended consequence of challenging all aspects of HEP development. One example, covering a significant area of the DDC's HEP opportunities, is the Peak District National Park's management plan (2018-2023), which states that the park 'need[s] energy production that does not produce greenhouse gases. However this must not result in harm to the National Park's special qualities' (cited in Scene Connect, 2022 29). It is not clear if the PDNP are expecting communities and industries to significantly reduce electricity consumption or are planning to import clean energy generated outside the park, to 'support thriving and sustainable communities and economy' (ibid).

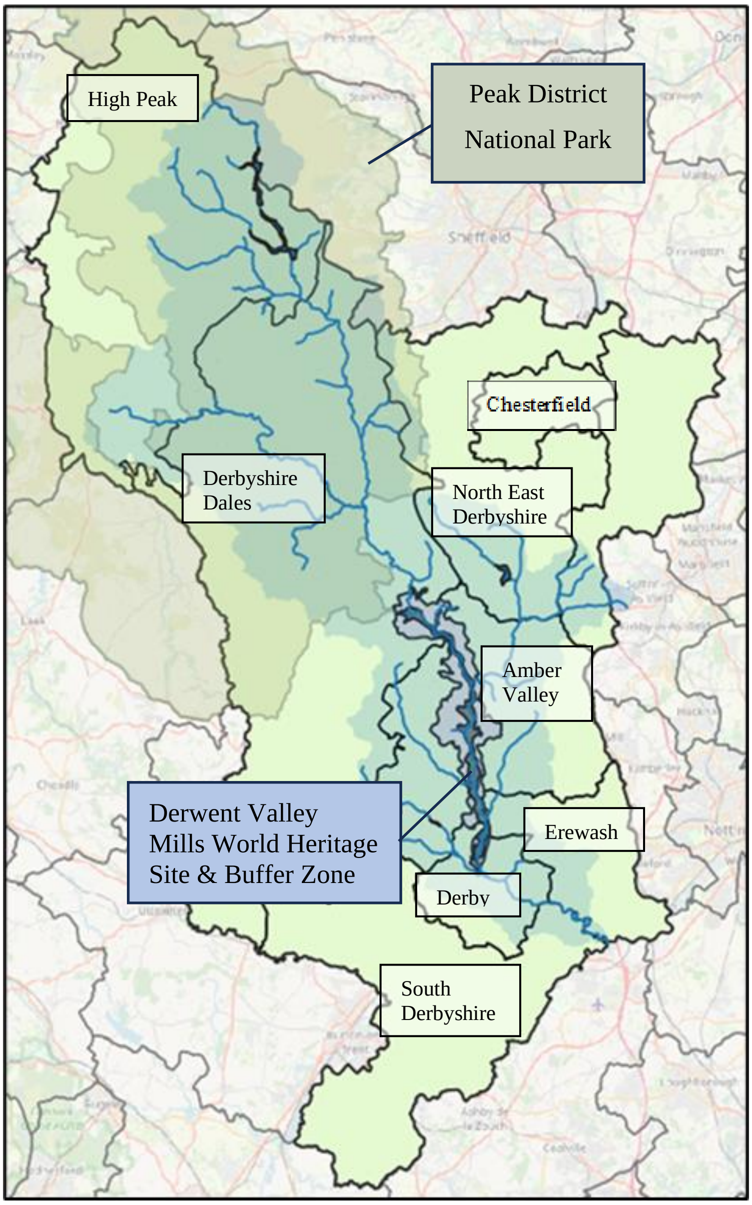


Figure 5.30 Derbyshire Derwent catchment, local authority areas and planning constraint areas.

Waterpower sites and opportunities exist in the High Peak, Derbyshire Dales, North East Derbyshire, Amber Valley, Derby, Erewash and South Derbyshire local authorities (Figure 5.30). Planning authorities are required to reference local (different for each authority), regional and national policies in processing any HEP development planning application (Scene Connect, 2022). Reviewing the publicly available climate change and renewable energy policies for each of the local authorities within the DDC, found that each local authority (LA) has a different approach to climate change and the resultant neighbourhood, climate change action or local plans, and individual policies, are different. Apart from Erewash, all of the LAs in the DDC declared a climate emergency in 2019. Most, not all, neighbourhood and local plans in the DCC include reference to small-scale hydropower as a renewable energy sources option. North-East Derbyshire District Council's Local Plan includes (Policy [Sustainable Development and Communities] SDC10: Decentralised, Renewable and Low Carbon Energy Generation) a requirement that:

> '5. Developments along water courses will be expected to investigate the feasibility of using small-scale hydro power, taking into account flood risk' (North East Derbyshire District Council, 2021 138).

There is the opportunity to unlock some of the DDC HEP potential via a supportive Supplementary Planning Guidance document relating to the geographic DDC area. This could include clauses as above, offering guidance for a range of HEP developments, including former industrial watermill brownfield sites.

National Planning Policy Framework (NPPF)

Studies investigating the development of HEP in recent years reference consenting and planning complexity. Planning at the national level is underpinned by the National Planning Policy Framework (NPPF), first published in 2012 and updated in 2018, 2019, 2021 and 2023. The NPPF states that the purpose of the planning system is to contribute to the achievement of sustainable (economic, environmental, and social) development (DLUHC, 2023 5). LA interpretation of the NPPF is critical; a potential DDC community hydro project, seeking to repower a former industrial watermill site in the DVMWHS, received the following pre-application response from the Local Authority officer, 'we would be unlikely to support this under the NPPF policies', with no clarification as to why and despite the obvious benefits to the local community, delivering sustainable development and promoting a key attribute of a world heritage site (J Watson, personal communication 10th July 2023).

A number of clauses within the NPPF (2023) are relevant to the development of HEP (Table 5.5). Section 16 refers to the conservation and enhancement of the historic environment, such as listed buildings (DLUHC, 2023 57). With many of the HEP opportunities in the DDC being located within historic watermill assets and the 24 km long DVMWHS site, this section is critical when considering the HEP potential. The guidance offers many positive aspects that a HEP reinstatement in an historic watermill may deliver, such as protecting ‘at risk’ assets, making a positive contribution to local character and improving viability, but the constraints leave interpretation of the guidance down to the decision maker, the local planning authority. The value or benefits of reinstating HEP in historic watermills, including the WHS industrial watermills, is not clearly stated in DDC local authority planning guidance or Historic England’s own guidance for HEP developers (Historic England, 2014), which in 2023-24 is under review.

Table 5.5 National planning policies relevant to HEP development, including historic watermill repowering (DLUHC, 2023)

Policies (December 2023)		HEP Development
The presumption in favour of sustainable development		
11.	Plans and decisions should apply a presumption in favour of sustainable development and for plan-making that includes plans seeking to mitigate climate change.	HEP is a renewable energy, mitigating climate change.
Strategic policies		
20 d)	Strategic policies within a local plan should make sufficient provision to address climate change mitigation	HEP is an option available in all DDC local authorities
Supporting a prosperous rural community		
88	Opportunities to support prosperous rural communities would be encouraged.	Historic watermills offer sustainable development opportunities.
Making effective use of land		
124 c) & 125	Local planning authorities are required to be proactive in identifying development land, including brown field sites	Former industrial watermill sites.
Meeting the challenge of climate change, flooding and coastal change		
157	‘The planning system should support the transition to a low carbon future in a changing climate, taking full account of flood risk and coastal change. It should help to: shape places in ways that contribute to radical reductions in greenhouse gas emissions, minimise vulnerability and improve resilience; encourage the reuse of existing resources, including the conversion of existing buildings; and support renewable and low carbon energy and associated infrastructure.’	All historic watermill sites with infrastructure in place.
Planning for climate change		
163 a)	Local planning authorities should ‘not require applicants to demonstrate the overall need for renewable or low carbon energy, and recognise that even small-scale projects provide a valuable contribution to cutting greenhouse gas emissions’	Conflicting with DESNZ policy of claiming HEP is insignificant and therefore not receiving fiscal support.
163 c)	Significant weight to the benefits of utilising an established site’ to repower or extend the life of a renewable energy site in their decision making.	Supporting the repowering of historic watermills.

5.7 People: individual, businesses, communities and society

5.7.1 Community energy

The 1983 Energy Act enabled decentralised electricity generation and, with concerns over climate change, the UK government set renewable energy targets which, combined with government supported programmes, led to a ‘surge in local project development’ (Walker, 1997). Many renewable energy projects in the 1990s, mainly inland windfarms, faced significant public opposition. One solution, offered by bodies such as Friends of the Earth, was to improve public engagement in projects, including promoting smaller scale community-based schemes, with local people having a stake in renewable energy developments (ibid). However, involving the community in the development has not automatically removed contentious obstacles from HEP; issues relating to fish passage, the HEP design and operation (from the perspective of both the local angling community and the EA), had the most significant impact in preventing the development of the proposed Hexham River Hydro scheme (Bracken, Bulkeley et al., 2014).

A new form of HEP developer, Community Energy, evolved, with not-for-profit organisations (with restricted returns for investors) delivering local infrastructure improvement, not unlike the Georgian canal builders (Section 3.7.3). The not-for-profit community energy model also allows direct government subsidy (Walker, Hunter et al., 2007 72). During their review of thirty years of climate change mitigation measures in the UK, Lees and Eyre (2021) highlight community energy as a cause for optimism, with its aim to put people at the heart of the energy system (Lees and Eyre, 2021 37). Ed Davey, the UK Secretary of State for Energy and Climate Change (during the 2010-2015 coalition government), said that ‘he wanted nothing more than a community energy revolution’ (cited in Armstrong and Bulkeley, 2014 74). DECC published the UK’s first and only *Community Energy Strategy* (CES) in 2014 (DECC, 2014a), which imagined that 1,000,000 homes would be powered by community energy schemes by 2020. By 2018 the strategy, and vision, had been abandoned, with only 67,000 homes benefiting (Kumar and Green, 2019).

5.7.1.1 Community hydro projects in the UK

Community Energy (CE) now faces challenges, including the dilution or removal of supportive government policies (Hannon, Cairns et al., 2023). There has only been one attempted community hydro project in the DDC, Amber & Derwent Valley Community Energy's (ADVyCE) Ambergate Hydro project, so this section will draw on successful and unsuccessful community hydro projects across the UK, to illustrate the key drivers and challenges faced by this sector.

Many community energy groups derive from local, voluntary, sustainability groups, such as Transition Belper (Ambergate Hydro) and Transition Tynedale (Hexham), aiming to generate renewable energy, engage the community in a low carbon future vision and secure funds for future low carbon and regenerative projects (Armstrong and Bulkeley, 2014). The first Community Hydro development in the UK was the pioneering Torrs Hydro HEP installed in New Mills, Derbyshire (Figure 5.2). In June 2008 a reverse Archimedes screw was installed in the location of the former 18th century Torr Mill, adjacent to the original weir at the confluence of the river Goyt and river Sett.(Brumhead, 2015). Torrs Hydro is an example of 'the power of communities to take action and begin to address the challenges that climate change presents to us all' (Torrs Hydro, 2023).

As part of the awareness raising for the Ambergate Hydro project in 2014, a map of community hydro projects (Figure 5.31) was developed that included five operating sites (green), fifteen sites working on potential projects (amber) and two failed projects (red). A review of these sites in 2023 found that only six of the fifteen 'in progress' projects managed to complete the installations before the ending of the FiT scheme, and are operating today. The local news headlines relating to unsuccessful projects during this period (Feed-in Tariff degression phase [Section 5.2.2]) focus on time and cost as the key issues, such as 'Tutbury mini hydro generator plans scrapped after delays and grant reductions' (Kreft, 2017). For press releases and media headlines it was necessary to reduce the complexity of these project failures to time and cost. Each HEP project is individual in their design and challenges but there are a number of common and interrelated elements and themes that will be impacting project timescales and costs, such as planning complexities and WFD associated costs (Bracken, Bulkeley et al., 2014).

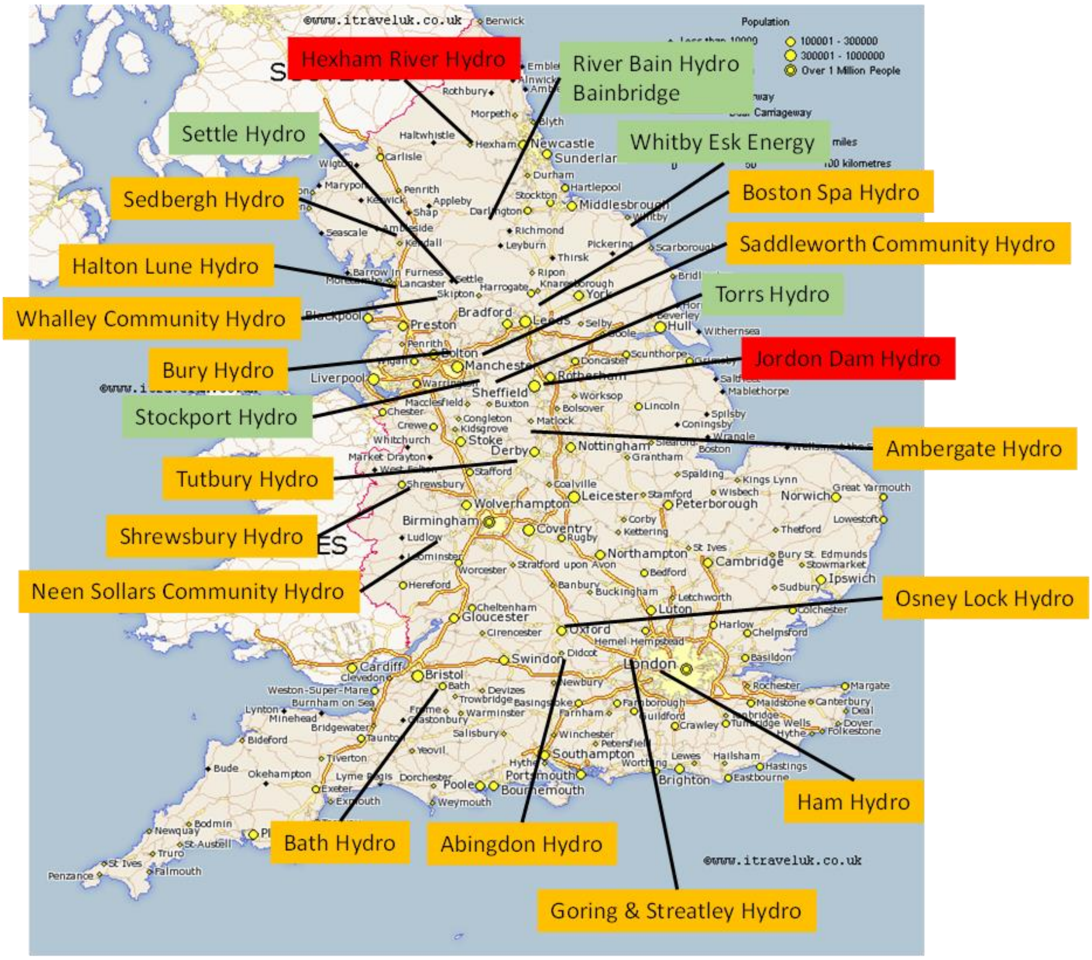


Figure 5.31 Community hydro projects in England, (Ambergate Hydro unpublished presentation), Author, 2014.

Both the Settle and Ruswarp HEP (Whitby Esk) developments completed their installations, using ‘fish friendly’ Archimedes screw technology, and included the required EA approved fish passes, but both community organisations had contentious issues to overcome and continue to face operational challenges. The main challenges raised during public consultations with local communities and other river users, were impact on local fisheries, noise levels, value for money, harm to historic buildings and the impact on natural beauty (Armstrong and Bulkeley, 2014, Bracken, Bulkeley et al., 2014, Punys, Kvaraciejus et al., 2019).

Complexity and changing policies are particularly challenging for CE groups (Armstrong and Bulkeley, 2014, Bracken, Bulkeley et al., 2014). The EA *Guidance for run-of-river hydropower development* (EA, 2013) highlights the skills required by the small HEP developer, with links to their technical guidance documents: flow and abstraction management, geomorphology (including weir pools), screening requirements, fish passage, WFD regulations, nature conservation and heritage, flood risk, monitoring, impoundments, the use of weirs and competing hydropower schemes.

Community hydro networks, such as the Community Hydro Forum facilitated by Kate Gilmartin of CO_2Sense, worked together to share best practice and understand the challenges faced by the new sector (Whitby Esk Energy, 2015). Workshops were organised by 'leaders' of case studies, highlighting the key success factors and barriers to overcome, such as the peer mentoring forum led by Whitby Esk Energy in 2014-5 (ibid).

5.7.2 Derbyshire Derwent catchment stakeholders

Today, whilst there is national representation for the HEP industry in the form of the British Hydropower Association, in the DDC there is little collaboration among HEP developers. Individual HEP site developers are dealing with the EA, planning authorities and statutory consultees on an individual basis. As Thomas C Hewes overcame the challenges faced by the millwright c.1900 (Section 3.7.1), sharing best practice among the new industrial mill owners, HEP specialist engineers such as Olly Paish (Derwent Hydro Developments Ltd) and Dave Mann (Mannpower), have played a key role in the recent repowering of HEP, and more, similar, engineers will be required to deliver its future potential.

During the 20th century the ESCC, with three of the largest HEP generating sites in the DDC, led negotiations on behalf of other waterpower users (Section 4.4.1.1). Many of the HEP reinstatements in the DDC during the 1990s, including at the former ESCC sites, were carried out by Derwent Hydro Power Ltd (DHPL), led by Jon Needle (Section 5.2.3). Owning and / or operating sites, such as the former

ESCC premises, the Borrowash Mills and Derby City Councils Longbridge HEP, all on the River Derwent, DHPL have a unique level of understanding of the DDC waterways. This makes DHPL, a key stakeholder in the waterways of the DDC.

The EA sponsors the Derbyshire Derwent Catchment Partnership, whose vision is to create and protect a healthy and wildlife rich water environment within the DDC, that will bring social, well-being and economic benefits to all (Derbyshire Wildlife Trust, 2015). Whilst it would appear that the Georgian watermill owners’ knowledge of the river facilitated some wider stewardship good practise similar to that being striven for now, today’s more complex regulation and stakeholder interests create conflict rather than collaboration. The DDCP may offer an opportunity to enable partners, including the different departments of the EA and HEP developers, to work together to learn from the past, share their knowledge and work collaboratively to tackle the climate (mitigation and adaption) and nature crises in a more balanced, sustainable way.

5.8 Lessons to Learn

Within the relatively short ‘renewable energy’ period, there are important lessons we can learn about the key influencing factors that initiated the renaissance and boom in small HEP development in the DDC, and the changes that put the boom on pause.

The HEP industry continues to innovate, accommodating concerns over the impact of turbines on the fisheries (e.g. fish friendly archimedes screws). Improvements in efficiency and cost-effectiveness, with improved monitoring, control and automation (e.g. screen cleaning systems) is critical, as water availability becomes more restricted and flows are restricted due to finer screens (e.g. eel regulations). Working with other river stakeholders may also introduce more flexible flows and power generation, to optimise the power available to match peak demand. Global research and innovation suggests that the use of non-mill applications, in particular the water utilities network, can provide more HEP generation and energy storage opportunities.

A government willing to listen to representations from the watermill owners was critical to HEP’s use up to WWII, with the final *Derwent Valley Water Act* (1944) including compensation flows for the industrial watermill owners on the Derwent. Understanding the additional ‘value’ of waterpower as a renewable energy encouraged the UK government to open the market to local generators and offer fiscal support, initiating a boom in HEP reinstatements and new HEP project, often on non-mill locations. Unfortunately the withdrawal of the fiscal support, and resultant pause in HEP installations, highlights the important role the government has in energy transitions, including the current low carbon transition. Current government energy policy does seem to be heavily influenced by the scale of power generation opportunity, with small HEP considered insignificant. The NPPF 2023 identifies the value of all renewable energy generation, of any scale, and small HEP is an opportunity in most communities across the UK. If scale of the HEP opportunity continues to be a government focus, then, as the low HEP potential identified in the (highly constrained) *Derbyshire Spatial Energy Study* (Scene Connect, 2022) shows, a comprehensive site-by-site study of technical (not constrained) potential, which challenges the man-made constraints, is required, to improve future national, regional and local decision making.

The conflict between the Water Framework Directive and Renewable Energy Directives continues to challenge HEP development across Europe. Within the UK we have two separate government departments responsible for these directives, potentially leading to unnecessary challenges and bureaucracy. The UK version of the WFD does not include key clauses embedded in the Salmon and Freshwater Fisheries Act since 1861, which acknowledge and protect waterpower generation. Incorporating these protections, and identifying other aspects of flexible operations of sluices, offers an opportunity to deliver the river ecology aims of the legislation as well as support climate change mitigation efforts. Acknowledging the wider stewardship role of the Georgian watermill owners, there could be an opportunity for the Minister for Water (within DEFRA) to assume responsibility for delivering the remaining renewable energy HEP potential of the rivers. As the 19th century fish conservators introduced licence fees to raise funds for waterway improvements, the new Water Restoration Fund could be made available to support not-for-profit, community hydro groups in delivering win-win HEP and waterway improvement projects.

Whilst the 'generic' National Planning Policy Framework has been used as a barrier to community hydro by a planning authority, individual clauses within the NPPF 2023 appear to positively encourage the repowering of historic, brownfield, sites, often located in rural communities. For the DDC, with its highly constrained National Park and World Heritage Site, the repowering of historic watermills also facilitates the protection of heritage buildings and structures, and tells the core story of waterpower's role in the industrial revolution. A better understanding of the river's management in the early 19th century, restoration of weirs, sluices and floodgates, and a more flexible approach to compensation and abstraction flow management, may offer a win-win solution for improvement of our waterways, saving heritage assets and reducing the risk of harm to the wider heritage landscape through inappropriate development (e.g. modern fish passage or weir removal).

Historically, local infrastructure, such as the Derby Canal, was financed by local people who were willing to invest in local improvement, despite the restrictions in shareholding and dividends payment incorporated into the Act of Parliament approving the project. Faced with the threat of climate change, local communities, in the form of not-for-profit community energy developers, offer a similar opportunity to introduce, or reinstate, local renewable energy power generation. The local support and interest for the community energy Ambergate Hydro project (2012-2018) in the DDC, highlighted the enthusiasm of local investors wanting to repower their heritage sites, as part of the sustainable development of their communities. Community energy may also be able to unlock a larger range of HEP opportunities through local engagement, accepting the lower financial return of a marginally feasible project, compared to the private developer.

Chapter 6 Conclusions: Unlocking the potential

6.1 Introduction

Chapter 3 (1752-1878) covered a period of rapid development of waterpower to meet the power demands of the industrial revolution. Entrepreneurs used the natural topography and the waterways of the Derbyshire Derwent catchment (DDC) to power the new textile factories. Water was the dominant source of power through the 18th century and early 19th century, and continued to be used throughout the 19th century, despite the alternative, more reliable and predictable source, steam power, becoming available. Chapter 4 (1878-1989) reported how over 40 of the waterwheels and water-turbines in the DDC adapted to self-generate hydroelectric power (HEP). Yet, despite this 'free' source of power being available, and a growing demand for electric power, by the 1980s only a handful of sites continued to self-generate HEP (mainly larger industrial concerns), with most sites opting to purchase electricity from the local, and later, national grid. Whilst regions with suitable topography and rural electricity demand, such as the Scottish Highlands, developed large scale HEP during the 20th century, small run-of-river self-generation almost disappeared (Francis, 1978, Wilson, 1974). Throughout the 1970s-80s HEP was often overlooked as a power source, despite the collapse of the coal industry, the oil crisis of 1973-74 and the problems relating to the privatisation of the nuclear industry. Chapter 5 (1989-2023) describes how a combination of law change (allowing the export and sale of electricity) and technology improvement (including automated controls) initiated small HEP reinstatements in the DDC. However, it was the need, and resulting government support, for renewable energy generation that created a mini boom in HEP reinstatements and new projects throughout the DDC, particularly during the Feed-in-Tariff scheme (2010 to 2019). Withdrawal of the FiT scheme and a combination of conflicting concerns from stakeholders, particularly the Environment Agency's implementation of the Water Framework Directive, has paused HEP development.

This final chapter synthesises the key learnings from the age of mechanisation (1752-1878), hydroelectric power (HEP) (1878-1989) and renewable energy (1989-2023) periods. The inability to install small HEP, including at former HEP generating sites, at a time of great need (climate change) has been viewed throughout the thesis as the critical problem. Compiling the watermill site gazetteer, including a range of watermills (types and sizes) and waterways, and investigating their use of waterpower through time. has enabled the identification of causes of the problem and potential solutions, particularly from the first phase of the industrial revolution (i.e. notably the Georgian period).

The research findings are reviewed against the overarching aim of the research and original (2020) research objectives. The overarching aim of the research was to identify the changes needed to enable river stakeholders to overcome the current conflicts, regarding run-of-river HEP, by learning the lessons from the past, enabling HEP developers in local communities to unlock the river's full power potential, using a sustainable and replicable process, to help mitigate climate change on revitalised waterways.

Throughout the study period (1752-2023) governments have played a significant role in waterpower's development and use, or not. Specific policy 'themes' have been identified, which could potentially help to unlock HEP potential and offer further research opportunities across a number of different academic fields. This chapter ends with a vision of the potential future of HEP in the Derbyshire Derwent catchment (DDC).

6.2 Achievement of aims and objectives

6.2.1 Objective 1

> Understand the key success factors that enabled the early industrialists in the Derbyshire Derwent catchment to develop mass production factories powered by industrial scale waterpower, despite being faced with challenges similar to those we see today (e.g. water-rights, floods, drought, impact on local communities, alternative power sources and fisheries).

A combination of improvements in textile thread manufacture and the government responding to the cotton manufacturers' call to repeal the restrictive laws banning the sale of pure cotton products, opened up the UK thread markets to manufacture calicoes, requiring new levels of power to enable 'mass production'. The ability to harness waterpower effectively and efficiently was critical for the early industrialists, leading to innovation in the capture and control of the fuel, the river, and in the equipment used to harness and transmit the mechanical power. Mill owners competed for waterside locations, utilising natural falls where possible (e.g. waterfalls, meanders, knickpoints and cascades), and existing watermill sites, raising weirs (limited by the impact on adjacent watermills) and extending channels, to optimise power output. Where possible, mill ponds, dams and floodgates managed the variable flow of the river (including the extreme flood and drought conditions). An improved understanding of the science of waterpower and the introduction of new materials, such as iron, enabled significant waterwheel and control improvements (fivefold power outputs), making the river, rather than the wooden waterwheel, the constraining factor. In the late 18th century, steam pumps were added to some industrial watermills, to recycle water from tailrace to mill pond. Steam technology developed to power mills directly, becoming scalable and cost-effective by the 1830s, and the primary source of industrial power by the mid-19th century in the UK. In spite of this, where available, waterpower continued to be of great value and improved throughout the 19th century, often in a hybrid arrangement, with the 'free' waterpower providing a base-load and coal-fired steam meeting the additional power needs.

Lead mine owners in Derbyshire were building drainage channels (soughs) to de-water the lower levels in the 1600s, and quickly adapted to use these man-made drainage flows to drive waterwheels, often underground, to pump water and ventilate mines. All waterflows, natural and man-made, were used to power industries, with Richard Arkwright's first water-powered cotton mill (1771) utilising both the natural Bonsall Brook, which had been powering small watermills for hundreds of years, and the man-made Cromford Sough tail.

The soughs, many still flowing now, were a form of local infrastructure developed through local investment. Parliamentary acts enabled improvements in infrastructure to be delivered by local investors. For example, the Derby Canal Act (1793) supported the canal's development by local investment but included controls on share ownership, limits of shareholder dividend payments and restrictions on canal use charges.

Industries reliant on waterpower were clearly viewed as an important part of the country's economy, with new parliamentary acts that impacted water use offering protections to Derwent Valley industrial watermills between 1789 and 1944, including the *Cromford Canal Act* (1789) and the *Derwent Valley Water Act* (1899 to 1944). The *Salmon Fishery Act* (1861) was introduced to protect the country's fisheries, without impacting 'milling power'. The DDC industrial millowners were listened to by parliament, individually and collectively, with fair solutions to competing water uses incorporated into the Acts.

Watermill owners in the DDC appear to have played a wider 'river steward' role, in addition to operating their factories. Only the water required to power the mills was abstracted from the river and waterway modifications, combined with floodgates, protected their mills and local communities from the impacts of flooding. Many riverside land and mill owners had interests in the fisheries and fishery rights. Evidence shows that industrial watermills on the Derbyshire Derwent, such as the Strutts' mills in Milford and Belper, facilitated salmon passage for many years after the building of their industrial revolution weirs. Watermill leases on the lower Derwent included salmon catch clauses and there is specific reference to the Belper and Milford mills having fish passage (Section 3.5.3.1). Whilst no specific records have been found of how fish passage was facilitated, an understanding of waterpower infrastructure at a site such as Belper offers some ‘practical’ fish passage options. Fish passage at times of flood continues to be recognised as an opportunity for salmon to migrate, due to the reduced water height difference at weirs. However, many weirs in the DDC, built in the 18th and early 19th century, included floodgates that would be fully opened at times of flood, offering a ‘free gap’ for the migrating fish. These same gates would be opened during normal operations at times of excess water, to manage upstream river levels, offering additional free gap opportunities for fish passage. Most mills did not operate on a Sunday, and the Belper Watchman records include routine maintenance activity requiring the opening of flood/sluice gates, often from Saturday evening to Sunday evening. The inclusion of free gaps, nighttime and weekly close times (Saturday 12:00 to Monday 06:00 ‘to enable the fish to distribute themselves more evenly’ (Bund, 1873 195)) in the *Salmon Fishery Act* (1861), suggests that conservators understood the dynamic, operational aspects of the weirs and gates. It also suggests that the river stewardship practices of the Strutts in the DDC must have been repeated across England and Wales, for the Salmon inquiry commissioners to incorporate them into the legislation. Fundamentally, the legislation suggests that the weir isn’t the solid, fixed, obstacle in the river, as often described today by river stakeholders, and that a solution to the current fisheries challenge is already available at some of the historic industrial weirs.

6.2.2 Objective 2

> Identify the main cause(s) of the decline in waterpower use to generate electricity post-WWII, despite the apparent availability of 'free' fuel from the rivers.

By the end of the 19th century waterpower was adapted, from being a source of mechanical power to a generator of electricity, initially for electric lighting and later for electric power (i.e. hydroelectric power [HEP]). Initially, with no electricity grid available, many watermills and country houses generated their own electricity, harnessing the power of the waterways (c.40 run-of-river (small) HEP sites in the DDC by the 1920s). National and local factors impacted on the use of waterpower in the DDC during the 20th century, leading to the number of small, self-generating hydroelectric sites across the UK declining dramatically, with only five or six sites continuing to produce HEP in the DDC by the 1980s.

In the 1920s, the UK government chose to exploit its reserves of coal in the development of the rapidly growing electricity generation and supply industry. Where the government had protected water-powered industries in the past, the early 20th century instead saw support for the coal industry (owners, miners and associated communities). The need to consolidate local electricity networks (technically and commercially) led to a power generation model that utilised a small number of large, coal-fired power plants, to produce cheap electricity. This national grid, offering cheap electricity, led to the demise of local, small-scale electricity generation post WWII, including small run-of-river HEP. Sales of water turbines from Gilkes (the largest UK manufacturer) confirmed the DDC gazetteer research findings (Section 2.3.5.1) of a sharp decline in new HEP installations post WWII. Whilst challenging for Gilkes, the company was able to continue selling water turbines abroad, to countries whose different energy and water policies provided more favourable conditions for HEP use.

In the early 20th century, water availability governed the quantity of HEP generated and was therefore critical to businesses dependent on HEP self-generation. The building of the Derwent Valley reservoirs in the DDC for drinking water, and associated abstraction of water from the catchment, impacted sites on the Noe and

Derwent rivers, leading to the removal of HEP at some locations. Affected sites were compensated, in the form of one-off payments, compulsory purchase agreements (i.e. closure) or an agreed compensation flow, based on $^{1}/_{3}$rd of the historic rainfall records. Despite large HEP being developed around the world (e.g. Niagara from 1893), the Howden (1912) and Derwent (1916) reservoirs in the DDC were built with no HEP generation. The later Ladybower Reservoir (1943) did incorporate HEP turbines, to recover electricity during pump transfer operations, but did not start harnessing the power available from the continuous compensation flow until 1999, when legislation changed to allow self-generated electricity to be exported and sold to the national grid. The Ladybower turbines were upgraded in 2006 and 2010, supported by the government's renewable energy subsidies. Similarly, the newer Ogston (1959) and Carsington (1992) (pumped water storage) reservoirs, which also offer a potential pump energy storage opportunity via their abstraction link to the River Derwent, have never recovered or generated HEP.

By the 1960s there appears to be no acknowledgement by the state of the value of waterpower, with the Water Resources Act 1963 allowing the newly formed regional water boards to introduce abstraction licences and charges for the water diverted, and returned, to produce 'milling power', effectively ending the self-generation of electricity using waterpower for most watermill owners. Lobbying by the newly formed NAoWPU helped to remove these charges many years later (Energy Conservation Act 1981), but the damage to the HEP industry had already been done, particularly in regions of the UK faced with the highest rates of water charges, such as Wales.

6.2.3 Objective 3

> With the current stagnation in HEP development, deduce the lessons to be learnt from the past, including the recent 1990 - 2018 renaissance in hydroelectric power generation.

The findings of this thesis indicate that the voices of individual and collective industrial watermill owners were listened to in the 18th, 19th and early 20th centuries, with the UK government repeatedly protecting the access to water for power generation. The compromises reached in the past during water abstraction conflicts (e.g. Cromford Canal supply water) and fisheries improvement (e.g. Salmon Fisheries Act, 1861), which protected businesses dependent on waterpower (milling power), allowed development and improvement whilst facilitating waterpower's continued use.

Waterpower continued to be harnessed during the 19th century energy transition, when steam became the primary source of power: sites with infrastructure in place (i.e. weirs, sluices, channels, wheels or turbines), continued to use the 'free' waterpower throughout the 19th century, as a baseload, in a hybrid arrangement. Today, HEP offers a similar baseload opportunity as part of the low carbon energy transition. The millowners used the precious fuel, the river flexibly, storing and releasing the required flows to meet the demands of the factory. Flows today, including compensation flows, offer an opportunity to generate more HEP (including at existing HEP sites) at peak demand times, and develop flows (seasonal and time of day) to improve river ecology.

Since the early 1900s UK governments have intervened in a series of energy transitions based on state priorities at the time, including the exploitation of coal, the development of a national electricity grid, nuclear power, the introduction of gas central heating (North Sea gas), and the current decarbonisation of energy supply. The use of waterpower only started to decline from the mid-20th century, with the development of the coal-powered nationalised electricity grid and the newly created regional water boards.

From the 1980s there was a mini revival of small HEP, due to the Energy Act (1983) allowing self-generated HEP to be exported and sold to the national grid. Allowing access for electricity export sales encouraged sites such as Chatsworth House to repower their turbines. In addition, the UK government, understanding the need to reduce greenhouse gas emissions, introduced renewable energy subsidies, encouraging small HEP development. The impact of government support has been highlighted, in more recent years, by the effects of the withdrawal of renewable energy support for small HEP in 2019, which effectively paused the repowering of the remaining historic waterpower sites in the DDC. With the current energy market pricing shaped by government policy, and following the successful Feed in Tariff intervention (2010-2019), small HEP requires fiscal guarantees to unlock its available potential, such as the Contracts for Difference scheme offered to other, large, low carbon technologies.

The Friends of the Peak District (2010) identified HEP as a relatively hidden form of renewable energy generation suitable for the Peak District National Park (compared to solar farms and onshore wind), as exemplified by Chatsworth House's turbine house hidden in the garden. However, the recent spatial study (2022) completed for Derbyshire County Council identified the rivers in the Peak District National Park and Derwent Valley Mills World Heritage Site as 'Constrained' or 'More Constrained' for HEP opportunities (Section 5.6.1). Unlocking the potential of small-scale HEP in these constrained, but suitable, locations requires the UK government to directly protect and support 'milling power', by reducing the 20th and 21st century man-made planning constraints (e.g. heritage impact statement duplication) and consenting processes (e.g. electrical grid connections).

In 2010, the Environment Agency completed a mapping of HEP opportunities across England and Wales based on their river barrier database (EA, 2010). One of the outputs from the study was a list of win-win locations that could combine HEP generation with fish passage, both producing renewable energy and improving water quality status, to achieve Water Framework Directive targets. Whilst the Salmon Fisheries Act (1861) identified fish passage improvement opportunities without impacting 'milling power', the Environment Agency regulation and associated guidance for run-of-river HEP, developed at a time when full FiTs were available (2013), did not consider the impact on 'milling power' potential. The HEP developer effectively became the deliverer of the WFD objectives (on EA win-win sites), being required to fund river improvements, as part of the abstraction licence conditions, incurring additional capital costs and ongoing water flow losses, and making previously economically feasible waterpower projects unfeasible; this created lose-lose situations, with neither HEP nor fish passage. This, in spite of both the current Salmon and Freshwater Fisheries Act (SFFA, 1975) and The Water Environment (Water Framework Directive) (England and Wales) Regulation 2017 (WFD UK) including provisions for less stringent environmental objectives where improvements would be 'infeasible or disproportionately expensive', and the current SFFA (1975) requiring 'no injury to milling power' (including any site developing waterpower) (Salmon and Freshwater Fisheries Act, 1975 10(1) 41).

With many fisheries owned by industrial mill owners in the 19th century, and the value of milling power acknowledged, appropriate solutions to the problems of fishery decline were collaboratively sought. Today's HEP developer faces significant challenges in the river consenting processes, a problem identified in the *Community Energy Strategy* (DECC, 2014a) which recommended the establishment of a hydro-power working group to look at a number of issues, including the joining up of Environment Agency processes (i.e. abstraction licencing, flood assessments, fish surveys and fish pass consents). This has not happened. The challenges have worsened, with abstraction licence application costs increasing from £135 to £1,500 (2014) and to c.£13,000 (2022) (Nuclear Free Local Authorities, 2022), and new regulations, such as eel screening, impacting on existing HEP generators as well as new HEP developers. With both climate change and nature conservation requiring urgent action, a HEP working group, or taskforce, may help all interested parties move from the current lose-lose situation to a win-win scenario.

Whilst this research has provided evidence that industrial mill owners on the lower River Derwent facilitated some salmon passage beyond their 'industrial revolution' weirs, we still do not fully understand how. The Salmon Fisheries Act (SFA) (1861), and current Salmon and Freshwater Fisheries Act (1975) appear to incorporate the working practices of the mill owners, in particular the free gaps created by floodgates and sluices. Today, many of the substantial industrial revolution weirs, floodgates and sluices are in place but in a poor state and require urgent attention. Their condition not only puts HEP (current and future) generation at risk, but also limits the opportunity to facilitate fish passage and manage floods using the historic gates, sluices, channels and tunnels. Reinstating floodgates and sluices to improve fish passage, rather than building new fish passes, offers a less expensive, quicker, opportunity, with a positive heritage impact. Creation of gaps or the complete removal of weirs were measures also included in the SFA (1861), and remain a priority for the EA to achieve river quality targets in the WFD UK regulations, supported by the UK government's *Plan for water* (DEFRA, 2023). Historic, unlisted, weirs not currently generating HEP could be classed as 'redundant water modifications' and removed under current WFD UK (2017) regulations. Currently (2023), the Minister for Water and Rural Growth within DEFRA, has no responsibility regarding climate change mitigation, and does not acknowledge the potential value of waterpower as a renewable energy. If the need to deliver the remaining available renewable energy potential of the waterways was incorporated into the WFD UK (2017) regulations, the government department responsible for water (i.e. DEFRA) could also deliver climate mitigation solutions. Past Secretaries of State for DEFRA have appreciated the value of small HEP, particularly in more constrained areas such as the Peak District, with Hilary Benn MP in 2009 stating:

> 'The challenges which face us on climate change are huge and will require a global agreement. But they also need small scale answers with individual households and businesses taking responsibility for doing something …. It is striking that in many of our rural areas we were making more use of waterpower in the 19th century than we did in the 20th' (cited in Woods, Tickle et al., 2010 iv).

One of the most worrying 'lessons from the past' in Chapter 3, was the fish conservators' focus on the weirs as the cause of salmon migration numbers falling, despite consultees in the 1860s raising concerns about new types of pollution impacting on river ecology. Today the WFD UK regulations continue to focus on weirs as a major problem, with 200-250 year old industrial revolution weirs being identified as the main obstacles to salmon repopulating the DDC, despite evidence of other causes. Considerable research effort is taking place around the world to understand the causes of the recent (last 50 years) decline in Atlantic salmon numbers (marine and rivers), including the potential threat of climate change. In continuing to mainly focus on fish passage, rather than identifying and dealing with the other more recent causes of salmon population decline, we may be repeating the mistakes of the mid-19th century, which took 100 years to recover from. By removing weirs to facilitate passage, we also reduce the ability of local communities to help mitigate climate change.

During the early stage of the industrial revolution, a combination of inefficient wooden waterwheels, a demand for more power from the finite waterpower sites and competition from the new steam power, drove waterpower innovation, such as the breast-shot wheel, the iron suspension wheels and water turbines. The HEP industry continues to innovate today, accommodating concerns over the impact of turbines on the fisheries (e.g. fish-friendly Archimedes screws) and improving efficiency and cost-effectiveness with improved monitoring, control and automation (e.g. screen cleaning systems). Faced with further challenges to water availability, due to EA abstraction reviews and finer screen requirements restricting flows (e.g. eel regulations), the HEP industry continues to focus on improving the efficiencies of existing installations.

The original scope of this research project was focussed on the traditional run-of-river watermill small HEP sites, but the desktop research and walkover surveys identified notable non-mill and man-made water flow HEP opportunities. As early as the 17th century, man-made lead mine soughs powered waterwheels for pumping and ventilation. Today, the man-made water utilities network, which abstracts significant volumes of water away from the run-of-river HEP turbines in the DDC, has HEP opportunities throughout the water storage, distribution and waste treatment assets. In the 1970s, the water authorities were viewed as the most significant HEP opportunity in England and Wales by the Department of Energy, but they did not deliver their HEP potential as they had other priorities, supplying water and treating and disposing of wastewater, similar to the Ofwat requirements on the privatised water industry today. We do not know the current HEP potential (technical or economic) within the UK's water industry, but the DEFRA minister responsible could require the water utility companies to identify HEP opportunities within their assets, as part of their existing environmental management responsibilities (e.g. the mandatory four yearly Energy Saving Opportunity Scheme report). The identified

HEP opportunities could then be developed by the companies themselves or third parties (including local community energy groups), as per the current Scottish Water programme (Scottish Water, 2018).

Like Smeaton (1752) and Armstrong (1835) before them, communities, today concerned about climate change, can see the waste of unutilised waterpower at sites in their local area. The revival in HEP in the 2010s saw the formation of a new type of HEP developer, community energy groups. In developing infrastructure in the 18th century, parliament included restrictions on share ownership and dividend payments, as seen with the Derby Canal (1789). Not-for-profit community energy groups, governed under similar share and dividend restrictive rules, offer many benefits in allowing local ownership of renewable energy generators to supply local communities. Critically, the less demanding economic return on investment required by reduced dividend payments, increases the number of potentially feasible HEP opportunities available.

6.2.4 Objective 4

> Assess the hydroelectric power potential of the Derbyshire Derwent catchment and wider Derbyshire area, utilising the information collated for the waterpower site gazetteer, including past and present waterpower application and generation.

By the mid-18th century many of the waterways of the UK were already well populated by smaller watermills. Industrial millowners competed to identify suitable sites with waterpower potential. The DVMWHS mill owners built many of their larger industrial mills on sites with a long history of harnessing relatively modest levels of waterpower. Following the example of these early industrialists, this research's process to identify the HEP potential of the DDC is based on proven waterpower sites, using historical OS maps supplemented by walk-over surveys. This novel approach is repeatable for catchments across the UK, using historic OS maps and existing regional watermill gazetteers. The walk-over surveys also led to the identification of non-mill waterpower sites, including the water utilities network assets.

HEP power calculations were undertaken using different sources of information, with varying levels of confidence (i.e. sites with installed HEP [accurate], versus quantity of historic mills [with infrastructure visible] multiplied by an average power per waterway [less accurate]). Section 2.3.6 includes the methodology, assumptions and findings of the HEP potential assessment for the 164 historic waterpower sites and 34 non-mill sites in the DDC (Table 6.1). Questions about HEP potential, especially from policy and decision makers, focus on total HEP capacity, or percentage of overall UK power demand. In existing data and reports, this stated total power capacity generally refers to the lower, currently economically viable HEP potential, which regularly changes dependent on energy markets and government policy and support, rather than the larger, but unassessed, technical potential. Focussing on the overall total potential also ignores the value of HEP to an individual waterpower site owner (private or business) or local community.

Table 6.1 Summary of HEP potential capacity studies in Derbyshire (2011 to 2023)

		HEP Installed Capacity MW	HEP Installed Sites	HEP Potential Capacity MW	HEP Potential Sites
East Mids. Council 2011	Derbyshire			5.4 [1] 13.6 [2]	
Scene Connect 2022	Derbyshire	1.7	14	1.7	14
This research project as at Dec. 2023	Derbyshire Derwent catchment	2.2	17	5.5	145
	Derbyshire	3.2	26	6.5 [3]	154
1 – Based on EA, 2010 win-win sites in Derbyshire 2 – Based on EA, 2010 all barriers in Derbyshire 3 – Derbyshire total based on DDC total + Existing HEP sites outside the DDC (in Derbyshire) No Potential sites outside DDC (in Derbyshire) or the Severn Trent Water opportunities are included					

In the mid-18th century the industrial millowners were only concerned about an individual site's power capability. A 'conservation' recommendation, from a UNESCO advisory report for the DVMWHS (31 January 2024 to 2 February 2024), was the exploration of compatible (i.e. heritage impact) developments that could generate income for heritage site owners, 'such as the use of turbines and wheels for hydroelectric power' (UNESCO, ICOMOS et al., 2024 5). A practical example of the value of HEP to a heritage site is the 2023 'rescue' of the Masson Mills in the DVMWHS, built by Richard Arkwright (1783); 'Derbyshire company seals takeover of historic cotton mill with plans for new generation of hydropower' (Dingwall, 2023). The number of potential HEP sites and their location, often distributed throughout rural communities (Figure 6.1), should be considered in the value of HEP, as a generator of renewable energy.

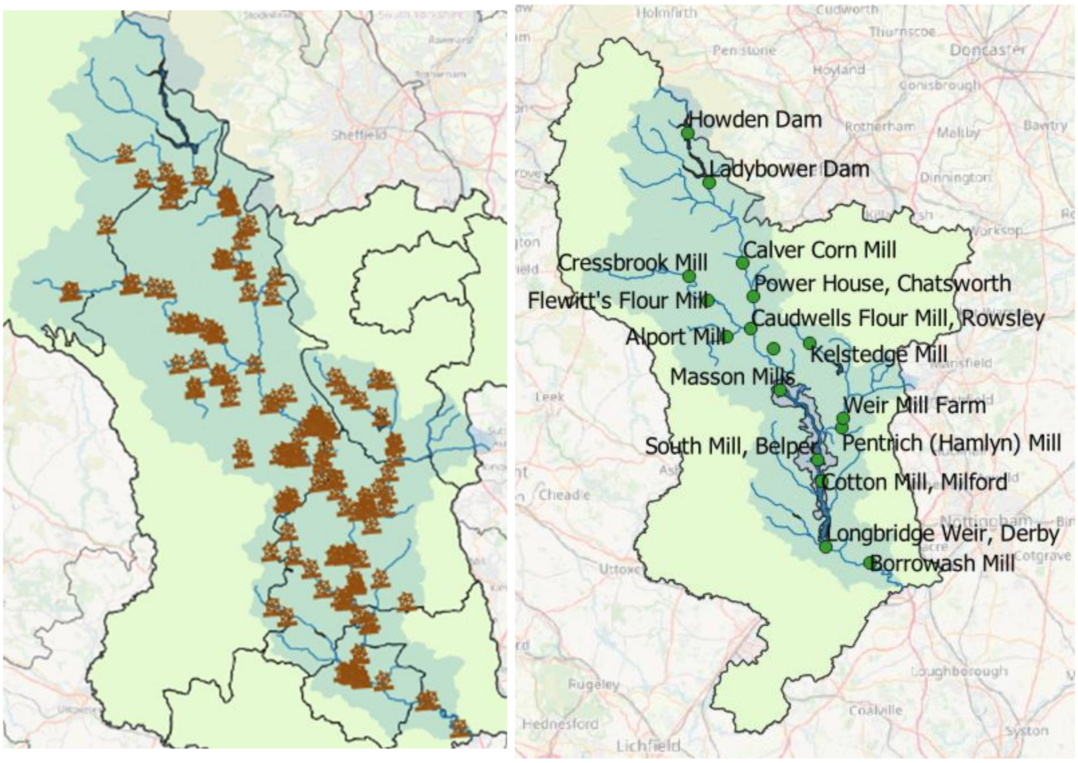


Figure 6.1 164 historic waterpower sites in the DDC (left), HEP generating stations in the DDC (December 2022) (right).

The pragmatic approach, of basing an assessment on historic waterpower sites, overcomes the challenge of scale noted during regional and national HEP studies carried out in the past. The 2022 Derbyshire HEP renewable energy potential study, declared that it was not possible to ascertain the HEP potential of the county's 1,068 identified weirs, possibly due to the scale of the task (Scene Connect, 2022). The 1989 Department of Energy study of HEP potential for the UK, carried out by Salford University Civil Engineering, ruled out sites with less than 25 kW potential due to the available time and resources, effectively removing the majority of historic watermill sites on smaller waterways. The 2010 Environment Agency study, an update of the 1989 assessment, attempted to include more of the smaller sites but was only able to calculate the potential based on concentrations of sites, rather than individual sites. By focussing initially on historic watermill locations, the scale of the potential opportunity assessment task is reduced.

The first (1978) HEP assessment for the UK was based on the assets, mainly reservoirs, owned and operated by the water authorities. This research recognised that the development of the 20th century Derwent Valley reservoirs and associated infrastructures created additional HEP opportunities. Despite current UK government guidance stating that ‘larger scales of [HEP] development are considered unlikely in the UK, due to the most attractive sites having already been developed’ (BEIS, 2013 2), an attempt has been made to include some of the HEP potential of the Severn Trent infrastructure in the DDC. Only information available in the public domain has been used, so the calculation does not include the potentially significant opportunities associated with STW’s currently non-powered reservoirs and their distribution and treatment network, an opportunity for future research.

6.2.5 Engaging with stakeholders

The overarching aim of the research was to identify the changes needed to overcome the current river stakeholder conflicts regarding run-of-river HEP, by learning the lessons of the past, enabling HEP developers in local communities to unlock the rivers' full power potential, using a sustainable and replicable way, to help mitigate climate change on revitalised waterways.

Section 1.4.4 discussed the opportunity to share the developing research findings with many of the stakeholders who could participate in unlocking the HEP potential of the DDC. Indeed, the feedback and questions, resulting from formal presentations of the research and informal conversations, helped to identify the key issues and potential learning opportunities to unlock small HEP potential for today's stakeholders. Aspects of the research have been of interest to different key stakeholders.

EA archaeologists and Trent catchment EA officers, tasked with the challenge of fish passage by the listed weirs in the DVMWHS, have shown particular interest in the historic use of their water infrastructure, proposing practical investigation, to understand the design of the complex weirs, flood-gates, channels and tunnels. The Derbyshire Derwent Catchment Partnership steering group were interested to learn about the mill owners' stewardship of the river during the early industrial revolution, and the infrastructure still in place that could be used, if reinstated, to improve the current river management and quality.

Historic England were interested in the operational aspects of the water mill landscape, such as the weirs and sluices, concerned about the risk to the historic assets through decay or planned removal. In discussions about the current problems of HEP development, Historic England were unaware of the duplication and complexity of repowering historic waterpower sites in a World Heritage Site, which potentially requires three different heritage impact statements (local, national and international). The DVMWHS technical group were encouraged by the sustainable development opportunities through HEP generation at critical heritage sites, understanding the need to protect the historic weirs that are so important in visually promoting the core waterpower story of the WHS.

The recent (2015-2024) focus, for government ministers responsible for the decarbonisation of the UK's electricity supply, has been supporting developing technologies/solutions, identifying small HEP as insignificant, despite proven technology and existing sites across the UK being available. In 2022 the British Hydropower Association provided evidence to the UK government of additional HEP capacity deliverable with different levels of fiscal support, but did not include the much larger, as yet unquantified, 'technical' potential for the UK. The significance of developing a technical potential for the UK was presented to the 2023 BHA annual conference, as a potential opportunity for the BHA committee to pursue. Derbyshire MPs' questions relating to the research have been repeatedly focussed on the number of HEP sites and individual site opportunities within their constituencies, reflecting the National Planning Policy Framework's view of the value of local renewable energy generation.

Midlands Net Zero, responsible for supporting local energy projects and government fund distribution, are aware of the unusually complex nature of small HEP. Communities across the midlands have shown interest in repowering historic waterpower sites and Midlands Net Zero hope to use these research findings to address a variety of issues raised, including capturing both the technical and economic potentials of any future potential HEP projects. They will also consider the sustainable development benefits of repowering historic sites, using the hidden power of HEP, despite the apparent constraints of the Peak District National Park and DVMWHS.

6.3 Research impact and future research

The time constraint of the PhD study period, and to some degree restrictions related to Covid-19, limited the depth of research in some areas. The role of the leading millwrights during the Georgian period, from a technical development and good practice dissemination viewpoint, may offer additional lessons to learn. Follow up visits to current mill owners, not possible in 2021, may identify further challenges and lessons for a broader range of historic watermill sites. Despite the original run-of-river HEP scope of the research, HEP opportunities were identified in non-watermill locations such as sough tails, water management weirs and water utility infrastructures, all worthy of additional research.

This research provides information that can improve stakeholders' understanding of the use of waterpower, past and present. Additional research and actions, related to the following three aspects, could help these stakeholders, working collaboratively, to both improve stewardship of the river and unlock HEP's potential in the future.

The HEP potential (technical) of the UK, by river catchment, by site.

Government support is critical to unlocking HEP potential across the UK and, as such, the incumbent government needs to properly understand its total, technical, potential capacity, in order to appreciate the baseload and power storage role that HEP can play in a future mixed fuel, low carbon power system.

Waterpower has been harnessed for hundreds of years in the UK, with the most suitable sites identified by the early watermill owners and optimised by the industrial mill owners in the late 18th and early 19th century. Many of these sites retain the critical elements of their waterpower systems which could be restored into local renewable power stations. The gazetteer of historic watermill sites for the DDC enabled a technical HEP potential to be calculated. A similar process could be followed for catchments across the UK, prioritising rivers with a history of industrial activity, to build a site by site, catchment by catchment, total potential for the UK. Other historic sites also offer the opportunity to generate HEP, and relevant organisations, such as the Canals and Rivers Trust, the National Trust and Gilkes (turbine manufacturer), could help to build a more comprehensive HEP potential, including historic navigation weirs and dams and country houses that self-generated HEP in the late 19th century. To complete the assessment of UK HEP potential, the opportunities in the water utilities' infrastructure must also be identified and incorporated, potentially through the mandatory Energy Savings Opportunity Scheme, by the water companies, Water UK or Ofwat.

Floodgates and sluices

Floodgates and sluices were critical to the operation of the historic industrial watermills. In addition to the diversion of water to the waterwheel or turbine, the gates played a key role in river stewardship, including river levels and flood management. However, there is still much to learn about how Sunday gate openings facilitated navigation down the lower Derwent, the impact of regular gate opening on silt movement and the role that gate openings, at weekends and at times of high flow, played in fish movement.

The Belper weir complex, at the heart of the DVMWHS, is one of the best-preserved, listed, historic weir complexes, due to its continued harnessing of HEP (1776 – today), and offers an opportunity to learn more about the wider use of weirs, floodgates and sluices, to improve our stewardship of the river today. In addition to the site's ongoing role as a green power station, the Belper floodgates continue to function, controlling the river levels, enabling maintenance of the weirs and supporting flood management. We do not understand how the opening of the floodgates today impacts fish movement or river morphology, but the occasional openings to facilitate maintenance do disturb and move silt built up in the dam. Critically we have yet to learn exactly how the Strutts, and other mill owners on the Derbyshire Derwent, facilitated fish passage during the early industrial revolution and how the 'most complete salmon pass' reported on by Farey (1817) functioned. These apparent river steward 'good practices' must have been in use nationally, as they were incorporated into the England and Wales Salmon Fisheries Act (1861), which points to the opportunity for similar research in other UK 'industrial watermill' river catchments such as the River Dee, Chester (Wilding, 1997).

Similarly, understanding how the fisheries were improved in Ireland prior to the 1860 commission, may also enhance our understanding of the industrial watermill owner's role in river stewardship.

HEP planning and consenting: value stream mapping

Historically, the UK government's perception of the value of industries reliant on waterpower enabled its development, not through financial support, but through preventing physical and policy obstacles from impacting on businesses and protecting 'milling power'. In today's complex situation of conflicting government department priorities, river regulators and statutory planning consultees with other priorities, HEP developers are not offered similar safeguards by the UK government.

The pre-planning and pre-consenting requirements are considerable for any size of HEP facility, requiring a wide range of skills, time and costs. The government fiscal support, that led to a revival of HEP development in the 2000s, may also have had the unintended consequence of adding bureaucracy and capital costs (e.g. fish passes), made affordable with Feed in Tariffs, but unsubsidised and uneconomic today. Examples such as the triplication of heritage impact assessments for one small HEP DVMWHS project in 2022, and the one-hundred-fold increase in EA abstraction pre-application costs, suggests waste and unnecessary bureaucracy in the current planning and consenting systems. The UK coalition government (2010-2015) identified an opportunity to improve the planning and consenting processes for HEP in its 2014 *Community Energy Strategy*, recommending the setting up of a collaborative Hydro working group (DECC, 2014a 63) but this did not progress following the 2015 change in government.

The UK government's Community Energy Fund, designed to kickstart small renewable projects, may be hiding unnecessary transactional studies, reports and associated costs for community HEP developers. A collaborative 'value stream mapping' exercise (Rother and Shook, 2003), including all river and water stakeholders, could eliminate waste from the planning and consenting processes, enabling more win-win projects to be delivered. In the same way that the

Environment Agency currently works with partners, such as the Rivers Trusts, to deliver fish passage improvement, new, leaner, processes could be developed by a HEP working group, or taskforce, enabling the river regulator to work with community hydro groups as partners, to deliver a network of HEP generation sites across the UK's catchments.

6.4 Closing Reflections

In addition to improving understanding of the development and use of waterpower by the early industrialists, this research introduces a new aspect of the industrial watermill owner, that of the river steward. The DDC offers examples of good river stewardship during the Georgian period, with watermill and landowners working together in catchments. We have the opportunity today for river stakeholders, including HEP generators and developers, to similarly work together as ‘collective river stewards’, through agencies such as the Derbyshire Derwent Catchment Partnership. However, for these partnerships to be effective, the clauses protecting waterpower in the Salmon Fisheries Acts (1861 to 1975) need to be incorporated into The Water Environment (Water Framework Directive) (England and Wales) Regulation 2017.

The Salmon Fishery Acts were developed based on an understanding of watermill operations, using floodgates and sluices, to facilitate fish ‘distribution’. Throughout England and Wales, historic (restored) weirs, floodgates and sluices may offer an opportunity to deliver river improvements (flood management, fish movement, silt dispersal and HEP generation) relatively quickly and cost-effectively, with support from bodies such as Historic England, Natural England and planning authorities.

Whilst developing the original SFA (1861), the conservators ignored the threat of pollution, continuing to pursue fish passage as the primary solution to salmon fishery recovery. In modern times, salmon numbers have been in serious decline globally since the 1970s, but the Environment Agency continues to identify the historic waterpower weirs and poor fish passage as the pre-eminent threat. Hopefully we are not repeating the error of the 1860s, neglecting a more significant threat(s) to the fisheries, and focussing on the removal of weirs that could help to mitigate one of those potential threats, climate change.

Waterpower has had a significant impact on local communities for hundreds of years. Supporting local small renewable energy (2010-2019), allowed individuals and local communities to engage and act, faced with the challenge of climate change. The FiT scheme’s higher than planned deployment led to its demise (DECC, 2015), but it did mobilise communities to identify and try to deliver community sized climate change mitigation solutions, something small HEP is ideally suited to. To move forward, it will require understanding and support across all government departments of the value that marginal gains of local renewable energy solutions can deliver (DLUHC, 2023 47).

The mission statement of the sustainability Transition Towns movement states;

> 'If we wait for governments, it will be too late, if we act as individuals it will be too little. If we act as communities, it might just be enough, and it might just be in time' (Hopkins, 2019 6).

This is laudable, but the current barriers (or lack of support) from the government and its agencies, possibly unintentionally, are preventing communities from acting. A collaborative, critical, review of existing processes, and a change in the WFD UK 2017 regulation that rebalances the needs of all river stakeholders, would save time and costs for all parties involved in HEP development. Combined with cross-governmental support, including DEFRA, and fiscal assurances (facilitating the low carbon transition), communities could unlock the remaining HEP potential of the Derbyshire Derwent catchment, and similar catchments across the country.

Epilogue: 2035 Vision

Today (2024), the River Derwent's steady flow, varying with the rainfall patterns, is a relatively new feature of the river. Between 1776 and 1986, at locations such as Belper, the dam would be refilled overnight during the working week and water, no longer needed for power at the end of the day, would be released over the weir, accompanied by a warning siren. During dry periods, mills would store the fuel (water) in their dams and release the water to match their power demands.

Towards the end of the 20th century the need to reduce emissions and decarbonise the electrical supply network was understood and actioned. The most significant emission reduction action was the closure of the coal-fired power stations, largely replaced by gas-fired facilities. The gas stations not only reduce carbon emissions, but the technology also allows flexible generation to effectively match demand. To achieve the UK's Net Zero plans the gas stations need to be replaced by 2035, using low carbon generation that can store or produce electricity, on demand. With the highest HEP outputs typically aligning with higher winter demand, and reservoirs offering the opportunity to store and release water on demand, HEP could play a role in the replacement of gas-fired power stations. Using proven technology and existing infrastructure, the Derbyshire Derwent catchment has the opportunity to deliver a model for renewable energy storage and generation, matching the demand of local communities, mirroring the success of the early Derwent Valley industrial mills (Figure 6.2).

By 2035, the Derwent Valley and pumped water storage reservoirs, owned and operated by Severn Trent Water, should be dual purposed, storing both water and power. Dynamic compensation and drawdown flows from Ladybower, Ogston and Carsington reservoirs, would be designed to increase flows to DDC HEP generators, to produce electricity at times of peak demand. A combination of environmental flow development for the DDC, repowered HEP sites on the Derwent and restored historic sluices and floodgates would deliver the win-win-win opportunities of renewable energy generation, improved river ecology and flood management. The two reservoirs functioning as pumped water storage facilities, Ogston and Carsington, would also have a pumped energy storage function, filling overnight using surplus renewable energy (e.g. Carsington or Spondon onshore wind turbines) and releasing water to the downstream Derwent HEP generators during peak demand periods.

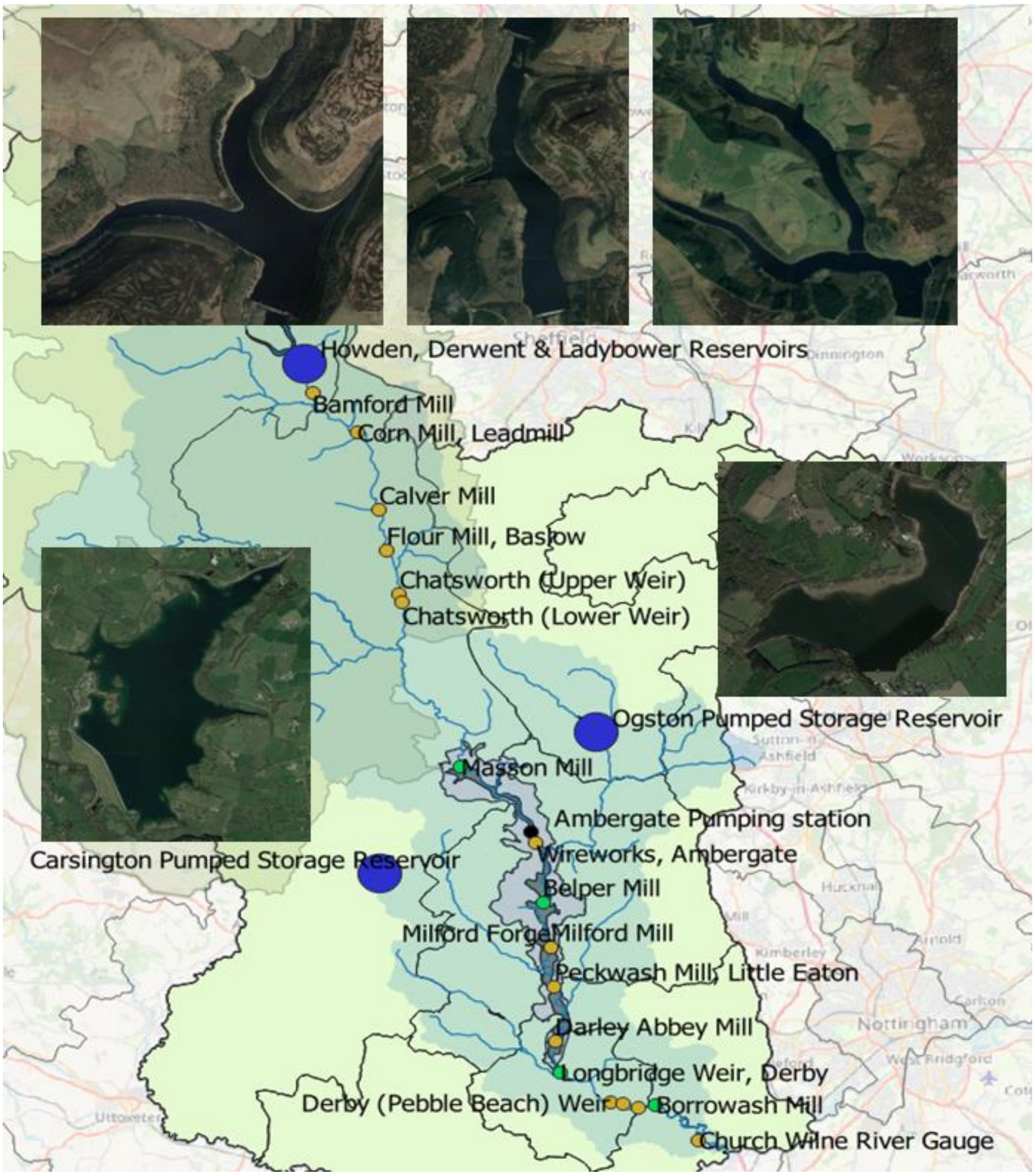


Figure 6.2 Existing assets delivering renewable energy, matching the demand of Derbyshire Derwent catchment communities.

In 2024 we face a serious challenge: to ensure energy security at the same time as transitioning to a decarbonised energy system, mitigating climate change. The UK has faced energy security challenges in the past and a statement made by Lord Wilson in the House of Lords in 1978, in a debate into Energy: Alternative sources, resonates with the researcher today:

> ‘I agree that the amount of waterpower available is extremely small, almost infinitesimal, but as other noble Lords have pointed out, we must explore all avenues; and it seems a shame, almost an act of stupidity, that we should not be examining the sources of conventional hydro-electric power that are available to us and which have no effect at all upon the atmosphere or on the water which passes through the turbines and which is replaceable with the sun as our boiler‘ (PA HC Deb 1, 1978).

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