ENGINEERING AND TECHNOLOGY OF INDUSTRIAL WATER POWER AT CASTLEFORD MILLS FROM THE SEVENTEENTH CENTURY TO THE TWENTIETH CENTURY

by

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This article tells the story of engineering and technology at Castleford Water Mills from the seventeenth century to the twentieth century through the presentation of recently discovered design plans and deeds, supplemented by other historical research. One of Castleford’s mills was operated by Dr Thomas Allinson’s Natural Food Company and therefore retained stoneground milling when fashions for white flour prompted other mills to switch to roller systems. The millstones were powered by a high-efficiency breastshot wheel, believed to be the last of its type taken out of industrial service in Britain. Many of its features, and its subsequent longevity, can be attributed to the influential works of William Fairbairn and John Smeaton. Detailed colour designs show the construction specifications of this water-wheel and its civil housing, along with other engineering plans such as a previously unrecorded Henry Simon horizontal turbine. Links with John Smeaton and the entry in his catalogue of designs for Castleford Oil Mill are also explored, and a former flood mill is identified at the site.

Keywords: John Smeaton; William Fairbairn; water-wheel; milling; flood mill

1. INTRODUCTION

Despite the current necessity for greater uptake of renewable energy technologies, it is difficult in the twenty-first century to find recent information on the science and engineering of vertical water-wheels. Two hundred years ago however, the situation was completely different. Vertical water-wheels were powering the early stages of the industrial revolution in Britain, and water-wheel engineering was at its peak. Industry was demanding more power, and rivers had become saturated with water-wheels. As a consequence, and to compensate for the lack of new available water-power sites, theoretical analyses and experimental enquiry pushed water-wheel design to its most optimized form in the pursuit of greater efficiency.
Millwrights became highly skilled engineers, and the preferred design for lowland rivers in Britain was the breastshot wheel.

John Smeaton (1724–92) is widely acknowledged for his contribution to improving water-wheel efficiency, and is credited by both contemporary and modern authors as being singularly responsible for the widespread application of breastshot water-wheels in Britain during the mid to late 1700s. He was born 8 km from Castleford but moved to London aged 18 years and became apprentice to a philosophical instrument-maker. There he joined in with meetings of the Royal Society and began to submit works of research. At the age of 27 years, Smeaton had completed a series of experiments with different types of model water-wheel, and for this he was awarded the Royal Society Copley gold medal ‘On account of his curious experiments concerning water-wheels and wind-mill sails’. From this study he was able to conclude that gravity wheels (where water enters in line with or above the axial plane—‘overshot’ or ‘breastshot’ types) were almost three times more efficient than impulse wheels (where the wheel is turned by the momentum of natural water flow velocity—most ‘undershot’ types). This led to the subsequent replacement of many undershot impulse wheels with gravity breastshot wheels by Smeaton and his contemporaries.

Through his management of engineering arrangements at the Carron ironworks in Falkirk, John Smeaton also introduced alterations that improved the quality of iron production, resulting in the making of the first iron water-wheel axis (axle) there in 1769. By the end of the eighteenth century, quality iron could now provide both strength and resilience (it did not expand and contract like wood, thus alleviating some of the stress on internal fixings) in addition to its being easier to shape into curves; as a consequence it enabled the building of larger wheels, which could supply more power. The breastshot wheels that Smeaton designed were, however, relatively narrow in comparison with those that were to follow. The wide breastshot wheel was favoured for large industrial power by the Scottish and later Manchester engineer William Fairbairn (1789–1874). Fairbairn went on to win two Royal Society gold medals (the Bakerian Medal and the Royal Medal), 100 years after his predecessor. His importance in the history of water power is embodied in a two-part treatise on mills and millwork that includes all aspects of water-wheel engineering design and is a defining text of the technology at its most efficient. The efficacy and longevity of the wide breastshot wheel based on Fairbairn’s designs in the nineteenth century are demonstrated by the fact that many of these wheels remained operational well beyond the change in preference towards first steam and then grid electric power. Two of the latest surviving examples, both built by Fairbairn, were finally decommissioned in the late 1940s, in Perthshire (built in 1830) and Ayrshire (built in 1827).

The Castleford Mill wide breastshot wheel, however, continued in industrial use into the 1970s, later than any previously reported. Major building works had occurred at Castleford Mill in the latter part of the 1880s, and in commemoration of Queen Victoria’s Diamond Jubilee it became known as Queen’s Mill. Some time around 1900, Queen’s Mill was taken over by Dr Thomas Allinson’s Natural Food Company, and for most of the next century it was known locally as ‘Allinson’s Mill’. It remained as a working stone-grinding flour mill until 2011, when it was taken over by a local charity. This led to the discovery of a previously unreported dossier of old deeds, plans and other legal documents, most of which are in excellent condition. This paper presents these documents and the story of the Castleford Water Mills.
2. LOCATION

Castleford Mill stands on the southern bank of the river Aire (National Grid Reference SE 4278 2593), which flows west to east towards the Humber estuary, in England. Upstream by about 200 m, the Aire is joined by the river Calder, which causes it to broaden, and just after this confluence the Aire is 67 m wide, with a mean average flow rate of 53 m$^3$s$^{-1}$. At some point a weir was built to raise the water level to create an increased head of pressure so that water would flow with greater momentum through a water-wheel channel. This channel has numerous colloquial names such as millrace (head race upstream of the wheel, tail race downstream), goit and leat.

Before the weir’s construction, fording of the river Aire was possible, approximately 100 m upstream. This was the crossing point for Roman armies as they journeyed north to York or south to Doncaster and Lincoln. The route allowed them to bypass the Humber estuary, which was the more direct route. This geographical situation made Castleford a Roman settlement of major importance, and its name originates from this ‘ford’, adjacent to where there was once a Roman fort, ‘Ceaster’. The naming of the river Aire, which has its source in Malham Tarn in the Yorkshire Dales, was suggested by the antiquarian William Stukeley (1687–1765) to come from its characteristics at Castleford.

Here [Castleford] the Hermen-street passes the river Aire, remarkable for its smooth face and gentle current: It is broad and deep withal; navigable hither: thus the River Arar, synonymous in Gaul. The place where the Roman ford was, is a little above the cascade: the stones are in great part left, but the mill-dam lays it too deep under water. The country people have a notion of its being an old city, and of the Roman road crossing the meadows by the ford; and of great feats and palaces having been here formerly. Great coal-works here.

The brevity of Stukeley’s final sentence would resonate throughout the subsequent years of Castleford’s history. First the canals came to take advantage of a developing glass and pottery industry, and then industrial coal mining. These industries, along with coal gasification and chemical processing, made Castleford a boom town during the latter part of the nineteenth century. Hardcastle describes how the population grew from 1140 in 1841 to 12500 in 1888. From the mid 1980s onwards, Castleford began a rapid social and economic decline, as almost all of its heavy industries closed.

A fitting way to take this story to its focus is to follow the Roman road into Castleford, using I. D. Margery’s vivid description. The time was 1955 and the water-wheel had fifteen years left in this stage of its working life:

To the east of Featherstone [about 3.5 km away] a lane and a hedgerow beside the golf-course mark it until the [Roman] road plunges into the smoky horrors of Castleford, which necessarily obliterate everything. In this blackened town, the course of Beancroft Lane and Rectory Street do, however, preserve part of the line, which has now turned on to an alignment due north.

3. CASTLEFORD’S EARLIER WATER MILLS—CORN, FLINT AND BONE, SMEATON AND FLUDD

In John Smeaton’s Catalogue of Civil and Mechanical Engineering Designs, there is an entry entitled ‘Copy of Mr Crowther’s Draught for Castleford Oil Mill’. It is undated, and nothing else is known about it. The plan shows a vertical water-wheel 16 feet in diameter,
with the main focus appearing to be the bevel gear transmission mechanism and the two vertical runner stones (stones, positioned on edge and fixed to a central and continuously rotating post, which crushed the grist as they rolled over it). The intended location of this design has never been discovered, with one author unable to speculate more than that it was for either the Aire or the Calder. None of John Smeaton’s water-wheels are reported to have survived, and many of the mills that housed them are also gone.

A number of newly discovered, consecutively dated plans from 1884 show progressive stages of the project to install the present wide breastshot water-wheel at Castleford’s Queen’s Mill. Figure 1, dated August 1884, illustrates how the old water-wheels and building were to be changed to accommodate the new designs (highlighted in pink and superimposed over the pre-existing structures), along with detailed river depth measurements. It can be seen that before these changes, the mill head race separated into two channels, providing water for two wheels. The diagonal linear feature in the head race aligned southwest to just above centre in figure 1 marks a ‘Coffer Dam’, a temporary structure to isolate the site from water ingress during the works. Smiles describes how these were built according to John Smeaton’s designs with ‘a row of piles driven into the bed of the river, on which a quantity of gravel and even mould earth mixed together was thrown’. When work was completed and the cofferdam had been removed, a wooden boardwalk was installed that served as a boat mooring point, but its principal function was to divert flotsam and jetsam away from the wheel sluice.

Figure 1. ‘Castleford Mills’, dated August 1884. (Canal and River Trust Archives, Leeds, E0700; reproduced with permission.) (Online version in colour.)
The two pre-1884 water-wheels, shown more clearly in earlier plans from the same year (figure 2) as being 19 ft 2 in x 6 ft 1 in and 18 ft 9 in x 4 ft, therefore do not match the dimensions given for the Castleford wheel that appears in the John Smeaton catalogue. The difference of 100 years makes it reasonable to assume that if the design in Smeaton’s catalogue had been installed here, it would probably have been replaced by one of the two wheels in figures 1 and 2. There is, however, the possibility that the Smeaton design may never have been built at all, because it is not within the ‘List of Mills Executed by Mr Smeaton, from a paper in his own handwriting’. Although there are other omissions, this list has been suggested as evidence of only the select few designs that were actually built.

At the time of Smeaton’s design, and for many years before this, there were, however, two mills on this part of the river Aire in Castleford. The earliest published records that refer to them are from A.D. 1122. The same source reports that there was also a ford in 1155, implying that the weir had not yet been constructed. With one on each side of the weir (north and south bank of the Aire), more of the newly discovered plans show both these mills dated 1821 (figures 3 and 4). As Castleford was a relatively small town in the early 1800s, unless the wheel was commissioned for a totally new building construction (which seems unlikely because there is no evidence from maps or records that any other mill site existed) it is practically certain that Smeaton’s wheel would have operated on the Aire at Castleford weir, and so would have been for one of these two mills.
The present site of Queen’s Mill (the southern bank of the Aire) is the one shown in figure 3, and parts of this structure survive. In 1821 this building was supporting two water-wheels, with one milling corn: ‘two pairs of French stones and two pairs of grey stones, two wire dressing machines, corn screen, shilling machine, and machinery. 1, 2, and 3 floors, fourth floor corn chamber’; the other was used for grinding previously bone, but subsequently flint: ‘Flint mill and machinery, 3 stories high’. Grey stones were Derbyshire millstone grit. The flint mill (annotated also as ‘now bone mill’), relates to the pottery industry of Castleford and indicates a change in production from white earthenware using flint as an ingredient to bone china.27

On the north bank this mill building is named as ‘Allerton Mill’, and it again accommodates two water-wheels and two separate applications. One section is a corn mill with ‘three pairs of French stones and one pair of grey stones for shilling oats. Two wire dressing machines and machinery on the 1st, 2nd, and 3rd floors, 4th and 5th corn chambers’. The other section of the building had two oil mills, with the first comprising ‘One pair of stones, 2nd, 3rd, and 4th floors corn chambers in the occupation of J. Ramsden’ and the second ‘One pair of stones, two presses, and two kettles’. With five floors and three mills, this will have been an imposing structure of comparable size to its southerly partner, both combining to create a significant landmark for a town that at the time held about 1000 people and was essentially farmland or pasture with a pottery cottage industry.28 No other documentary records have been found for this north-bank Castleford mill, and no evidence or remains of a structure

Figure 3. Plans for ‘Castleford Mill’, now known as Queen’s Mill, dated 1821. (Canal and River Trust Archives, Leeds, E0701/1; reproduced with permission.) (Online version in colour.)
now exist other than a Derbyshire grey stone that was recovered from the site in the last few years when a fish pass and bridge were built at the weir.

There is evidence for and against this northern site’s being the location for Smeaton’s Castleford Mill water-wheel. It is the only one designated as an oil mill. Yet the 1821 plan gives it the title of Allerton Mill, rather than Castleford Mill. A search through local historical archives yielded no record of Mr Crowther in connection with either mill. The search did, however, uncover two documents, the first dated 1619 and the second 1642, that describe one of the mills at Castleford as ‘the fludd mills’. 29

The actual definition of a fludd/flood mill is currently obscure. The title appears infrequently in older documents, and seems to have disappeared from use completely after the eighteenth century. One possibility is that the term could indicate some connection with the English Renaissance scholar Robert Fludd (1574–1637), who devised numerous water-wheel, Archimedean screw and water-powered pressure engine systems for pumping and turning. 30 Indeed, a flood mill is defined in places as being one built for raising water with the purpose of draining land, more commonly known as a ‘drainage mill’. 31 However, there is no evidence to support a connection between Robert Fludd and this or any other type of mill practice. The prevailing view has always been that Fludd was more of a theoretician, essentially an alchemist, physician, natural philosopher and mystic, and that none of Fludd’s designs were ever built. 32 Furthermore, there are documented fludd/flood mills that pre-date his ideas.

Figure 4. Plans for ‘Allerton Mill’ on northern side bank of the river Aire, dated 1821. (Canal and River Trust Archives, Leeds/E0701/2; reproduced with permission.) (Online version in colour.)
The earliest recorded evidence of a flood mill relates to a tide mill operating in Kent from the eleventh century. Tide mills were estuarine buildings, usually situated some distance from the coast. They operated by collecting the high-tide waters in a pond adjacent to the mill so that when the tides changed, the outward flow of this impounded water was channelled through the leat of a water-wheel. Another reference mentions a ‘Fluddmill keye’ (quay) in a different part of Kent in about 1566, although no further description is given. Of most relevance, however, are two descriptions of a flood mill with the attributes of a conventional inland water-wheel operable in times of extreme river flow. Such a ‘Fludmill’ was worked in Newark-on-Trent from 1576 until at least 1772, where it was described as ‘very convenient and necessary in times of flood, as it could be used many times a year when other mills could not grind’. John Smeaton also describes a ‘flood-mill’ with identical functionality, which he designed for Knouch Bridge in 1776. Smeaton’s ‘flood-wheel’ was a low breastshot type stated to be half as efficient as the two overshot wheels he was also proposing as part of the same installation. Its value can be gauged by Smeaton’s advising that the proprietors might consider dispensing with one of the two overshot wheels because of the flood-wheel’s ability to operate at a wide range of flow conditions (both high and low water).

There is no detailed drawing of Smeaton’s flood-wheel design. A description of its features is limited to its having floats (flat paddles) rather than buckets (hence its lower efficiency), and being 17 ft 4 in high and 5 ft 2 in wide. An overall plan of the site is provided, and in it the leat to the flood-wheel is marked as a dashed line. Because of this, and by its position on the plans, this mill head race seems to be an overspill channel, an observation supported by Smeaton’s text, which describes a gate that may permit closure of the inlet, implying that the flood-wheel was used only when necessary. However, it is possible that the dashed line could also represent a deep-water or even underground mill head race. This is supported by the height differences between the three wheels annotated on the site schematic. Comparisons can be made here with the plans for Castleford’s Allerton Mill. When one looks at figure 4, it is puzzling that the building seems to be landlocked on the southerly side, which is the upstream section, therefore showing no means of water entry. The absence of either head race on figure 4 cannot be dismissed as a lack of detail in the plans, because the counterpart design in figure 3 accurately shows the mainstream situation of the water flow through the mill building. This could therefore indicate that the inlet channels were also situated below the water line and/or were kept closed except in times of flood. A plan of the same location from 1866 shows Allerton Mill marked in pink and now seemingly in a derelict state (figure 5). It is identified as a faded outline of an unmarked rectangle, but this plan does show two water entry points now exposed, suggesting perhaps that once out of use, the channels were demolished and/or allowed to naturalize and erode.

4. THE PRESENT VICTORIAN WATER-WHEEL

The wide breastshot water-wheel that was designed for Castleford Queen’s Mill in 1884 is an iron and timber hybrid with a diameter of 20 ft and a width of 13 ft 1 in (see figure 6). Not surprisingly, having been built late in the history of this technology, the present wheel follows many of the recommendations made by William Fairbairn, at exactly his specifications of a 1:1.5 ratio of width:diameter. It is broad and was slow turning, being geared directly to the axle, and it fits tightly by 1 1/2 inches either side of its civil housing.
to accommodate the maximum possible water volumetric capacity (the ‘wetted width’). Being a gravity wheel, this ensures that the maximum mass of water enters and creates the greatest turning force (torque). The maximum wetted width is also achieved by having the arm (spoke) retainers on the inside of the shrouds (the iron rims). The shrouds are an efficiency feature: they stop water spilling out at the sides through the lower entry quarter where the energy is transferred.

The water-wheel has 24 curved buckets. This is, however, much fewer than recommended by Fairbairn, who suggested between 40 and 60 for a 20-foot diameter wheel. Following on from Smeaton’s model experiments, curved buckets were introduced to increase efficiency, on the basis of the work of three French engineers. Jean Charles Borda (in 1767) and Lazare N. M. Carnot (in 1782) emphasized the need for optimum transfer of (what is now conceived of as) kinetic energy such that greatest efficiency is achieved by water entering without impact and leaving without velocity. Carnot was an important figure in the French revolution, and like many early engineers, he developed his skills through military work. The first introduction of curved water-wheel buckets is, however, attributed to General J. V. Poncelet (1788–1867), who had previously served under Napoleon. Poncelet’s curved bucket design of 1823 allowed water to enter tangentially with the flow (no splashes) and also to dispense the water at the base of the wheel with zero velocity. A detailed exposition of Poncelet’s theoretical calculations and practical designs can be
found in Fairbairn’s *Treatise on Mills and Millwork*, part 1. The two engineers were contemporaries, and seemingly held each other in high regard, as letters published in Fairbairn’s autobiography show. A year after Fairbairn was made a Fellow of the Royal Society, it was Poncelet who instigated his admission to the National Institute of France, an accolade bestowed upon few other Englishmen.

Being a breastshot, the Castleford wheel is engineered so that water enters in line with the axis (as shown in figure 7). There are subsets of the breastshot wheel designated as high or low breast depending on whether the entry point is slightly above or below the axial plane. As can be seen from the original plans (figure 7), this wheel is a low breastshot. The ‘breast’ is a closely fitting section of civil construction in the lower near side (water entry) quarter, and its purpose derives from how it closely follows the wheel’s circumference, thereby stopping water losses from the front. The aim was therefore to permit the maximum amount of water to enter as smoothly and easily as possible, and then to hold it there until the base of the turn. The longer its mass remains in the bucket, the greater is the transfer of kinetic energy to the wheel. The breastshot gravity wheel therefore achieved the higher efficiencies according to Smeaton’s experimental results, but they were relatively easy to retrofit in place of the less efficient undershot impulse wheels and did not need the challenging construction methods often necessitated by full overshot gravity wheels. The importance of geographical location should also be noted, such as the wheel’s ability to cope with flow variations (flooding and
drought), many of which could be caused by nearby mills. The advantage of the breastshot wheel was that it afforded greater versatility in its ability to provide high efficiency at a range of river head conditions.\(^47\)

The water enters through a sluice gate, which is a sliding hatch that permits a controlled high velocity and directed ‘sluice’ of water, as shown in figure 7. It comprises three independent guide plates, channelled at 25° to the horizontal, with a distance between each of \(8\frac{3}{4}\) inches, thus again built to the recommendations of Fairbairn.\(^48\) An iron rack-and-pinion gear raises and lowers the timber gate, spanning a total depth of 2 ft 6 in. The sluice gate is closed when fully raised, and the primary channel for water entry is the topmost of the three, then the middle and finally the lower channel should the water level in the dam fall. This is also in accord with the designs of Fairbairn: it ensures that the water is ‘always drawn off at its highest level and the fall economised to its utmost extent’.\(^49\) The sluice gate is still in situ and currently fully raised (in a closed position). The shaft (which connected to both pinions) went through into the mill building so that the sluice gate could be controlled internally. It was explained to me by a former operator of the mill that in the 1960s the sluice gate was controlled manually by a belt linked to the rotation of the water-wheel, and the belt connected to the first floor (where the millstones were being worked). A bell attached to this belt mechanism indicated the speed of rotation; when required, the miller would then walk down to the ground floor and adjust the sluice gate according to the frequency of the soundings of this bell.
The headstock (iron bearing box), which houses the 10-inch diameter axis, rests on a three-tier stone block structure. Directly below the axial centre line of the wheel, a section of stone marks the lower radius and provides a 6-inch clearance above the tail water. This was to stop the wheel from becoming tail-bound and thereby inhibiting free rotation. Figure 7 also shows that the ‘head’ or ‘fall’ of water available (distance between ‘top of deals of dam’ and ‘water level in low pond’) is given as 7 ft 2\(\frac{1}{4}\) in. The bucket timbers are full-length pieces, 8 in \(\times\) 1\(\frac{1}{2}\) in, with two planks at the back of each bucket (soleplate) and four comprising the radial section. All planks are flat butted. The straight bucket timbers are made to curve by being slotted and bolted into iron grooves on the shrouds (see figure 8). Analysis has identified that the current bucket and soleplates are pitch pine (\textit{Pinus rigida}), probably because of its high resin content. Also making pitch pine a suitable material for water-wheels are its relative lightness and strength. Although the timbers are only wetted for one-quarter of each rotation, water repellence is important to protect against decay and because expansion and contraction impose pressure on the iron spacers (bucket-board brackets), of which there are two equidistant sets separating the buckets into three segments. These brackets form a line along two inner circumferences of the wheel and help to maintain the bucket curvature. Some are broken on the outer edges, suggesting that the wheel has experienced some impact damage. The brackets are not described on the 1884 plans, although a single design plan exists dated 1946 (not shown). Either the need for replacement had occurred or a full set was produced to replace a previous design. With the 13-foot width it is inconceivable that
unsupported timbers would have been used across the full length. Because the wheel is protected from the front by a sluice gate, it is likely that this damage occurred after decommissioning. A former miller tells of an episode of high water during which the wheel broke free and began spinning rapidly. Once access was safe, it was rechained.

The bucket-board brackets align with arms (spokes) connected to the axis by 58-inch iron hubs (figure 8). There are four hubs, marked as ‘Arm Nº 1’ to ‘Arm Nº 4’ on the annotated plan drawing of the water-wheel dated December 1884 (figure 6). Note that, by December 1884, only the present water-wheel is shown on the plans. The outer arms connect at the wheel’s outer radius, as described previously, to the shrouds. These hubs and the wheel arms take the highest operational torque stresses; thus the timber used here is oak (	extit{Quercus} sp.). John Smeaton is reported to have struggled with single-axis and hub flange castings in his efforts to introduce iron to water-wheels. This was due to weak points in these high-stress regions because when cast the flanges cooled more quickly than the axis, resulting in higher porosity and making them more brittle and prone to catastrophic failure.\textsuperscript{53} Smeaton’s solution was to cast the flanges separately and then wedge them into the axis, a method that was used in the construction of the 1884 Castleford mill wheel (see figure 8).\textsuperscript{54} The shrouds of the water-wheel are formed of eight individual segments, revealing how the wheel was probably built 	extit{in situ} (a rough estimate of its weight is 30 tonnes) with the axis and hubs 1 and 2 inserted first, then hubs 3 and 4 added afterwards, along with arms and soleplate ironwork. Of note also in figure 8 are the ventilation gaps in the soleplate. These were a later feature in the pursuit of higher efficiency, coming from practical experience in which it was found that trapped air resisted the influx of water at its entry point and also restricted (through suction) its release at the bottom of the turn.\textsuperscript{55}

All the gearing from 1884 remains 	extit{in situ} today, probably because of its size and weight, within the original gear pit from before 1884 (shown to the left of the leftmost water-wheel in figure 2). This power transmission mechanism comprises three motions, with two 12-foot diameter iron spur (large) gears and three pinions (small gears). The spur gears are visible on both the plan view (figure 6) and the sectional elevation (figure 7). The rotational speed of the water-wheel was directly connected to the first spur gear and was initially written in red ink on the design plans as 9.37 revolutions per minute (r.p.m.), but this was crossed through and amended in pencil to 8.5 r.p.m. Beside this spur gear is another amendment, with a speed of 8 r.p.m. annotated. Because the second and third motions are also amended to 32 and 128 r.p.m., it seems likely that the gearing ratio was a 4:1 for each motion, the spur and pinion gears of the first motion being each 11 inches wide and 4 inches pitch, and the spur and pinion of the second motion 9 inches wide and 3 inches pitch. Accuracy in the fabrication of iron gearing was of utmost importance for frictionless engagement and disengagement of each gear tooth, and a thorough discussion of this subject is provided by Fairbairn.\textsuperscript{56}

Fairbairn provides a formula for calculating the power available from gravity wheels.\textsuperscript{57} This is shown in the following equation, where \( n \) is the volume of water entering the wheel per second, \( h \) is the height of fall (head), and \( \mu \) is the efficiency factor for the wheel:

\[
\text{horse power (hp)} = \frac{nh\mu}{8.8}.
\]

On the basis of the Castleford site data, this gives a potential power availability of 58 hp (43 kW). Efficiencies for this type of water-wheel operating on such a site (categorized as medium in terms of fall and volumetric flow) are between 65% and 75%.\textsuperscript{58} Therefore the ultimate power output of the 1884 wheel can be estimated at between 37 and 43 hp. This is above average for
all late-nineteenth-century vertical water-wheels, but small in comparison with some of the largest industrial types, for example the Laxey wheel estimated at 230 hp, and the Burden wheel at 280 hp (see §5). From 1870 onwards the trend was to build water-wheels of a more moderate size relative to the largest examples that had been built in the mid 1800s, and the 1884 Castleford wheel was typical of this class.60

None of the documents provide the name of the millwright responsible for the design of this water-wheel. Local records show a Horne and Brewerton, Iron Founders and Millwrights, on Aire Street in 1861, but by 1877 this partnership had ceased to exist.61 A plan for a mechanism to permit control of the sluice gate from the first floor of the mill exists, attributed to J. Marsland, and dated 1900 (not shown). The discrepancy of 16 years suggests that it was an improvement on the 1884 design of control. For the gearing, there are also blueprints from 1925 stamped by Pollit and Wigzell, Engineers and Millwrights, Sewerby Bridge (not shown). The dimensions are identical with those from the original designs. A repair can be seen on the 32 r.p.m. second-motion spur wheel, suggesting that Pollit and Wigzell may have been commissioned to undertake this repair.

5. AFTER 1884—A SYSTEM OF HYGIENIC MEDICINE

It is interesting to speculate why the Castleford water-wheel remained in industrial use after others of its type had been decommissioned, and why it was ever built at all considering that in the 1880s many vertical water-wheels were being displaced by steam engines and water turbines. No other documented historical records about the Queen’s Mill water-wheel are known to exist, and the available information on Castleford in general provides no explanation.

The argument for converting to steam power in 1884 would have been strengthened by the abundance of locally mined coal. This, then, would have been balanced against the general considerations that there were fewer modifications necessary for the installation of another wheel at the site and that there was the presence of suitably skilled staff experienced in water-wheel management, in addition to the lower operating costs of free water power. Any new water-wheel would have had to offer a high degree of continuous reliability to resist the conversion to steam. Yet there were additional influences at this specific site. A focus on hygiene in food production methods, with perhaps also a desire to maintain traditional practices, may explain why both water-power and stone grinding were preferred at Castleford Queen’s Mill from 1884 onwards.

This research has shown that the 1884 wheel was both efficient and tolerant of a relatively wide range of water characteristics. It was durable because of the strength of iron axles and segmented hubs based on Smeaton’s experiments. However, although many other eighteenth-century water-wheels had iron axles, wood–iron hybrids had the extra benefit that timber applied to bucket planks and arms would permit easier and quicker repair in the event of wear or damage relative to fully iron types. Just such a distribution of component parts (iron axis and shrouds, and timber buckets, sole and arms) appears in other long-lasting hybrid wheels built in the latter part of the nineteenth century, such as the Lady Isabella ‘Laxey’ wheel on the Isle of Man, which still operates as a tourist attraction, and the Burden Ironworks wheel in New York, which was stopped when the factory closed down in 1896.62 Another feature of the Burden wheel was that, like the one built for Castleford in 1884, it had cast-iron spacers circling the wheel between the shrouds to support its bucket timbers.
Combined with the efficiency of the water wheel, the favourable characteristics of the site would also have been influential. It has been discussed how there were no nearby mills to affect the availability of water adversely, and that there was a steady and smooth flow at this location. Such conditions would have meant that the wheel would be operable more often than not, rarely if ever affected by lack of water at low river levels, nor tail-bound if the river was in flood. Commercially, good access for the transportation of goods to and from the mill was also excellent. It was provided by the Aire and Calder Navigation, which had been improved with the help of John Smeaton’s expertise in the 1770s. This waterway is still used by commercial traffic, and its importance to the continued operation of Castleford Mill has extra significance when considering that major changes began to take place in the industry towards the end of the nineteenth century.

A revolution in flour milling was occurring in Britain between 1875 and 1900, which started in continental Europe and concerned the replacement of stone grinding with roller machinery. This was driven in the main by a fashion for white flour, which roller mills could provide more effectively by milling in a series of stages, in contrast with the single stone grinding and dressing (sifting). Many mills completely replaced all their grinding stones with roller systems; as part of these changes, many country mills closed down as business moved to larger premises at the major ports or in city centres. Why Castleford Mill kept its grinding stones therefore requires further examination.

There are several plans in the Castleford Mills dossier that seemingly relate to engineering works for which no present evidence exists, and among these are indeed designs for large-scale roller milling. In 1888 a new five-storey warehouse was constructed at Queen’s Mill. Plans for this new warehouse show that the whole of the ground floor of the room adjacent to the water-wheel and gearing is marked as ‘Roller Mill’, with other plans showing that in addition to the water-wheel there was a proposal by Henry Simon to build a turbine in the river Aire main sluice gate. Henry Simon, a Silesian immigrant who settled in Manchester, was famous for installing more roller mills in Britain than any other engineer. Yet there is no physical record of roller milling ever having occurred at that location. Either these roller systems were never installed, or Castleford Queen’s Mill was for a short time operating both and producing wholemeal and refined white flour. From 1970, 20 pairs of millstones were being driven by electricity; before this, at least six millstones were producing stoneground wholemeal flour. The answer to what became of the indicated roller mill plan undoubtedly lies in a change of ownership at the turn of the century and a certain Dr Thomas Allinson.

Dr Thomas Allinson (1858–1918) ardently promoted the nutritional value of wholemeal bread and its benefits to human wellbeing in comparison with white flour, maintaining that lifestyle choices and a wholesome vegetarian diet were better for health than taking medication. These opinions conflicted with the popular view of the medical profession at the time, to the extent that his outspoken radicalism led to his being struck off the medical register. Allinson’s Natural Food Company produced wholemeal flour at Castleford throughout the greater part of the twentieth century, and he used the old-fashioned methods of stone grinding to do it. As early as 1892, grey stones for coarse milling were being installed, demonstrating how this mill was completely bucking the trend for roller milling. This reveals that an additional driveshaft was to be connected to the 128 r.p.m. water-wheel gear and routed across the back of the water-wheel for the powering of two sets of stones on the mill island. It is not known when Allinson took over at Queen’s Mill. A transcription of a registered trademark court case in 1898
describes that Harry Goodall and his son Joshua Hamilton Goodall were responsible for the major redevelopments there in 1884/5.\textsuperscript{69} The document interestingly details how the Goodalls were producing, from 1885 onwards, a health food made from wholemeal flour ‘suitable for infants and invalids’. Extracts from letters by Dr Allinson brought before the court describe how he supported the health benefits of a similar product made by a former competing mill. It therefore seems that the continuation of a stone-grinding water-wheel system was central to the Goodalls’ plans for wholemeal health food production, and that they were participating in a market in which Allinson was then also actively involved. The Goodalls won the case, but the circumstances leading up to the takeover by Dr Thomas Allinson remain undiscovered.

If any roller milling machinery was installed, it had been removed by 1921, because blueprints for the mill when under the occupancy of Allinson’s Natural Foods Company show the operation of six sets of stones in the room designated as Roller Mill.\textsuperscript{70} These stones were driven by the 1884 wide breastshot water-wheel. Thereafter, only stone grinding continued at Castleford Mill, and as more sets were installed, the site was claimed to be the largest stone-grinding flour mill in the world.\textsuperscript{71}

6. CONCLUSIONS

From at least A.D. 1122 there have been two water mills on the river Aire in Castleford, slightly downstream from a ford and a strategically important Roman settlement. Both mills survived until at least 1821, and by 1866 only one on the southern bank remained. The classic Victorian wide breastshot water-wheel designed for this mill in 1884 was one of the last installed, and it remained operational until 1970, at least 10 years after others of its type had been taken out of industrial service. Its longevity is probably a testament to its high efficiency, reliability, compatibility with the smooth and constant flow rates of the river Aire, continuous navigable access for trade to and from the site, and a preference for traditional milling operations. The wheel saw revolutionary changes in both power and milling technology, the latter undoubtedly due to the influence of Dr Thomas Allinson. Newly discovered documents provide a unique and detailed understanding of how this wheel was built and designed to operate, highlighting the high-efficiency features of a technology at its peak, according with the design recommendations of William Fairbairn and based on previous work by John Smeaton. They also permit a greater elucidation of some uncertainties related to the Castleford Mill water-wheel plan in John Smeaton’s design catalogue.

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Notes

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18 Margery, *op. cit.* (note 14).
21 *Ibid*.
24 Wilson, *op. cit.* (note 20).
26 Ibid., p. 106.
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36 Fairbairn, op. cit. (note 11), part 1, p. 142.
37 Reynolds, op. cit. (note 1), part 1, p. 124.
40 Fairbairn, op. cit. (note 11), part 1, pp. 154–156.
41 Ibid., pp. 114–142.
42 Fairbairn, op. cit. (note 8), pp. 246–249.
43 Ibid.
44 Fairbairn, op. cit. (note 11), part 1, pp. 114–142.
45 Ibid.
46 Farbairn, op. cit. (note 11), part 1, p. 143.
47 Fairbairn, op. cit. (note 11), part 1, p. 154.
48 Fairbairn, op. cit. (note 11), part 1, p. 109.
49 Fairbairn, op. cit. (note 11), part 1, p. 112–113.
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59 Reynolds, *op. cit.* (note 1), pp. 311–313.
63 Skempton, *op. cit.* (note 3).
70 ‘J. J. Armfield and Co., 12th April 1921, drawing number 8228, For Messrs The Natural Food Company, Queens Mill, Castleford.’ This plan drawing (not shown) is part of the Castleford Mills Canal and River Trust Archives, Leeds, reference 70984545.
71 M. Slush, *2000 Years of flour history at Allinson’s Castleford Mill* (Allinson’s, London, 1981), pp. 1–3. This reference is a pamphlet held by Castleford Library. Numerous other claims were found that Castleford Queen’s Mill was the world’s largest stone grinding flour mill from 1970 onwards, but none of these claims have been substantiated. I contacted *The Guinness book of world records*, but was told that no relevant records could be found in their archives (personal email communication, 22 July 2015).