A survey of Chatsworth Mill

A vernacular building in polite clothing

Chatsworth Mill, also known as Edensor Mill or Calton Lees Mill, is a ruined structure at the southern end of Chatsworth Park, Derbyshire, UK, located at OS GR SK259688. This report describes the physical remains as seen in December 2007, and discusses the design, development , operation and decline of the mill between its construction in 1761-62 and the present day. It is arranged into two parts. Part 1 is this text, containing the description and analysis, and part 2, from page 5 onwards, contains the photographs, which form the main evidence for the report, illustrations and maps referred to in the text, and an appendix in which the output power of the mill is calculated.

Significant documentation on the mill is held in the Chatsworth archives, but unfortunately these were inaccessible at the time of writing, and hence reliance has been placed on secondary references in Barnatt & Williamson (2005). I am also very grateful to Clive Robinson (interviewed on 11 December 2007 by the author), whose ancestors, the Strutts, and relations, the Hodkins, operated the mill for much of its working life, for providing a lot of background information, and many of the copies of documents and photos mentioned in this report. I refer to these as (CR 2007:x).

Milling ended in the early 1950s (Gifford, 1999), and the building was then used as a store for animal feed until 1952 (Naylor, 2005). The Mill as it is today is shown in Photos 1-20 taken by the author in December 2007, except for Photo 8, which was taken in 2005 by Clive Robinson. Illustration 1, (CR 2007:1) shows the mill in 1939, and faithfully represents some poor quality photos of a similar date from the Chatsworth archive (CR 2007:2). This shows the extension added between 1785 and 1879 (CR 2007:3, and see below for discussion of dates). The extension was demolished after the storms of February 1962, in which a large tree fell on the Mill, severely damaging it. Notes from the archives (CR 2007:4) describe how the wreck was to be completely demolished, and how the (now dowager) Duchess of Devonshire ultimately decided to preserve the oldest part of the building as a ruin.

The original Mill building (Photos 1-4) was designed by James Paine and built by James Booth, the site and orientation having been chosen by Lancelot (Capability) Brown, according to Barnatt & Williamson (2005). A copy of an account from Mr Booth, signed off by Paine (CR 2007:5), details £171-16s-4½d for masonry work on the new mill, plus £79-15s-3d for demolishing the old mill it replaced (located much nearer to the house - according to Barnatt & Williamson, 2005). Other bills seen by the author total more than £140 for joinery, millstones, iron work, screens and labour. A labourer earned about 9s per week at that time (CR 2007: 5) or about £22 per annum. Using this to equate to modern prices, with building labourers paid up to £25,000 pa, the building cost is equivalent to about £400,000 today.

The Mill building is constructed of rectangular sandstone ashlar blocks (Barnatt & Williamson, 2005), finely dressed and fitted. Illustration 5 is a ground plan based on my measurements and observation of the remains. On it, four main parts are defined: the central mill house, the east and west wings, and the wheel house, with its broken pediment. The Mill is carefully aligned, almost on a true N-S axis, to present its north side square on to Chatsworth House, approximately 1 mile away. Photo 17 shows the vista from the south end of the Emperor Lake. Illustration 2 (which I based on Photo 1), demonstrates that the whole north elevation, the surviving east wing, and the smaller wheel house, to the apex of its broken pediment, are all dimensioned as 'golden rectangles' (see Curl, 2000, for definition) - where the ratio of longer to shorter sides is 1.618. The mill house building, excluding its triangular gable, is almost a cube of side 24.5 feet, and the two wings are of identical proportions, arranged symmetrically. The wheel house is entirely decorative, and unusual, as vertical mill wheels are not normally enclosed (there are no examples of enclosed vertical wheels in Syson's (1980) book). As discussed below, later additions, now demolished, masked the original symmetry for over 100 years.

The remains of the water wheel are shown in Photos 11 and 12, and Illustration 4 is a reconstruction based on observation and estimated dimensions. I estimate that the wheel was about 12 ft in diameter (plus paddles), and about 5 feet wide. Gifford (1999) suggests 14ft diameter, in total, and 3ft wide, but this would be significantly narrower than the wheel pit. The cast iron axle and wheel hub remain in place, and a number of (wrought iron?) spokes remain attached to the hub, joined to several sections of iron rim. There are no remaining paddles or buckets. The millpond weir (Photo 10) and spillway appear to be intact, and enough of the control gate (Photo 12) remains to deduce that this was an undershot wheel, with the water flow directed to strike the wheel circumference tangentially between 4 and 5 o'clock, to use Syson's (1980) terminology. He discusses the basic design and merits of different types of wheel, and it appears that the Chatsworth mill-wheel would have been similar to that shown in his Plate 9 (Syson, 1980, page 64). With both an angled control gate and a shaped spillway to take the exhaust water away from the wheel, this is of an 'improved' type (Syson, 1980, p 65). Syson also summarises (pp 40 - 44) the experimental work of the civil engineer, John Smeaton (1724 - 1792), who won the Royal Society's Copley medal in 1759 for his paper (1760) on water mill design, and went on to engineer water mills in many parts of the country. While I have no evidence that Smeaton was involved in the engineering of Chatsworth Mill, it would be no surprise that the Duke of Devonshire would expect the latest technology to be incorporated into his new (1761) mill. Alternatively, the engineering may have been improved at a later date, but only a thorough study of the Chatsworth archives might settle this.

Denny (2004) describes how to determine the efficiency and power of traditional water mills. Using this approach, and ignoring the effects of leaks, splashing, friction and other wastage, I calculate (see pages 20-21) that the available output power of the water wheel was between 2 and 5 kW (3 and 8 HP), for water impingement velocities between 3 and 4 m/s, and a wheel speed of between 7 and 10 rpm. This a modest figure, limited as it is by the siting of the mill in an area where the land slopes only very gently, preventing the use of the more efficient and powerful overshot and breastshot designs (Smeaton, 1759; Denny, 2004)

An extract from the Chatsworth estate accounts for 1858 (CR 2007: 6) shows the annual rental paid by Henry Strutt for the Mill in that year was £30. This document also describes the Mill as follows:

> "The water corn mill is stone and slated, and contains three of stones and a shelling mill. The water wheel is good. Drying [?kiln] requires repairs. The roof is bad, floors much worse. Goit sludged. The whole has a dirty forlorn appearance. Some active labour is required to put and keep the premises in order. Stable for three horses [?with] floor over it."

A copy of an invoice from the mill dated June 1897 (CR 2007: 7) shows that William Hodkin charged the Duke £11- 10s for three months supply of animal feed - 30 cwt of bran and 2½ sacks of (??) linseed. By this time, the nearby Caudwell's (Rowsley) mill, powered by highly efficient water turbines and using steel roller mills (and still working today, albeit as a museum piece), would have taken over the fine flour market, leaving only the animal feed market to older mills like Chatsworth (See Gifford (1999) for more details). Mr Hodkin did however invest in some new technology - he had his own 'telegraphic address' - the 1897 equivalent of e-mail. Gifford also mentions the mills upstream at Baslow (closed c 1930) and Calver (converted to flats, 1987), which added to the local competition.

Today, almost no mill machinery remains. Photo 13 shows the iron pit wheel, a large flat belt pulley to the right of it in the pit, and a section of line shafting with pulleys on the left. The latter items would have driven ancillary equipment, such as hoists or bag stitchers. Mills of the time followed a fairly common design consisting of a great upright shaft, driven by the pit wheel via a 'wallflower' bevel gear. The upright shaft carried one or more spur gears, which drove the millstones and other machinery. Syson (1980) shows this well in his Figure 9 (p 78). The millstone in Photo 15 is 5 ft in diameter - but it may not be an original stone, as millstones are common in Derbyshire, where many were made. Syson (1980) estimates that a single pair of stones of 4ft diameter, driven by a mill of this type, could grind 5 bushels (180 litres) of corn per hour, to make either 2cwt (100 kg) of fine flour, 3cwt (150kg) of rough flour, or between 5 and 6 cwt (250 - 300 kg) of coarse grist for cattle food. Allowing for downtime for maintenance etc., one pair of stones could perhaps therefore have ground about 5 or 6 tonnes of animal feed per week. Chatsworth Mill had three pairs of stones, further increasing milling capacity, but the stones may have made different grades of flour, and the water wheel may not have had enough power to drive all three sets at the same time. Graffiti carved into the stone (Photo 16) record the names of some of those who perhaps worked here.

Maps 1 (CR 2007: 8), 2 - 4 (Edina Digimap 2007a) and 5 (Edina Digimap 2007b) show the area around the Mill from 1785 to 2007. (I have added dotted blue lines to map 5 to indicate where the tunnels run.) These show that the mill pond (photo 14) was significantly wider when the Mill was in use, and also the additional buildings attached to the south-western side of the Mill referred to in CR 2007: 3. These are not shown on the 1785 map, but have appeared by 1879. Illustration 1 (CR 2007: 1) shows the additional wing in 1939, particularly its quite different architectural style. There is also an apparent extension of the west wing to third floor level. The last known use of these additions was as an office and stable (CR 2007: 3). They were extensively damaged by the falling tree of 1962 (CR 2007: 2), and subsequently removed. A faint mark on the south face of the mill house (Photo 19) shows where the roof line ran. As this cuts across the mill house masonry, it confirms this as a later addition. There are also indications of possible joist holes. The fine dressed finish of the masonry on the west and south sides of the west wing would have been rough and simple if these were originally constructed as internal walls. Photo 4 shows this - the rough interior masonry is exposed where the roof has gone.

The present weir (Photo 5) was constructed in 1838 (Barnatt & Williamson, 2005) to replace the original of 1761. This curved structure is just over 40m long, and raises the river by about 2m. Water is taken off at a sluice (Photo 6) and fed via an underground conduit about 100m long to the north end of the mill pond (Photo 14). (Some surface evidence of the tunnel can be seen in photo 20.) A small side stream also feeds the pond, which is about 100m long, but only a few metres wide. Photo 9 shows the bypass sluice, used to divert excess water around the water wheel direct to the outfall tunnel. The older maps show the pond was once considerably wider (and probably deeper) - which would have been necessary to store a reasonable reserve of water. After flowing through the wheel house, the exhaust water flows swiftly out through another conduit about 30m long to an outfall (Photo 7), which is big enough to enter (Photo 8, Clive Robinson, 2005), although the author did not do so himself.

Matthew Johnson (1993) defines 'polite' architecture as being

> "... in opposition to traditional principles: polite houses are out of the ordinary, exceptional, national or international in taste and style and large in size." (p 140)

In summary, I would suggest the original design followed the classical Palladian principles (see Curl, 2000, for definition) prevalent in mid 18th century polite architecture, to complement the design of Chatsworth itself. How else could one describe a working flour mill which looked like a classical temple, was dimensioned according to mathematical rules, was carefully positioned to look 'right' from Chatsworth House, and was located precisely within a carefully designed landscape? Although modern for its time, technical advances during the 19th century soon rendered it obsolete and ultimately uneconomic to operate. At least, as a polite ruin, the Mill is still meeting one of the functions intended for it by those who commissioned, designed and built it.

Photographs, illustrations and maps

Most of the photos and illustrations which follow were taken, or are based on conditions as found, in late 2007. Where this is not the case, the date is given in the caption.

Photo 1: The north side (all openings have security grilles)

Photo 2: The south side, with the main entrance in the middle

Photo 3: The east side (the sign just says 'Welcome to Chatsworth Park' etc.)

Photo 4: The west side - note rough masonry of internal wall at apex


Photo 5: The intake sluice (by tree on left of picture) and new weir


Photo 6: The intake sluice


Photo 7: The outfall


Photo 8: The interior of the outfall tunnel (courtesy Clive Robinson, 2005)

Photo 9: The wheel house, end of the millpond, bypass sluice and pond weir

Photo 10: The millpond weir

Photo 11: Water exit tunnel and remains of mill wheel

Photo 12: Remains of the mill wheel and control gate

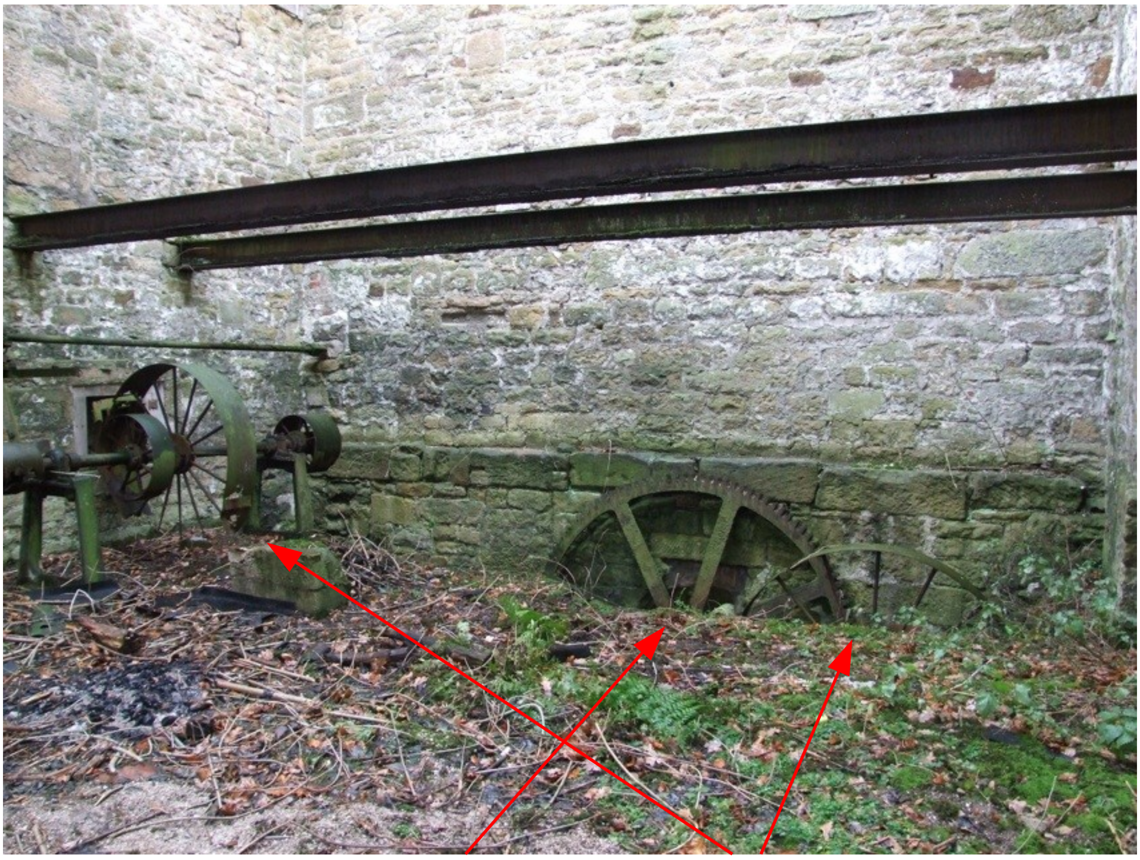


Photo 13: Toothed pit wheel and flat belt pulleys

Photo 14: The mill pond (leat tunnel exit in the middle foreground)

Photo 15: Millstone

Photo 16: Graffito 'S Gregory 1797'

Photo 17: The Mill, from the end of the Emperor Lake (aka The Canal)

Photo 18: Site of former extension (compare with Illustration 1)

Photo 19: Traces of former extension to SW corner of mill house

Photo 20: Surface evidence of (repairs to ?) leat tunnel

Illustration 1: Sketch of the Mill in 1939 by Mabel Hodkin (courtesy Clive Robinson)

Illustration 2: Golden rectangles on the north elevation (JPGM 12/07)

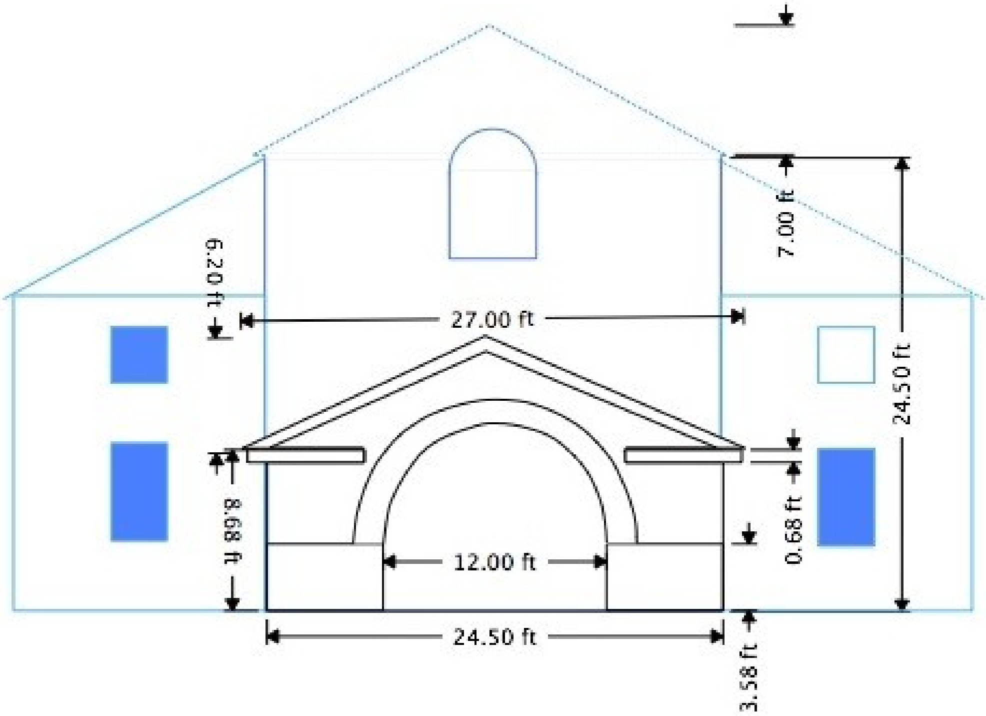


Illustration 3: Sketch of north elevation, dotted = reconstruction, wheel house in black (JPGM 12/07)

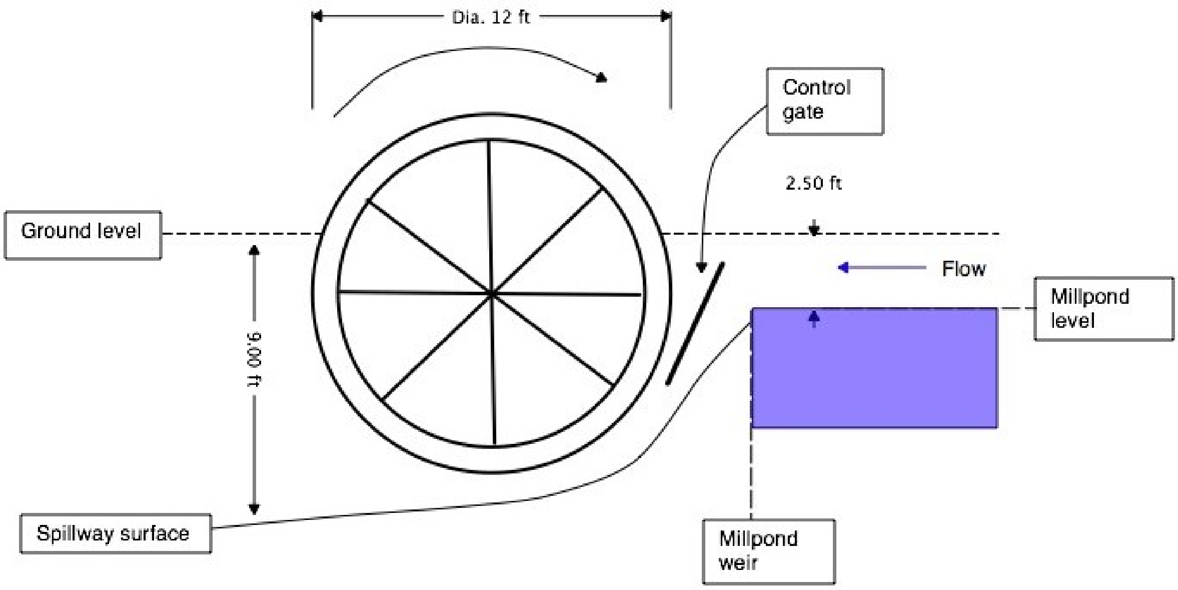


Illustration 4: Cross section of wheel and spillway - all dimensions approximate (JPGM 12/07)

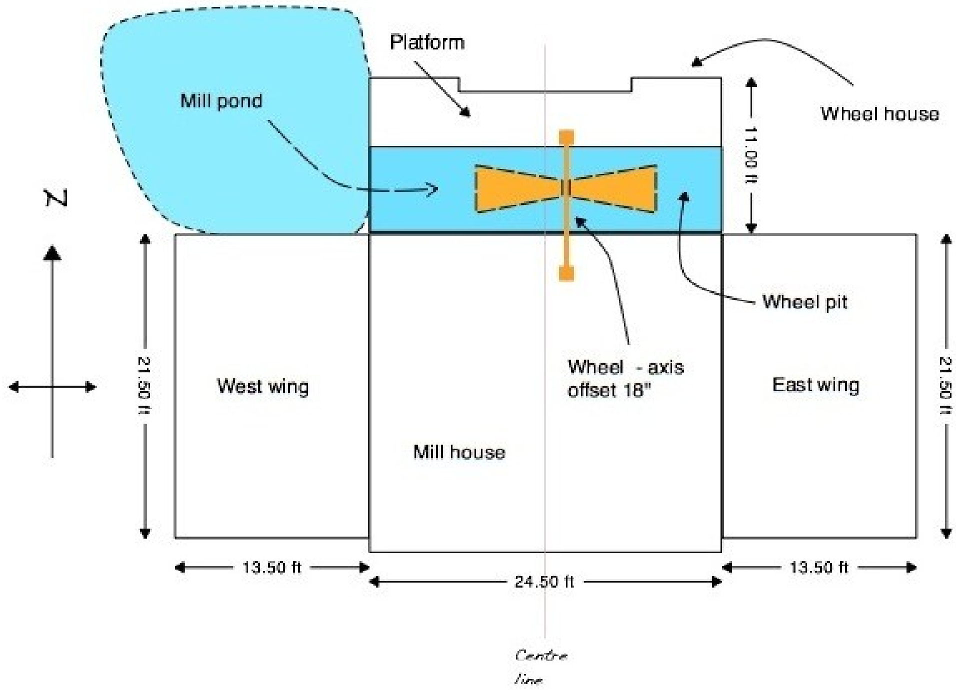
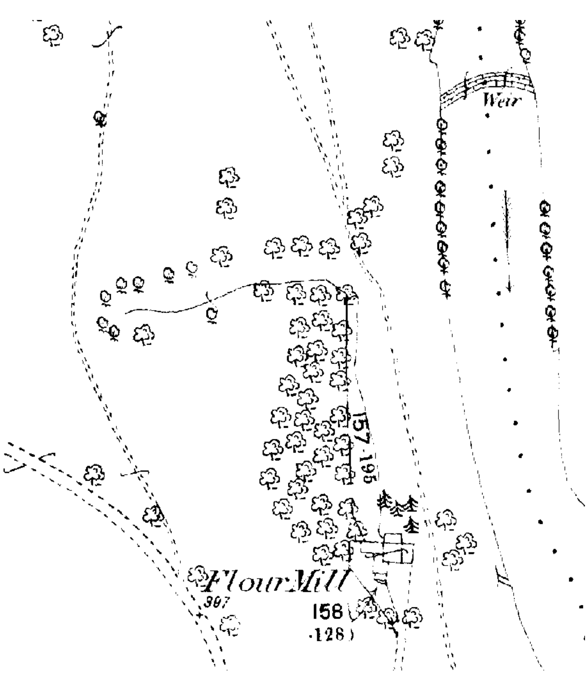
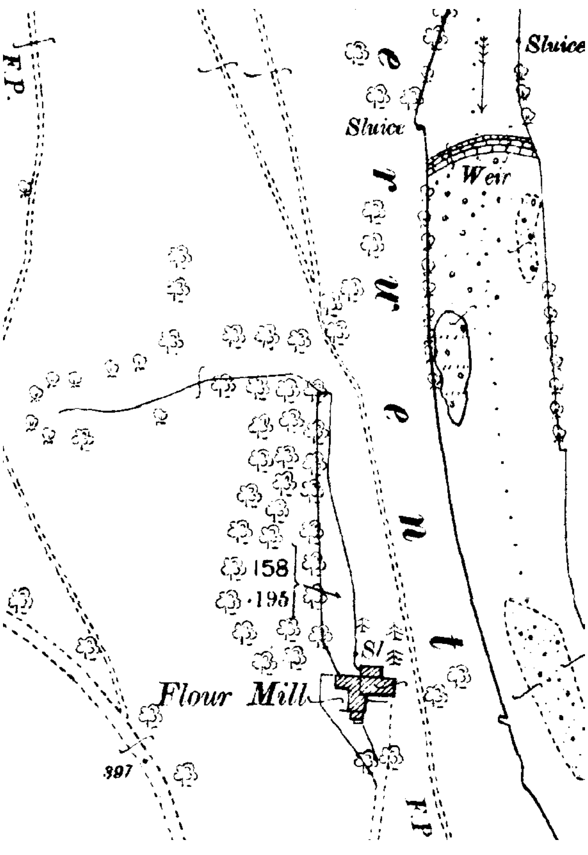


Illustration 5: Chatsworth Mill - General Plan (JPGM 12/07)

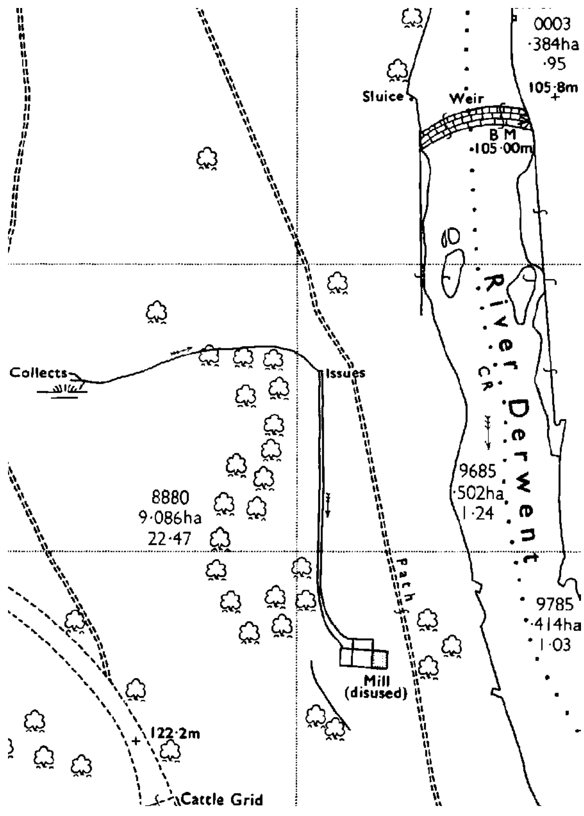
Map 1: 1785 (Chatsworth archives: CR 2007: 8)



Map 2: 1879 (Historic Digimap: Edina 2007a)

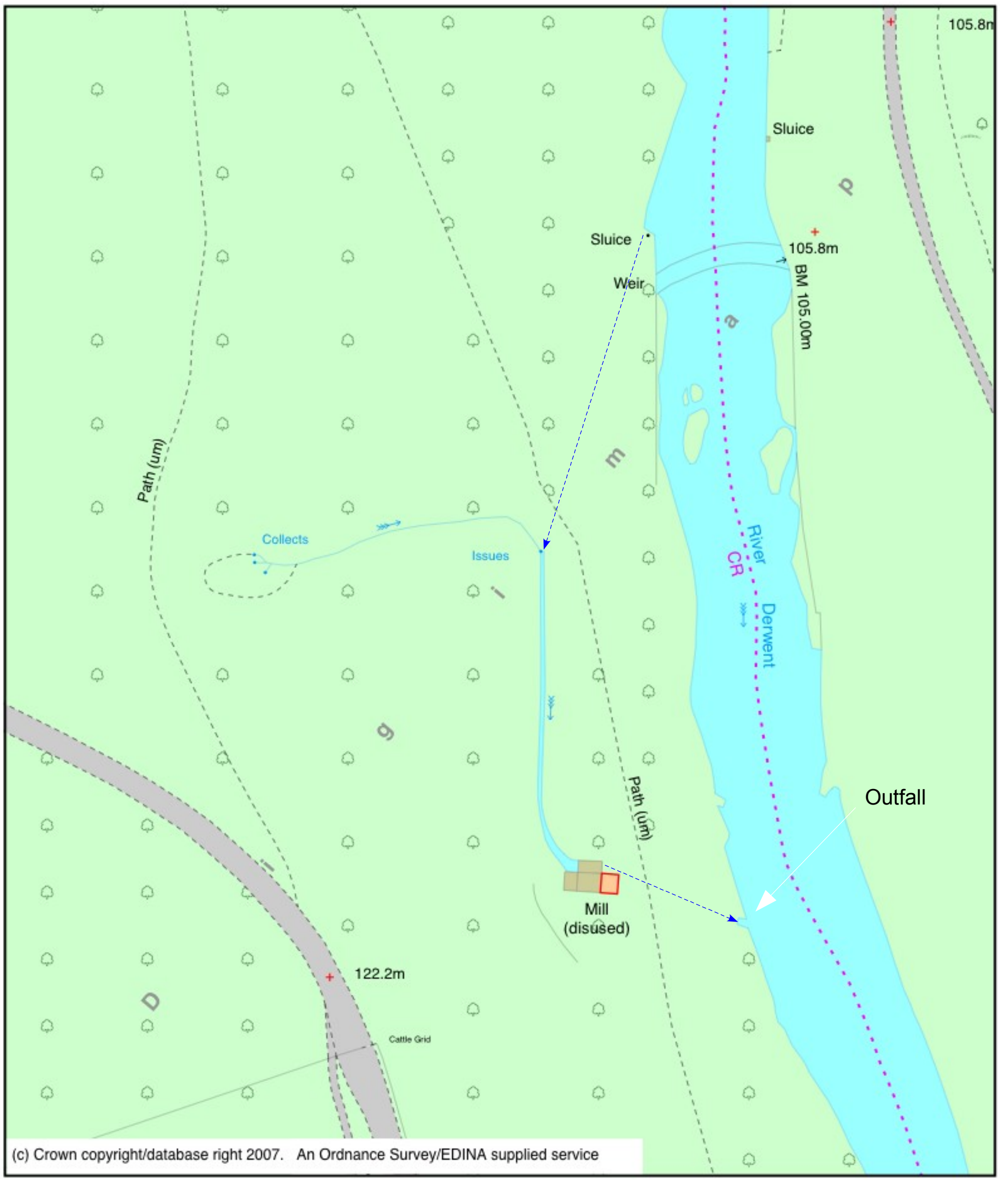


Map 3: 1898 (Historic Digimap: Edina 2007a)



Map 4: 1970 (Historic Digimap: Edina 2007a)

Chatsworth Mill 2007



0 20 40 60 80 100 120 m

This map is drawn on the GB National Grid

Tunnel

Heights (if given) are in metres above Newlyn datum. The representation of a road, track or path is no evidence of a right of way. The alignment of tunnels is approximate.

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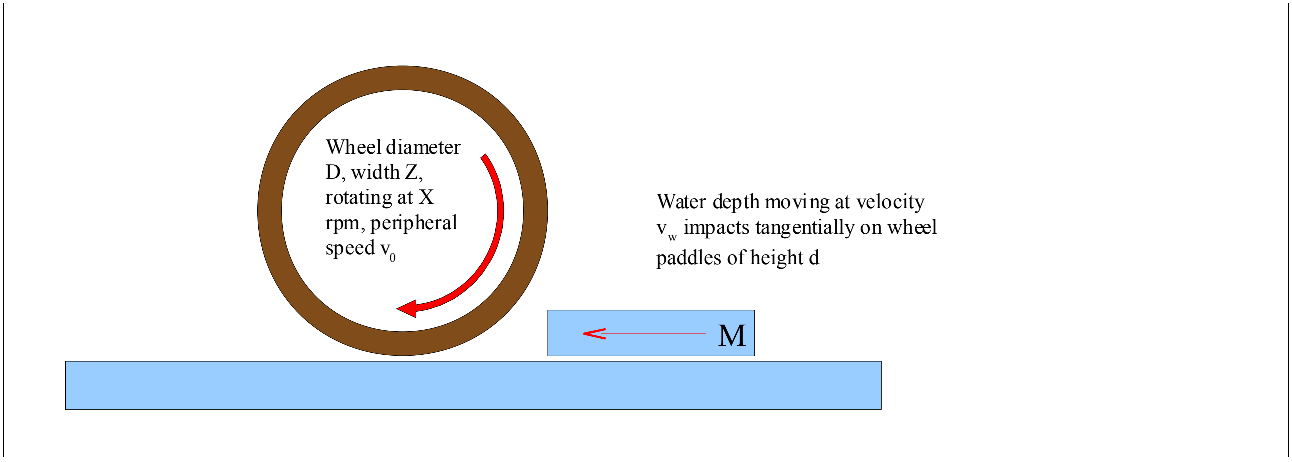
Map 5

Calculating the maximum available power for an undershot water wheel



This is based on the papers of Smeaton (1759) and Denny (2004)

The mass M of water striking the wheel paddle each second is given by:

$$M = ZdV_w\rho = A_wV_w\rho$$

where A_w = Zd, the cross-sectional area of the water flow and ρ = density of water (1000 kg/m^3)

If a mass of water δm strikes the wheel paddle during time δt, and slows to V_w', it imparts an impulse to the paddle wheel. This is equivalent to an impulsive force F acting over a time δt.

Conservation of momentum requires that

$$F\delta t = \delta m(V_w - V_w')$$

or

$$F = \delta m/\delta t\,(V_w - V_w')$$

In this model, $V_w > V_w'$, and maximum transfer of momentum occurs if $V_w' = V_0$, the peripheral speed of the water wheel. This should also equate to the maximum impulse or impulsive force F, and then

$$F = \delta m/\delta t\,(V_w - V_0)$$

With the wheel working, a load is applied to the wheel, and equilibrium is achieved with the wheel rotating at a constant speed (X rpm), delivering power P according to the equation

Power = Force x Distance moved in the water / time to move that distance, or

$$P = FV_0$$

$$= \delta m/\delta t\,(V_w - V_0)V_0$$

But $\delta m/\delta t = M = A_w V_w \rho$, the water flow rate hitting the wheel, hence

$$P = A_w V_w \rho \ (V_w - V_0)V_0 \ \text{(watts)} = A_w V_w (V_w - V_0)V_0 \ \text{kW}$$

Since $\rho = 1000$ kg/m3

Define speed ratio $R = V_0/V_w$, where $0 \leqq R \leqq 1$, and then $V_0 = RV_w$ then

$$P = A_w V_w (V_w - RV_w)RV_w \ \text{kW}$$

$$= A_w V_w^3 (1-R)R \ \text{kW}$$

A_w and V_w are fixed, but R can vary from 0 (wheel stalled) to 1 (free-wheeling at same speed as the water flow). So taking the derivative dP/dR = 0 will give the value of R for maximum power delivery. This occurs when

$$dP/dR = A_w V_w^3 (1-2R) = 0, \text{ or } R = ½$$

and the maximum power is then

$$P_{max} = A_w V_w^3/4$$

For the Chatsworth Mill wheel, which is approximately 1.6m wide, if we assume the paddles were 0.2m (8") deep, the cross-sectional area of one paddle (A_w) is 0.32 m^2 or $^1/_3$ m^2. In real life, several paddles are in contact with the water at any one time, to a varying depth. We can simplify this by assuming a single paddle, fully in contact with the water flow during the impulse, and then not at all. The simplifications of many paddles becoming one, and contact to a varying extent becoming in or out, will cancel each other out, at least partly. Then we have, for Chatsworth Mill

$$P_{max} = V_w^3/12$$

And we can then derive the following power table

V_w (m/s)	1	2	3	4	5
P_{max} (kW)	.08	.75	2	5	10
V_0 (m/s)	.5	1	1.5	2	2.5
RPM	2.5	5	7.5	10	12.5

(Since the diameter of the wheel D = 4m, the circumference = πD = 12.5m, and hence the rotational speed in RPM = $60V_0/\pi D \cong 5V_0$)

At higher speeds, frictional losses mount as the square of the speed, causing less power to be available than this simple calculation suggests.

The yellow area is the region where Smeaton's experiments showed undershot water wheels worked most efficiently.

References

Barnatt, J. and Williamson, T., 2005. *Chatsworth: A Landscape History.* Macclesfield: Windgatherer Press

CR 2007. Items provided by Clive Robinson privately in December 2007: Descriptions as follows:

CR 2007: 1 *Sketch of Mill in 1939* by Mabel Hodkin, from a print owned by Clive

CR 2007: 2 *Photos of mill of unknown date*, showing buildings in CR 2007:1, and of the mill just after it was damaged in 1962, from the Chatsworth Archive (CA)

CR 2007: 3 Memo from Charles Noble to Helen Marchant, dated 15 December 2003, referring to a south-west corner addition/extension to the mill, removed after 1962, containing an office at first floor and possibly a garage below, from the CA

CR 2007: 4 *Gale damage to Paine's Mill,* Chatsworth park, February 1962, Notes from Heads of Departments Meetings, Minutes 1-100, 1955-1964, from the CA

CR 2007: 5 *Masons Work done for His Grace the Duke of Devonshire at the New Mill at Chatsworth,* an invoice from James Booth (master mason) signed off by James Paine (architect), from the CA

CR 2007: 6 *Extract from Record C127, valuation, 1858*, giving the annual rental and a description of the mill, from the CA.

CR 2007: 7 *Invoice from William Hodkin, Edensor Corn Mill, to His Grace the Duke of Devonshire, for £11-10s-0d,* dated June 19th, 1897, from the CA

CR 2007: 8 *Map 2581, c 1785*, from the CA

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