The Garfield water wheel: hydraulic power on the Victorian goldfields

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Water wheels were widely used on the Victorian goldfields during the nineteenth century to drive mining machinery in areas where sufficient water was available. One of the largest wheels constructed was the Garfield water wheel, with a diameter of 70 feet (21.3 m), which operated from 1887 to 1904 near Chewton in central Victoria. It drew water from the Coliban System of Waterworks, a government-funded supply scheme that delivered water to mining communities in a region that was otherwise too dry for hydraulic power. In this paper we use the archaeological and historical evidence of the Garfield wheel to argue that water wheels offered a reliable and efficient alternative to steam power for many mining parties on the goldfields, and their use reveals the complex choices made by miners in terms of cost, industrial needs and environmental resources.

INTRODUCTION

Water wheels were widely used on the Victorian goldfields in the nineteenth century where sufficient water was available. One of the largest and best preserved examples is the Garfield water wheel, which operated between 1887 and 1904 near Chewton in central Victoria. Water came from the Coliban System of Waterworks, a government-built supply scheme that distributed water to the region from the 1870s, and permitted a number of mining companies to utilise water power in a region characterised by highly variable rainfall and limited stream flows. The massive stone abutments and other remains associated with the Garfield Company reveal how a traditional technology was imported and successfully adapted to local environmental and industrial conditions, and incorporated into a wider landscape of water management. In this paper we use the Garfield water wheel as a case study to challenge the view that water power in Australia was unreliable, used only for a limited period, and associated with poor management (Connah 1994; Jack 1983:40; Pearson 1996:49). Hundreds of water wheels were used on the Victorian goldfields from the 1850s to the 1880s and beyond (e.g. Smyth 1979:517). A number of mining parties in the Chewton area turned to water power from the Coliban scheme when it became available, making a careful and deliberate choice to employ water wheels in preference to steam engines. Their decisions were based on cost, environmental opportunity and industrial need, and recognised that hydraulic power offered advantages over the powerful steam engines and turbines that were also available to drive machinery at the time.

Water wheels were utilised on the Victorian goldfields almost from the beginning of the gold rush (Smyth 1979:517). In 1853, for example, American miners used belt-pumps driven by a water wheel to keep the bed of the Buckland River dry for working (Howitt 1972:141, 146). By the late 1850s, several small wheels were used by mining parties in the Blackwood area in the Central Highlands and at the Woolshed diggings in the north-east (Lloyd 2006:39; Milner and Churchward 1989:284). Beechworth miners utilised a 'wheel-head' or 'motive water right' to secure water for their wheels, with more than 100 in operation in the Buckland Division by 1862 (Royal Mining Commission 1862-3:359; Smyth 1863, 1979:407). During the 1860s on the Jordan goldfield in the upper Goulburn region, high rainfall and difficult conditions resulted in the construction of more than 130 water wheels on creeks and rivers to drive crushing machinery (Griffiths 1992:27; Milner and Churchward 1989:284-287; Smyth 1864), while more than 200 wheels were employed on Victorian mines throughout the 1870s (e.g. Minister of Mines 1880:21). Around Castlemaine and Chewton, where rainfall was much lower, water was supplied by a channel from the Coliban system, a large-scale government enterprise constructed in the 1860s and 1870s to provide water in central Victoria for domestic, mining and other purposes (Russell 2009). A number of mining companies around Chewton, including the Garfield Company, took advantage of the scheme to erect water wheels to power stamp batteries in the following years (Figure 1). Water wheels were

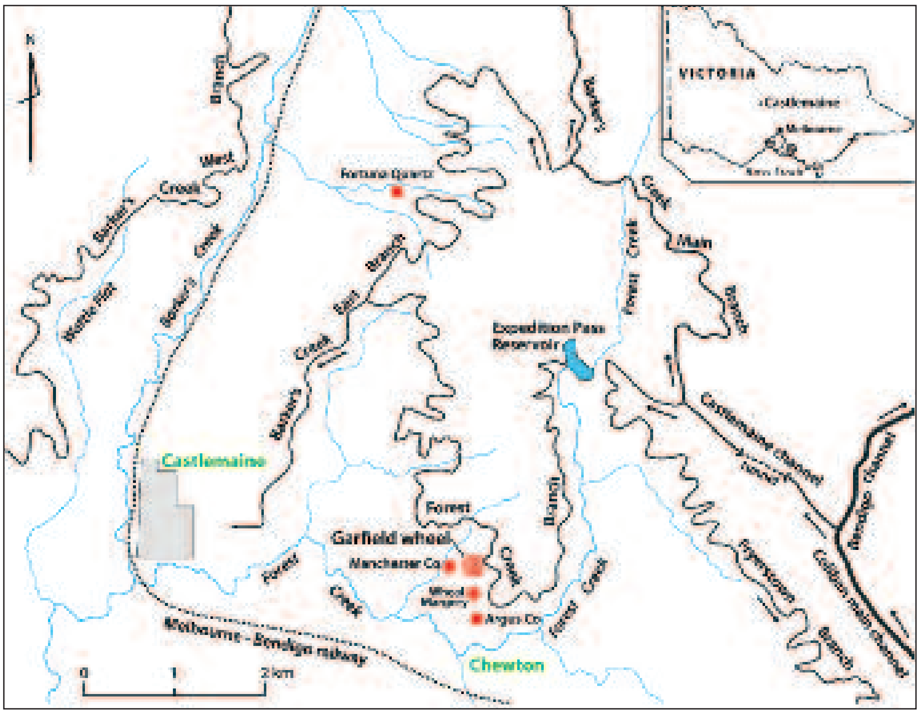

Figure 1: Location map of water wheels around Chewton and associated supply races from the Coliban System of Waterworks (P. Davies).

also erected around Victoria to drive flour mills and sawmills from the 1840s to the 1890s (e.g. Jones and Jones 1990; McCarthy 1987:1, 67), while a number of mining companies used water turbines to power machinery from the 1860s (Milner and Churchward 1989:282-283).

Previous research on water-powered flour mills in colonial Australia has identified a range of factors in the development of water wheel technology (e.g. Connah 1994; Jack 1983; Pearson 1996, 1997, 1998; Preston 2010). The most important was economic conditions, while environmental constraints, the availability of local skills to adapt and apply the technology, and access to industrial materials and production processes, also played important roles. Pearson analysed the archaeological remains of mills in Tasmania and northern New South Wales (and Anderson's Mill in Victoria), dating from the 1820s to the 1870s, and suggested they provided a sample of sites 'across the entire range of physical environments in which the technology was used in colonial Australia' (Pearson 1996:49).

Our work on the Garfield water wheel extends Pearson's analysis in temporal and geographical terms. The Garfield wheel operated during the late nineteenth and early twentieth century, drawing water from a government supply scheme in an environment that was significantly drier than Tasmania and New England. In this paper we acknowledge Casella's (2006:68) recognition of industrial places as historical landscapes, and relate the archaeology of industrial processes to a landscape of gold mining and water management. Analysis of the Garfield wheel reveals a range of environmental, economic and industrial factors involved in the establishment and use of water wheels, and the comparative advantage they could enjoy over conventional steam power and other sources of energy.

GOLD AND WATER ON THE CASTLEMAINE GOLDFIELD

The Mount Alexander (Castlemaine) and Forest Creek (Chewton) goldfield in central Victoria was one of the richest shallow alluvial mining areas in colonial Australia. Gold was first discovered in the district in July 1851, and by the end of the year the population had grown to approximately 20,000 miners (Bradfield 1972:14-15; Flett 1970:190; Serle 1963:23). The region was bisected by dozens of small creeks and gullies, most of which were subject to intensive alluvial mining during the 1850s, and quartz mining in the following years. Forest Creek itself arose on the slopes of Mount Alexander and flowed south towards Chewton, then joined Barkers Creek at Castlemaine, which joined the Loddon River at Guildford.

Alluvial gold was discovered in the area of Sailor's Flat north of Chewton in January 1852. The underlying reefs were extensively worked at shallow levels by small parties from 1855 to 1860, with steam-powered quartz-crushing machinery first used in the late 1850s (Bannear 1993a:6; Baragwanath 1903:28; Milner 1989:1). During the 1860s and 1870s, numerous small companies continued to prospect in Englishman's Gully, German Gully and Little Sailor's Gully, often using steam power for winding, quartz crushing and drainage (Baragwanath 1903:25-28). The earliest recorded water wheel in the district was constructed in 1859 on the Loddon River at Fryerstown. The six feet (1.8 m) diameter, 1 horsepower wheel was used for pumping water and driving a small puddling machine (Milner 1989:2).

The Coliban System of Waterworks was constructed by the Victorian government in the 1860s and 1870s to supply Bendigo, Castlemaine and surrounding townships with water for domestic, mining and manufacturing purposes. Supervised by the Victorian Water Supply Department (V.W.S.), the Coliban System was, at the time, one of colonial Australia's most ambitious water projects. The scheme included a large dam on the Coliban River at Malmsbury, a 102 km gravity-fed open channel, and numerous smaller dams, races, flumes and tunnels. Despite continual political controversy over the design, construction and costs of the system, water began flowing to Castlemaine in 1874, and finally to Bendigo in 1877 (Russell 2005, 2007, 2009; Sankey 1871).

The scheme included construction of a number of supply races around Castlemaine and Chewton, which provided large volumes of water for sluicing alluvial claims, and permitted several mining companies in the area to erect water wheels (Figure 1). In some cases these wheels replaced steam engines, but in others the new water supply stimulated investment in new, water-powered mining ventures. In December 1879, for example, the Manchester Reef Waterwheel Company began to erect a 40 feet (12.2 m) overshot wheel for a 10-head battery along the Manchester reef on the edge of Sailor's Gully (Baragwanath 1903:26). In the same year, the Renaissance Company built a water wheel 20 feet (6.1 m) in diameter and drew water from the Poverty Gully Branch of the Coliban supply system (Bannear 1993b:177-187; Milner 1989:65). In 1882 the Wheal Margery Company erected a water wheel and crushing battery on a 10 acre (4 ha) lease near the Garfield works, and also drew water from the Coliban System (*Bendigo Advertiser* 15 September 1882:3). The Fortuna Quartz Mining Association erected a water wheel and battery in Specimen Gully, 4 km north of Castlemaine, in 1884 (Milner 1989:31). At Mopoke Gully to the south of Castlemaine, the Bendigo and Fryers Company erected a 60 feet (18.3 m) diameter water wheel in 1887 to drive a 10-head battery. Water was secured from the German Gully Branch of the V.W.S. race via a supply race 19 chains (380 m) long. The supply was estimated at 2½ million gallons (11 ML) per day, enough to crush about 120 tons per week (Mining Registrar 1887a:26). An even larger water wheel was also built by the Argus Company at Chewton in 1887 to drive a 20-head battery. The wheel was, like the Garfield, 70 feet (21.3 m) in diameter, with a large proportion of iron components. The wheel itself cost £500 and the supporting masonry cost £140 (Milner 1989:6). Reliable water drawn from a large-scale government system thus provided the opportunity for mining companies to erect water wheels for winding gear and batteries in a more cost-effective way than installing steam engines, in an environment that was otherwise too dry to provide sufficient stream flows. Among all these companies, however, the archaeological remains of the Garfield operation are the most substantial and best preserved.

THE GARFIELD COMPANY

The Garfield Company was formed in 1882 by a group of Bendigo shareholders, and initially held about 20 acres (8.1 ha) on lease. It was also known as the General Garfield and the Madame Garfield Company. John Ebbott managed the enterprise from its founding in 1882 until it closed in 1912. Ebbott came to Australia with his parents from Cornwall in 1849, and worked in mines at Bendigo until he took up the position with the Garfield Mine. He lived in a five-room weatherboard cottage on site with his wife and children. More than 20 men were initially employed by the Garfield Company in building a dam on German Gully, sinking an engine shaft and erecting machinery. This included a new boiler, an 18-head stamp battery, and a Tangye pump for drainage. The dam was used to store water pumped from the main shaft and to stack tailings (*Bendigo Advertiser* 23 October 1886:2). The company had a main shaft on the south side of German Gully, with a poppet head and steam-driven winch for winding. Nearby were buildings for a blacksmith's shop, manager's office and change rooms for the miners (Figure 2). The

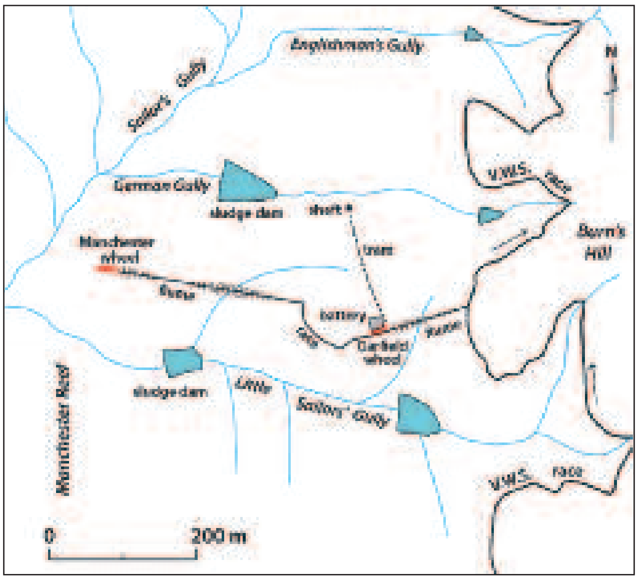

Figure 2: Location of Garfield water wheel and associated water and mining infrastructure (P. Davies).

12-horsepower horizontal engine was fed by a boiler 28 feet long. The six months of work to March 1883 yielded 1280 ounces of gold from 2536 tons of ore, and by this time the company employed 55 men in its operations (*Bendigo Advertiser* (supp.) 31 March 1883:1).

In the following year the Garfield Company began sinking a new engine shaft, and had an old boiler repaired to provide steam for five extra stamps. By the end of 1885 the group employed about 70 men and boys, with the shallower portions of the mine being worked on tribute. After three years of mining the lease had yielded 7385 ounces of gold, and the company occupied a prominent position on the field (Baragwanath 1903:28; Mining Registrar 1885:18).

By 1886 the Garfield Company was planning to expand operations even further. The company held 50 acres (20 ha) of mining lease by this stage, and had secured control of the Manchester Reef and water wheel, and the Wheal Margery Company's works, now known as the South Garfield Company (Bannear 1993b:46). The 23-head stamp battery of the Garfield Company had to be moved, however, as mine work 120 feet (36 m) below ground undermined the plant's foundations (Mining Registrar 1886:25). The managers decided to take advantage of the move by changing the power supply from steam to water, and shifting the battery site 500 feet (150 m) to the south. The new location would tap a secure source of water from the Forest Creek Branch of the Coliban supply system, which was conveyed from the Expedition Pass Reservoir, to drive a large water wheel. It was expected the operating costs for water power would be much less than for steam. The tail water would also be conducted from the wheel via another race and flume to drive the smaller 40-feet diameter wheel at the Manchester mine further to the west (Figure 2).

Figure 3: Stone abutments of the Garfield water wheel (P. Davies).

Extensive excavations were needed to build the foundations and 35-feet-high (10.7 m) heavy stone walls for the Garfield water wheel, with a large battery house built adjacent to it (Figure 3). A large elevated timber launder or flume was also needed to convey water from the V.W.S. supply race to the wheel, and a tramway to bring ore 150 m from the mineshaft and poppet head to the stamp battery (Figure 4) (*Mount Alexander Mail* 30 March 1887:2). Given the large scale of the wheel it is perhaps not surprising that there were early problems, especially relating to the teeth of the main gear wheel. Several breakages were reported in April and May 1887 which delayed operations, but the wheel appears to have worked satisfactorily thereafter (*Bendigo Advertiser* 15 April 1887:3, 14 May 1887:1).

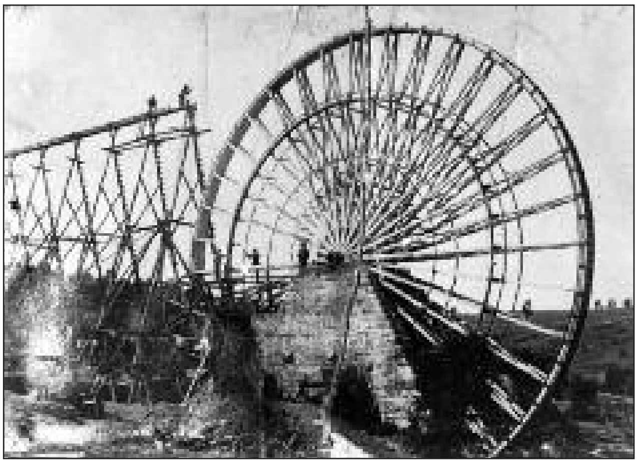

Figure 4: The Garfield water wheel under construction (State Library of Victoria image H2009.38/25).

In September 1887 the adjacent claims of the Garfield and the Manchester mines were amalgamated and floated as a new company on the English market, in 100,000 shares of 20 shillings each (*Bendigo Advertiser* 20 September 1887:4). The existing shareholders received £12,500 in cash and the same amount in shares (Mining Registrar 1887c:28). Historical references to the company begin to fade soon after, however, obscuring the difficulties the company appears to have faced. In 1888 manager John Ebbott took on the extra work of running the Francis Ormond Company, located nearby on Forest Creek (*Bendigo Advertiser* 21 April 1888:5), in addition to his directorship of the Bendigo and Fryers Company (*Mount Alexander Mail* 30 March 1887:2). Upper levels of the Garfield mine were worked by local men on tribute, with the company sharing the costs of hauling and crushing (*Bendigo Advertiser* 1 February 1890:3). While up to £30 a man per month was obtained at times, tributing was often a sign that gold was becoming scarce in a mine (Baragwanath 1903:28; Lloyd and Combes 2010:283). The decision by the original investors to float the company in 1887 may have been a recognition that the accessible gold was running out and the time had arrived to sell. Historian Geoffrey Blainey has noted that from 1886 to 1907, British investors paid Australians up to £50 million cash for shares in mines and holes in the ground, 'a disastrous loss', investing far too much for rich mines and poor ones alike (Blainey 1963:250). The purchase of shares in the Garfield Company by London investors may well have been part of this pattern.

By 1898 the company was known as the Forest Creek (Victoria) Gold Reefs Company and the crushed ore from a depth of up to 760 feet (232 m) yielded moderate profits over the next four years. In 1903 the company became Chewton Gold Mines Ltd. and discarded the Garfield water wheel as a power source. According to a report in the *Mount Alexander Mail* in 1904,

> ... the wheel became old, and the strong winds interfered with its efficiency, sometimes breaking cogs, when they did not mesh correctly. The wooden spokes of the wheel became worn, and then loose at the joints (cited in Bannear 1993b:49).

The Garfield water wheel was replaced with a high pressure steam boiler to drive an extra 10 stamp heads, making 25 head in total. Chewton Gold Mines continued operating until 1912, when the mine was closed and the machinery was sold off. The New Garfield Company was established in 1937 to re-open the old mines, but operations were suspended in July 1938 as the company was unable to secure water from the Government race to supply the battery. Work at the mine resumed in 1939, but was suspended in 1943 with the wartime call-up of manpower.

THE GARFIELD WATER WHEEL

The Garfield water wheel was 70 feet (21.3 m) in diameter. It was constructed as a wood-iron hybrid, with 36 timber spokes or arms and 220 wrought iron buckets, all supported on two large stone abutments (Figure 4). This substantial masonry obviated the need to excavate a deep wheel pit and pump out the tail water. The high breast wheel received water from the flume just before the wheel summit, in a pitch-back rather than an overshot design. Water from the flume was delivered to the buckets with minimal fall, meaning the weight and momentum of the water drove the wheel. Water drained from the buckets in the same direction as the tail race, which reduced turbulence at the bottom of the turn and added to the wheel's efficiency. Other iron elements in the construction included the axle, shaft bearings and a gear wheel 38 feet (11.6 m) in diameter. A curved rebate in the stone walling indicates that the gear wheel was fastened about two-thirds of the way towards the rim of the wheel. The gear engaged with a small pinion wheel mounted on the northern abutment, which drove a counter shaft attached to a wheel inside the battery house, with power transferred to the stamp heads via belts or pulleys (*Mount Alexander Mail* 30 March 1887:2; Ritchie and Hooker 1998:10). The use of rim gearing relieved the axle of torque stress from transmitting power, and meant the transmission shaft ran at much higher speed without the need for step-up gearing (Reynolds 1983:290).

The iron buckets were spaced one foot (0.3 m) apart and each bucket had a capacity of five gallons (22.7 litres). Wrought iron buckets were easier to shape than wood and were more durable. They also took up less volume than wood, which increased capacity and reduced splashing (Reynolds 1983:304). A system of levers regulated the flow of water from the flume, with a vertical chute built to divert water from the buckets down to the tail race and allow the wheel to be stopped when necessary. This flume may also have directed water into the battery shed for washing the crushed ore through the stamps.

Approximately one-quarter of the buckets contained water during rotation (McKimmie 2010:105). Assuming only 50 buckets were full as the wheel rotated this would mean 1135 litres (or 1135 kg) were enough to rotate the wheel once every 45–55 seconds. Using almost 6000 litres of water per minute, and a nominal head of 70 feet (21.3 m), the wheel generated approximately 27 horsepower (20 kW). This drove the 15-head battery at the rate of 78-86 falls per minute, with the rim of the wheel rotating at a speed of around 4½ feet (1.37 m) per second. It was estimated at the time that the wheel generated enough power to drive a 50-head stamp battery (Bradfield 1972:65). A layer of brickwork at the upper end of the wheel chamber was mortared onto the underlying bedrock, creating a smooth face and helping to retain water in the buckets as long as possible (see Connah 1994:25).

Water was carried to the wheel from the V.W.S. race along a flume 786 feet (239 m) long, on a sapling frame that ranged from 20 to 58 feet (6 m to 17.7 m) in height. The off-take at the head of the flume was a semi-circular construction in cement-rendered brick with an opening 60 cm wide and 40 cm deep (Figure 5). Tail water from the Garfield water wheel was conducted by a short race 90 m long to another flume about 260 m in length. This delivered the water to the Manchester 40-feet (12.2 m) wheel at Sailor's Flat 400 metres to the west (Figure 2). The latter wheel was altered from overshot to pitchback operation, and drove a heavier battery of 10 stamp heads (Mining Registrar 1887b). The site of the Manchester wheel today is marked by only a brick scatter and a tail race extending to the south-west. The lack of more substantial remains suggests that the wheel may originally have been mounted on lighter timber supports, rather than the heavy masonry of the larger Garfield wheel.


Figure 5: Rendered brick off-take from the V.W.S. supply race (P. Davies).

The V.W.S. race supplying the Garfield water wheel was a substantial construction and remains well preserved. It was excavated into gravel and rock, typically up to 1.5 m wide and 1.0 m deep. A surveyed traverse of almost 330 metres of the race revealed a fairly slight fall across the contour of 0.83 m per kilometre, or a little over four feet per mile. Despite the importance of this race network in supplying water wheels and gold mining in the area, few details are known of its construction, operation and maintenance.

The stone walls of the Garfield water wheel are well preserved and represent a substantial element in the network of water management features created and managed by the Garfield Company. The abutments are 8.20 m high with 1.70 m wide foundations, with the base of the wheel chamber obscured by up to 1.60 m of mud and silt. Tail water may originally have flowed through a culvert under the modern road surface (Giovanelli 2001:4). Each course of stone is 0.30 m high, with two lengths of hoop iron inserted to bind each course, using about seven hundredweight (355 kg) of iron in total. The masonry at the outer edge of each wall has been more carefully squared and shaped than the stonework used for the inner spaces (Figure 3). The distance between the top of each abutment indicates the wheel shaft or axle was originally up to 2.11 m (7 feet) long, with the wheel tapering to about 4 feet (1.22 m) wide or less at the rim. Steel rods and mortar impressions on the top of the walls indicate the heavy wooden bearing plates were at least 2.20 m long and 0.50 m wide.

It is not clear which foundry manufactured the iron components used in the Garfield wheel. The extensive ironworks of Thompson's Foundry, however, were located only a few miles away in Castlemaine, and the company regularly manufactured boilers, engines, pumps, batteries and other equipment for mining parties in the district. The production of parts for iron water wheels by Thompson's Foundry is also clear from its provision in 1889 of 84 cast-iron buckets for a water wheel at Harrietville in the far north-east of Victoria (Lloyd 2006:129).

The Garfield water wheel appears to have operated successfully until it was dismantled in 1904, after 17 years in operation. As a wood-iron hybrid, its lifespan was somewhat longer than a traditional wooden wheel, which generally had a life expectancy of about 10 years or less, while all-iron water wheels could last much longer, up to 100 years or more (Reynolds 1983:319). At Anderson's Mill near Ballarat, for example, an all-iron water wheel operated continually from 1861 to the 1940s (Department of Conservation and Environment 1990:24). Wooden water wheels larger than about 40 feet (12.2 m) in diameter could also warp under their own weight, and this may have contributed to the decline of the Garfield wheel. Continual wetting and drying of wooden components also meant that joints, pins and bolts worked loose, while wooden parts decayed and needed replacing every five to ten years (Byrne and Spon 1874:2557; Reynolds 1983:287).

DISCUSSION

Water wheels were an ancient and enduring technology that continued to be used on the Victorian goldfields, in some cases, well into the twentieth century. The State Battery water wheel at Warrandyte on the Yarra River near Melbourne, for example, was built in 1897 and was operated by a local trust for the Victorian government from 1909 to 1925 (Pertzel and Walters 2001:54). The Great Rand Proprietary Company re-opened an abandoned mine on the Howqua River in north-eastern Victoria in 1903 and rebuilt an earlier water race and water wheel (Lawrence *et al*. 2000:11-12). On the Walhalla goldfield, a water wheel was installed along Morning Star Creek between 1904 and 1910, while several other wheels operated in the area around the same time (Griffiths 1992:122-137). A water wheel was also used at the Weone mine near Wangaratta, with construction starting in 1939 just before the Second World War (Heritage Victoria 2013).

The use of water wheels for mining persisted, despite major advances in steam power, for a range of reasons. These included lower costs and safety, along with familiarity and reliability (Pearson 1996:58-9; Reynolds 1983:329-330). Water wheels were relatively simple to build and generally had lower operating costs than steam engines, especially where power demands were limited (Reynolds 1983:329). By the 1880s, mass-produced portable steam engines of up to about 8 horsepower were widely imported into Australia from Europe and the United States, despite tariffs protecting local manufacturers. The larger steam engines often used for mining, however, were usually custom-built by local foundries and these were more expensive to manufacture, install and maintain (Linge 1979:253). In the case of the Garfield water wheel, the capital cost of erecting a dam and reservoir, and excavating a race, had already been met from the public purse via the Coliban System of Waterworks. The main expense to the Garfield Company, in terms of water diversion, was construction of a flume to the wheel, along with a short race and a second flume to take advantage of the tail water to drive another wheel. It was reported at the time that this reduced the cost of crushing the ore to about one-third of the cost of using steam power (Bradfield 1972:65). It was also expected that the cheaper operating costs would allow greater quantities of lower-grade ore to be crushed (*Mount Alexander Mail* 21 March 1887:2).

The Castlemaine-Chewton area receives much less rainfall than other parts of Australia where water wheels were commonly used in the nineteenth century, such as Tasmania and northern NSW, and also less than the Victorian Central Highlands where mining companies often constructed water wheels. The average annual rainfall at Chewton from 1873 to 1921 was 627 mm, while at Wood's Point on the Jordan goldfield in the Central Highlands it was over 1500 mm (Bureau of Meteorology 2013) (Figure 6). The secure water supply provided by the Coliban System, however, permitted construction and operation of several wheels during the 1880s that would not otherwise have been feasible.

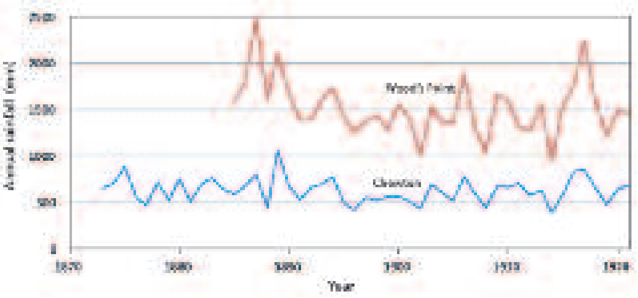

Figure 6: Average annual rainfall at Chewton and at Wood's Point in Central Highlands, Victoria (data from Bureau of Meteorology 2013, Climate Data Online, station 088024 and 083033).

Water for the Garfield wheel came from the Expedition Pass Reservoir, named after a ravine near Mount Alexander through which Major Mitchell passed in 1836. Construction of the reservoir commenced in 1867 as part of the Coliban System of Waterworks, with a dam wall 59 feet (18 m) high and a capacity of 120 million gallons (545 ML) (Chief Engineer 1868:18). Water was released from the network to begin filling the reservoir in 1874 (Russell 2009:198). The Forest Creek branch race extended from the reservoir for approximately five miles (8 km) and made water available to miners working in numerous gullies to the north and east of Chewton (Figure 1). Archaeological remains at the by-wash of the reservoir indicate, however, that water could only have flowed into the race when the water level in the reservoir was almost full, a point confirmed by high levels maintained through the late summer of 1887 (*Mount Alexander Mail* 22 March 1887). This suggests that the pessimistic assessment of the reservoir by engineer Richard Sankey in 1871 as a political 'white elephant' was justified, as mining debris and sludge flowed into and rapidly diminished the quality and quantity of the water storage (Sankey 1871:76). In spite of the reservoir apparently serving as little more than a conduit, it nevertheless functioned to store and divert water to mining groups such as the Garfield Company.

The direct cost of water to the Garfield Company appears to have been moderate, in spite of calls by the manager to reduce the charge. In 1890, for example, the Garfield wheel used 4 million gallons (18 ML) per week, at a cost of £8 6s, but the company manager, John Ebbott, believed 'a lower rate' was appropriate (*Bendigo Advertiser* 1 February 1890:3). In 1897 the Company asked the Minister of Water Supply for a reduction in the charge for water, in the face of limited profits from the mine. The government responded that water for the stampers was made available to the company for one penny per 1000 gallons, or 18 shillings per week for the 15 stamp heads. Water to drive the large wheel cost 1½d. per horsepower per hour, or about £1 13s for a 10-hour day (*The Argus* 8 July 1897:6). The cost of water was fixed and predictable, but the lack of gold in the mines appears to have been responsible for a much greater share of the company's troubles.

The comparative cost of steam versus water power was a delicate and ongoing calculus for many miners. Mining historians Brian Lloyd and Howard Combes (2010:282) argue that the total capital outlay for a water wheel system was of the same order as for a steam engine and boiler. For the Garfield Company and others with access to Coliban water, however, the high cost of building a storage dam and water race had already been met by the government scheme, and the re-use of tail water from the Garfield wheel to drive the Manchester wheel reduced operating costs even further. Eschewing steam power also eliminated the need for an engine driver, typically employed at a salary of around £120 per annum (Smyth 1979:539), along with the services of a wood-cutter to supply firewood.

Boilers demanded large quantities of wood fuel, a resource that was becoming increasingly scarce on the central Victorian goldfields by the 1880s. Alarm had been raised at the scale, speed and wastefulness of forest destruction as early as 1853, as miners recklessly cut down trees for firewood, pit props and building timber, and cleared forest and woodland in ever-widening arcs around mining centres (e.g. Howitt 1972:98; Ligar *et al*. 1865). The Victorian Government Botanist, Ferdinand von Mueller, argued that the profits from gold mining had sometimes been 'too dearly bought at the expense of very extensive forest destruction' (Mueller 1871), while a correspondent in Castlemaine noted in 1874 that it 'is now positively painful to see the wholesale destruction of timber going on' (*Castlemaine Representative* 31 October 1874). By the 1880s wood-cutters in the Castlemaine-Chewton area were travelling greater distances than ever to secure a load of firewood. The cost of firewood at Fryerstown at this time, a mining locality a short distance to the south of Castlemaine, was five to six shillings per ton, although 'old and well-seasoned timber' from the ranges 6 to 10 km away was no longer available and only 'sappling' timbers were being cut in spite of stringent regulations designed for their protection (Amos 1887:69). Nor were there any reliable sources of coal nearby to offer a viable fuel supply (Vines 2008:22-28). This may have been a significant factor in the Garfield Company's decision to develop water power instead of steam. By 1890, Garfield manager John Ebbott reported that miners were 'starving' for timber in the area, with firewood having to be carted for many miles (*Bendigo Advertiser* 1 February 1890:3).

The Garfield Company thus responded to the economic and environmental opportunities of water availability, and to the lack of accessible firewood, by building a large water wheel. A similar pattern is recorded in other parts of the world during the nineteenth century. The Cornish mining industry, for example, relied heavily on water power, despite being at the forefront of improvements in steam technology. In the 1860s, the Fowey Consols mine combined the use of 6 steam engines and 11 water wheels, and the Devon Great Consols operated 7 steam engines and 32 water wheels (Barton 1968:184; Buckley 2002:34; Lewis 1997:145). In Ireland, water power was widely used for power in the textile industry. Water wheels and turbines were applied more often than steam engines because flowing water was abundant and Ireland had only limited supplies of coal, most of which was imported from England and Wales (Rynne 2005). For similar reasons, water power in Scotland persisted as an important source of energy in grain, timber and textile milling for much of the nineteenth century (Shaw 1984), while in the Harz mining district in Germany almost 200 water wheels were in use in 1868 (Barton 1968:175). In France, Germany and the United States, water power remained a major source of industrial energy into the late nineteenth century (Blackbourn 2006:195; Hunter and Bryant 1991:110; Reynolds 1983:328-329). Industrialists thus responded to economic and environmental conditions by using water to generate power in the most effective way possible.

Turbines provided an alternative to both water wheels and steam engines as a power supply, and sources indicate a number of turbines were installed on the Victorian goldfields from the 1860s. The Morning Star Prospecting Company on the Jordan goldfield, for example, installed one of the first turbines in Victoria in 1866, spending £1200 to adapt it to drive a 12-head battery. The Thomson vortex turbine was 15½ inches (394 mm) in diameter, with four 'ports' and was driven by a head of 55 feet (16.8 m) of water. This turbine had been imported to Melbourne 12 months earlier from Scotland but remained unused until sold to the Morning Star Company, suggesting that turbine technology was still a novelty at this time (Milner and Churchward 1988:16-17, 1989:283). At the Royal Standard Reef at Mt Singleton near Wood's Point, a 15-inch turbine with three ports drove 20 stamps (Smyth 1979:307). The exact nature of these and other turbines is often unclear, as numerous designs were being manufactured in Europe and the United States during this period (Byrne and Spon 1874:3014-3022; Fairbairn 1864:157-180). Nevertheless, there was a growing awareness among miners and other industrialists of the power, utility and efficiency of turbines over traditional water wheels (Milner 1985:21; Shaw 1984:495-498; Smith 1976:161-177).

CONCLUSION

One of the problems traditionally associated with hydraulic machinery in general, and water wheels in particular, was the variable performance caused by changes in seasonal water flow. A common response was to build a storage reservoir and release water during dry periods to provide more uniform flow and a more even power supply. The Garfield water wheel and its water supply followed a similar pattern. The publicly funded Coliban System of Waterworks delivered water to the Expedition Pass Reservoir and from there into feeder channels around Chewton and Castlemaine. The Garfield Company, along with several other mining companies with water wheels, drew thousands of gallons of water from the system every day, permitting the use of a very large water wheel in an environment that was otherwise too dry to sustain operation

The managers of the Garfield Company made a calculated and deliberate choice in 1886 and 1887 to change from steam to water power. Having observed the constant flow of water along the nearby V.W.S. race over a number of years, the decision to use this water to drive a stamp battery took into account a range of economic, industrial and environmental factors. The eventual abandonment of the water wheel in 1904 owed less to the availability of water than to the lack of gold in the mine. Although distinctive for its large size, the Garfield wheel is broadly representative of similar water wheels built during this period. Its wood-iron construction followed conventional design principles, and it appears to have worked reliably for around 17 years.

The Garfield water wheel illustrates the complex integration of water management and gold mining at a regional scale. It was just one among scores of such machines built and operated successfully in Victoria in the later nineteenth and early twentieth century. Water wheels were constructed where good water supplies were available, and they provided a viable alternative to steam power. The wheel was one element in a regional network of water management features that integrated the supply and energy of flowing water with the extraction and processing of deeply buried gold.

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