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The Royal Society of Victoria, 127, 44 –54, 2015
10.1071/RS15017

MERCURY USE AND LOSS FROM GOLD MINING IN NINETEENTH-CENTURY VICTORIA

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ABSTRACT: This paper reports on preliminary research into gold-mining-related mercury contamination in nineteenth-century Victoria. Data drawn from contemporary sources, including *Mineral Statistics of Victoria* and *Mining Surveyors Reports* from 1868–1888, are used to calculate quantities of mercury used by miners to amalgamate gold in stamp batteries and the rates of mercury lost in the process. Some of the mercury discharged from mining and ore milling flowed into nearby waterways and some remained in the waste residue, the tailings near the mills. We estimate that a minimum of 121 tons of mercury were discharged from stamp batteries in this period. Although the figures fluctuate through time and space, they allow a good estimate of how much mercury was leaving the mine workings and entering Victorian creeks and rivers. Better understanding of historic mercury loss can provide the basis for improved mapping of mercury distribution in modern waterways, which can in turn inform the management of catchment systems.

Keywords: mercury, gold mining, pollution, water, rivers

In recent years, mercury in waterways has emerged as an important environmental issue in south-eastern Australia and in many other areas. Mercury and its compounds are highly toxic in freshwater environments and are capable of bio-accumulation in fish, microalgae, sediment-dwelling invertebrates and, ultimately, humans. The contamination of organisms has been reported in various locations, including Port Phillip Bay, the Gippsland Lakes, Lake Eildon and Tasmanian stream beds (Glover et al. 1980; Tiller 1990; Churchill et al. 2004; Fabris 2012). Determining the extent of historical mercury loss is thus an important step towards the remediation of metallic mercury in Victorian aquatic systems (Lomonte et al. 2010).

Historically, one of the major sources of mercury contamination in Victoria was the gold mining industry. Mercury (or ‘quicksilver’) was widely used by gold miners in colonial Victoria and elsewhere in Australia to amalgamate with small particles of gold and improve the rate of gold recovery. Some of the mercury used to process gold-bearing ores was lost to the environment and entered local waterways with tailings, sludge and other mining debris. Historical mining activity has thus contributed significantly to mercury contamination of numerous streams throughout Victoria (Bycroft et al. 1982; McCredie 1982; Tiller 1990; Churchill et al. 2004). Similar patterns have been reported from other major centres of nineteenth-century gold mining, including California (Alpers et al. 2005; Isenberg 2005; Singer et al. 2013), North Carolina (Hines & Smith 2006; Lecce et al. 2008), Nevada (Wayne et al. 1996) and New Zealand (Moreno et al. 2005), while extensive mercury pollution also resulted from silver mining and processing in both North America and South America during this period (Nriagu 1993, 1994; de Lacerda & Salomons 1998; Strode et al. 2009; Robins 2011). By the 1890s, nine-tenths of the gold produced around the world was recovered by the mercury amalgamation process (Birrell 2004).

In this paper, historical data from the annual series *Mineral Statistics of Victoria* (MSV) and quarterly *Reports of the Mining Surveyors and Registrars* (MSR), both published by the Government of Victoria, are used to analyse the amount of mercury used in ore processing and gold amalgamation, and the amount of mercury lost to the environment. This analysis principally covers the period from 1868 to 1888 inclusive, during which time records were published for both mercury use and loss per (battery) stamp head per week. Record keeping at this level was not maintained either before or after this period. The primary focus here is on quartz-reef mining and ore crushing for which good figures are available, but alluvial mining from the 1850s and 1860s and the treatment of ore containing sulphides, commonly known as ‘pyrites’, are also considered as important contributing factors in mercury use and loss. Victoria accounted for 64% of all the gold produced in Australia between 1851 and 1900 (Laughton 1911), implying a much greater extent of mercury loss in Victoria from gold mining than in other colonies during this period. The data from this study period can be used to drive

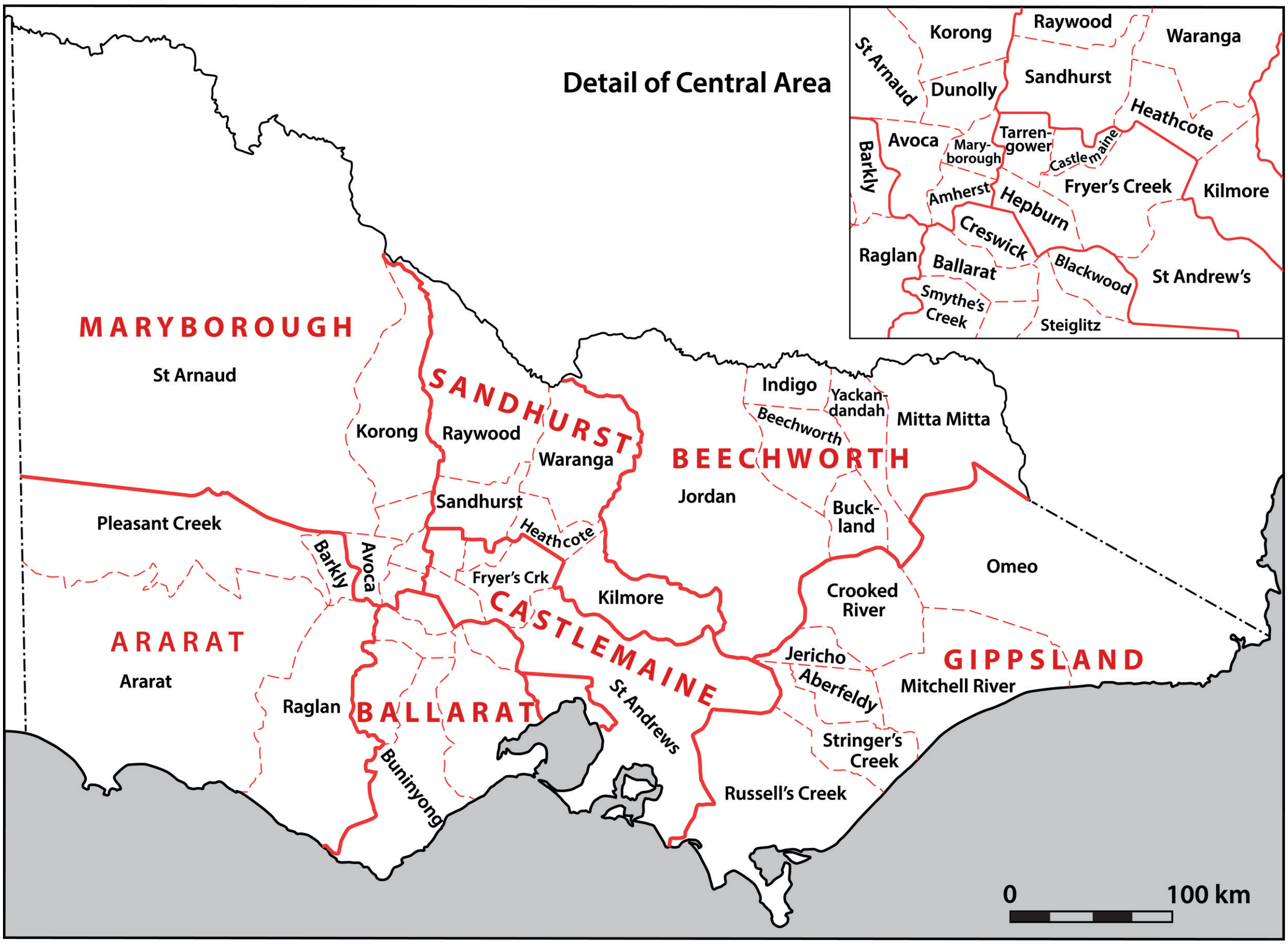

Figure 1: Mining Districts and Divisions in Victoria in 1867.

models for earlier periods, when mercury loss was worse, and later periods, when mercury recovery was better.

The paper begins by reviewing the history and technology of mercury amalgamation in gold mining, along with the processing of pyrites and alluvial deposits. The scope and limitations of the available data are then outlined. The analysis of mercury consumption is based on the seven historical mining districts of Ballarat, Beechworth, Sandhurst (Bendigo), Maryborough, Castlemaine, Ararat and Gippsland. These were established by 1867, with each district divided into smaller divisions and subdivisions for administrative purposes (Figure 1). The reported weekly use of mercury is used to calculate annual rates of consumption and loss in quartz treatment and compare this with quantities of quicksilver imported during the study period.

GOLD MINING AND GOLD AMALGAMATION

Gold is found in various formations in Victoria, each requiring different mining techniques. Shallow or surface alluvial deposits are associated with watercourses where gold has been eroded from original deposits and lodged in the gravels and clays of streambeds and adjacent alluvial areas. These were the main focus of mining activity at the beginning of the gold rush in the early 1850s, with pans and cradles used initially before long toms and ground sluicing were developed. Deep leads are much older gold-bearing water channels that have been buried below basalt flows or alluvium. These were mined from the late 1850s and required steam engines to drive pumps, winding equipment and, where the gold was in consolidated cement-like deposits, stamp batteries (Bate 1978; Canavan 1988). Quartz reefs are ore bodies containing gold and other minerals, and processing this material has involved a range of technologies, including roasting, crushing and amalgamation with mercury. By the end of the nineteenth century other techniques were also used to recover gold from ores, including chlorination and treatment with cyanide, but mercury continued in use in many areas (Clark 1904; Todd 1995; Davey & McCarthy 2002; Birrell 2004, 2005).

Amalgamation is a concentrating process in which particles of free gold are mixed with mercury, usually in an amalgamation drum or on an amalgamation table. In this process the precious metal bonds with the mercury to form gold/mercury amalgam and the waste ore pulp is diverted along a separate path. The ore containing the gold needed to be ground fine enough to allow the maximum exposure of the gold surface to the mercury. The ground ore was mixed with water to disperse it and to promote better contact between the gold and mercury.

Pure mercury absorbed about half its weight in gold in the amalgamating process. The relatively low boiling point of mercury of 357° C (675° F) meant gold was easily recovered from the amalgam by heating it over an open flame or forge to drive off the mercury as vapour. Miners could also assess the presence and amount of gold by simple observation. As mercury absorbed the gold and impurities it lost fluidity and effectiveness until it became crusty (Lock 1882). When the mercury developed a frosty appearance, miners knew that it was almost saturated with gold (Hines & Smith 2006).

Mercury was readily available for purchase in Victoria's mining districts during the nineteenth century and generally cost around 2s 6d per pound, although access to supplies could be irregular as prices rose and fell (see MSV 1880, p. 44; Poynter 2003; McQueen 2011). Gold was sold for about 75 to 80 shillings per ounce in the 1860s, according to MSR records. During this period the main sources of cinnabar (mercury sulphide), the chief ore mineral of mercury, were Spain, Italy, Peru, California and Slovenia (Tepper 2010). Small quantities of mercury were also mined in New South Wales and Queensland beginning in 1869 (McQueen 2011) and in Victoria during the 1890s (Lloyd 1978). After processing, mercury was generally enclosed and transported in iron bottles containing 76 lbs (34.4 kg) of quicksilver. Mercury could also be held in glass or porcelain vessels as it did not adhere to the interior (Byrne & Spon 1874). Colonial imports of mercury are described in more detail below.

Miners used mercury in a number of ways to amalgamate gold, with each mill or battery operator having their preferred method depending on the nature of the ore. By the late 1850s the most common way of crushing gold-bearing quartz ores or consolidated alluvial cements was in a stamp battery. The battery featured heavy iron stamp heads held in a frame, with each head often weighing up to 500 pounds (226 kg) or more (see MSV 1880, page 45) (Birrell 2005). Stamp heads were lifted and dropped by a rotating overhead cam shaft driven by a steam engine or water wheel. Ore was fed into a large cast-iron battery box, mixed with a steady stream of water, and pulverised by the stamp heads. In some batteries, mercury was placed in the base of the boxes to amalgamate with freed gold. The violent agitation of the mercury in the mortar box, however, could cause the mercury to break into myriad tiny globules that were carried away by the water with the tailings, thus losing a certain amount of gold in the process (Thompson 1867; Ritchie & Hooker 1997).

The water and sand slurry was splashed by the falling stamps from the box through fine mesh screens and onto inclined wooden tables below the mortar box (Figure 2). The tables were covered with copper sheets or plates coated with mercury, which caught and amalgamated with a portion of the gold. The grey putty-like amalgam was periodically scraped off the sheets and retorted in a furnace to collect the gold and recover the mercury for reuse. Mercury was inevitably lost from the plates, while poor maintenance resulted in further losses of gold and mercury in the tailings.

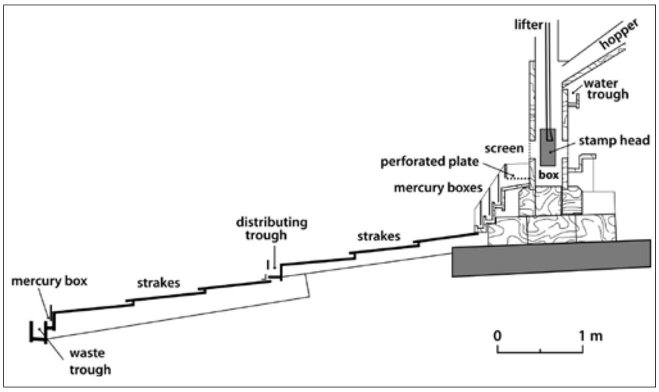

Figure 2: Section of stamp battery, strakes and mercury troughs at the Port Phillip Company at Clunes (adapted from Smyth 1980).

Additionally, ripple (or riffle) boxes were placed at the foot of the battery box where the pulp passed over troughs filled with mercury, which caught a portion of the gold (Lock 1882; Smyth 1980). The Port Phillip and Colonial Gold Mining Company at Clunes appears to have been the first mine in Victoria to use copper plates with mercury troughs, introducing the technique in 1861 (see *Colonial Mining Journal* May 1861, page 135; Davey 1996). The remaining residue of finely crushed waste material, containing mainly quartz but also fine particles of gold and mercury, was called tailings. In the early days, tailings were often stockpiled and gradually eroded away into the nearest watercourse. Significant amounts of mercury were thus lost into waterways during the early mining boom due to inefficient methods. While gold ores remained rich, the losses of gold and mercury were not considered significant and little effort was made to prevent their loss.

During the 1860s, many mines used blanket strakes as a complement or alternative to copper amalgamating plates. These were cattle hides or heavy blankets of woollen felt placed over wooden boards, over which the finely crushed ore was passed and the fine gold flakes were caught and held by the blanket fibres. The blankets were washed every few hours to collect the gold and crushed sand particles, which were then treated in an amalgamation barrel or in a 'Berdan' pan (Thompson 1867; Woodland 2001). This was a small revolving basin up to one metre or so in diameter, usually made of cast iron, and containing a heavy steel ball or weight for grinding. Blanket sand containing gold was placed in the Berdan with water and mercury and rotated for several hours until the gold had been liberated from the sand and amalgamated (Taggart 1954: 14–19). A charge of two hundred or three hundred pounds of mercury was common and, if the ore contained sulphides, up to half the mercury could be lost in the waste sand during the process (Thompson 1867). The amalgam was then removed and most of the free mercury was extracted by squeezing in a canvas or leather bag for reuse. The remaining amalgam was then placed in an iron retort and heated to vaporise the mercury, which was recondensed, collected and reused. The retorted gold, which still contained some mercury, was then sold to a bank or mint for further refining (Birrell 2004; Lloyd & Coombes 2010). As ore grades dropped during the 1860s, tailings were increasingly sent to specialised concentrators and the use of blankets was phased out (Lock 1882; Woodland 2001). Thus, during the period 1868 to 1888 the principal use of mercury was in ripple boxes (troughs) and in pan amalgamators.

Mine tailings could contain mercury from the batteries, the ripple boxes and the amalgamating plates and Berdan pans. Generally the tailings were allowed to flow into the nearest creek, with miners relying on an occasional flood to clear the channel and wash the tailings further downstream (Lawrence & Davies 2014). In some cases tailings were stored in settling dams from which water for processing was recirculated. The Port Phillip Company at Clunes installed pumps in 1866 to lift the tailings and discharge them through a flume further down the creek (Woodland 2001). In other cases the tailings were extracted from creeks and rivers into a sluice-box for re-treatment, in order to extract gold lost in the mercury amalgam.

Mercury use and loss appears to have decreased from the 1890s, with the introduction of the cyanide process in gold mining. This involved soaking finely crushed ores in dilute potassium cyanide solution over several days. The solution dissolved the gold and was passed through boxes where the gold content was precipitated on zinc shavings. Cyaniding enabled low grade ores to be worked profitably and improved the rate of gold recovery from pyrite ores (Todd 1995; Ritchie & Hooker 1997). The adoption of this technology was variable, however, depending on capital, expertise and the nature of ore bodies, so that mercury amalgamation continued in many mining areas well into the twentieth century. In some cases the techniques were used together—mercury amalgamation in the stamp mill and Berdans and cyanide for the tailings.

The mercury would have been refined out of the bullion recovered from the cyanide solution, thus reducing the amount of mercury released into the environment by an unknown amount. Today mercury is still widely used among artisanal gold producers in many countries (de Lacerda 2003).

AMALGAMATING PYRITES

Pyritic quartz commonly occurs below the watertable. After the shallow quartz had been mined, most of the gold-bearing ores excavated by miners in Victoria contained large quantities of arsenic-bearing sulphides and other minerals. These impurities created problems in terms of extracting gold efficiently and profitably, and processing the ores generated environmental and public health hazards. Mercury was often coated with other minerals, especially sulphur, preventing it from amalgamating with the gold (a state called 'sickened') and broke up into tiny particles (known as 'floured' mercury) when used with pyritic sands. It therefore failed to amalgamate with gold, before washing into the nearest waterway with the tailings (Sergeant et al. 1874; Smyth 1980). Numerous techniques were employed to overcome these difficulties, drawing on local experience as well as approaches developed in England, Germany and elsewhere.

Several different methods were used to amalgamate gold from sulphide ores. The ore was often crushed and roasted to oxidise it and drive off the sulphur and arsenic, and the concentrated sands were added to Berdan pans or a Chilean mill with mercury for rolling and amalgamating (Birrell 2004). Large amounts of mercury were used in these processes. A Chilean mill consisted of a circular trench around which a heavy iron-capped stone wheel was pulled by horse or steam engine to crush the ore (Ritchie & Hooker 1997). The crushed quartz sand and water were run off while the heavier gold-mercury amalgam accumulated in the base of the trough. Mercury often 'sickened' in this process and some gold and mercury were lost in the washing process. The amalgam was cleaned out periodically and squeezed in a chamois leather to remove the excess mercury. The Port Phillip Company at Clunes used 150–200 lbs (68–90 kg) of mercury with two hundredweight (224 lb or 102 kg) of calcined ore in a Chilean mill per charge, losing to the environment up to 1 lb 13 ounces (0.82 kg) of mercury per ton of 'roasted sand' (Sergeant et al. 1874). Ritchie and Hooker (1997) noted that Chilean mills were quite commonly used in Victoria, but were less so elsewhere in Australia and not at all in New Zealand.

Mining surveyors reported separate data for ore and gold from 'Pyrites and Blanketings' between 1869 and 1886, although no figures for associated mercury use and loss were provided. During this time a total of 114,822 tons of pyrites as sands were treated for a yield of 242,253 ounces of gold or approximately 2 ounces per ton of pyrites crushed. In 1873, the Pyrites Board heard from nine mine managers about their rate of mercury use and loss. Reported mercury losses generally ranged between 1 lb and 2 lb per ton of 'roasted ore'. Taking the lower figure as a conservative minimum, the processing of pyrite concentrates and blanketings by mercury amalgamation from 1869 to 1886 resulted in the discharge of at least 115,000 lbs (51.3 tons) of mercury to the environment. We assume that the mercury use and loss during amalgamation in Berdan pans or Chilean mills was in addition to the mercury use and loss per stamp head reported in MSV.

MERCURY IN ALLUVIAL MINING

Mercury was also used at times in alluvial mining in nineteenth-century Australia, although it is difficult to determine accurately the prevalence of its use, as no figures were collected by mining surveyors (McGowan 2001). Its value in amalgamating was recognised, however, as early as 1851 on the New South Wales goldfields. A newspaper correspondent reported several individuals on the Louisa and Meroo creeks who were improving their yields with the use of 'quicksilver machines', although ignorance of their proper use meant much gold and mercury was lost (as reported in *The Argus*, 8 September 1851). In August 1851 a party was also reported heading for Clunes in Victoria with a quicksilver machine (Woodland 2001). The use of mercury was advocated in contemporary accounts of sluicing processes. A reported practice, for example, was to sprinkle some mercury into the upper end of sluice boxes, from which it gradually progressed with the current to the lower ones. The quantity used depended on the amount of fine gold in the wash dirt (see *Australian Town and Country Journal*, 28 March 1874). The same article noted, however, that mercury was not used in ground sluices. Chinese miners also traditionally used mercury in their sluice boxes and this caused conflict with European miners (e.g. *Bacchus Marsh Express* 3 November 1877; C. Davey pers. comm. 28 October 2014). Miners on the Ovens goldfield in north-eastern Victoria used mercury to separate gold from alluvial tin in the 1850s, with the gold and mercury amalgamated in a revolving barrel to separate it from the tin sands (Woods 1985).

The use of mercury amalgamation in alluvial mining is also implied by the widespread use of 'quicksilver and compound cradles' reported by mining surveyors in the 1860s and 1870s. The Secretary of Mines, Robert Brough Smyth, defined a compound cradle as a large cradle 'about seven feet in length and five feet in width. It has three tiers of slides or blanket-tables, and attached to it is a shaking table with a quicksilver ripple in it' (Smyth 1980). These may have been similar to the large cradles described as 'quicksilver machines' used in the early days of the gold rush in California (May 1970). During the 1870s there were generally between 150 and 200 compound cradles in use in Victoria, with a concentration in the Maryborough, Castlemaine and Ararat mining districts. In spite of their popularity in these places, it is not certain how much mercury the cradles actually used and discharged. Hydraulic sluicing was also widely practised at this time but there is little or no evidence that mercury was used in the process (Smyth 1980). In the first part of the twentiethth century, mercury was used at times with bucket dredges to extract gold from concentrates removed from stream beds (Supple 1994; Lloyd 2006).

Mercury was used intensively in alluvial (placer) mining in California during the nineteenth century. Hundreds of pounds of mercury were added to the riffles and troughs of a typical sluice, and much of it was lost through water turbulence, flouring and other disturbances to downstream environments. Minute particles of quicksilver were observed floating on the surface of rivers up to 30 kilometres downstream from mine works. Alpers et al. (2005) estimated that the total amount of mercury lost to the environment throughout California from the 1860s to the early 1900s was around 10 million pounds, or 4464 tons. Other estimates put the figure at 1.4 million pounds (625 tons) per year, while one company estimated that canyons below the largest hydraulic mines contained up to 20 tons of mercury every mile (Bowie 1910; Isenberg 2005). Despite the influx to Victoria of mining technologies from California, however, there is little direct evidence that miners applied mercury to sluicing alluvial deposits. Instead, mercury use may have been sporadic and applied when opportunities arose.

DATA SOURCES AND LIMITATIONS

The most valuable data for this study derive from the MSR, in which various aspects of alluvial and quartz mining activity in regional divisions and subdivisions from 1859 were documented. The information was summarised in the MSV series, with records for mercury use and loss reported from 1868 to 1888. Mercury consumption for this period was described in relation to the weight, cost and fall of stamp heads used in quartz crushing, along with the horsepower needed to work each stamp and the volume of water used in crushing. Comparable data are not available after 1888 when reporting methods changed but it is expected that mercury continued to be used as previously.

Imports of quicksilver were also reported in MSV for the years 1867 to 1888, while the numbers of stamp heads in use were reported in the MSR. Estimating mercury consumption is thus a function of the reported number of stamp heads in use, minimum and maximum values of mercury used and lost per week, and tonnages of quartz crushed per year.

For the most part the original imperial measurements have been retained here for accuracy and clarity in data presentation. We also note, however, that mercury and gold were weighed according to two different systems of measurement in the nineteenth century (Kisch 1965). The system of weights associated with gold was the troy weight, where one ounce (oz) = 31.1 grams, one pound (lb) = 12 ounces (373 grams) and one short ton = 2000 lb avoirdupois (907 kg) (Lloyd & Combes 2010). Mercury, on the other hand, was weighed on the avoirdupois scale for commerce, where one ounce = 28.3 g, one pound = 16 ounces (453 g) and one long ton = 2240 pounds (35,840 oz or 1.016 tonne).

It has been noted above that mercury was used in a variety of ways during crushing and amalgamating quartz ores to recover gold. The data provided in MSV, however, relate specifically to 'the quantity of mercury used in the ripples per stamper', which implies most mercury was applied in troughs (ripples) between the strakes rather than in the stamp boxes. The amount of mercury lost (presumably from ripples) was then presented as a calculation per stamp head. These figures do not appear to apply to mercury lost during later stages of amalgamation. MSV data may thus represent only one aspect of mercury use and loss. Specific figures for the use of mercury in alluvial mining and in the treatment of quartz tailings, 'cement' (gold-bearing conglomerates) and pyrites were not reported, so these methods can only be noted as contributing to mercury contamination of waterways.

The wide variation between minimum and maximum values reported for mercury use and loss within and between mining districts can be interpreted in various ways. Mining registrars recorded minimum and maximum values from information provided by numerous individual companies within mining districts, and which was subject to a range of variables. These included the pyritic nature of ore bodies, richness of the ore, fineness of the gold, the temperature at which the mill operated, available equipment and, importantly, the skills of the mine manager, battery operator, amalgamators and retort workers. Thus even within one mill, the rates of mercury loss could vary greatly from year to year. The data presented here are based on median values over 20 years, so need to be read with caution, as it is unlikely that mercury loss rates were constant and considerable regional variation existed.

MERCURY USE AND LOSS IN QUARTZ MINING

To calculate rates of mercury use and loss, data have been drawn from MSV and MSR for the period 1868 to 1888 inclusive. Table 1 shows the median number of stamp heads used in each of the seven mining districts for the study period, based on quarterly MSR summaries. Individual crushing batteries were equipped with as few as four and as many as fifteen stamps each, although the number was eventually standardised at five stamps in each battery (Birrell 2005). Table 1 also presents the median value for the minimum and maximum amounts of mercury *used* per stamp head per week (in pounds), and the median value for minimum and maximum amounts of mercury *lost* per stamp head each week (in ounces).

Table 2 is derived by multiplying the weekly median mercury use and loss per stamp head by 40 (for working weeks in the year) and then multiplying this by the median number of stamp heads in use in each mining district, and converting the result to pounds. This gives a notional annual rate of mercury use and loss. Forty weeks of annual operation is a conservative figure that acknowledges potential loss of production due to mechanical breakdowns, labour strikes, lack of water and lack of ore to crush. The ratio of mercury loss to use is expressed in Table 2 as a percentage of mercury lost per year. In general terms, the rate of mercury loss was lowest in the Bendigo district, which may reflect several factors, including the nature of the ore bodies and the efficiency of stamp mills.

Table 3 shows the median weight in tons of quartz

Mining District	**Stamp heads in use per year (median)**	**Minimum mercury (lbs) used in the ripples per stamper per week (median)**	**Maximum mercury (lbs) used in the ripples per stamper per week (median)**	**Minimum mercury (oz) lost per stamp head per week (median)**	**Maximum mercury (oz) lost per stamp head per week (median)**
Ballarat	1269	5.0	32	0.25	5.0
Beechworth	1036	12	68	0.25	5.0
Bendigo	1478	15	36	0.13	1.0
Maryborough	712	4.5	30	1.0	12.0
Castlemaine	947	4.0	20	0.5	12.0
Ararat	347	20	75	1.5	29.0
Gippsland	484	7.5	41	1.0	10.0

Table 1: Median values for mercury use and loss per stamp head for the years 1868 to 1888 inclusive in each Victorian mining district, from MSV reports.

Mining District	Stamp heads in use per year (median)	Minimum mercury (lbs) used per year (median)	Maximum mercury (lbs) used per year (median)	Minimum mercury (lbs) lost per year (median)	Maximum mercury (lbs) lost per year (median)	Minimum mercury % lost per year	Maximum mercury % lost per year
Ballarat	1269	253,800	1,624,320	793	15,862	0.31	0.98
Beechworth	1036	497,280	2,817,920	647	12,950	0.13	0.46
Bendigo	1478	886,800	2,128,320	480	3695	0.05	0.17
Maryborough	712	128,160	854,400	1780	21,360	1.39	2.50
Castlemaine	947	151,520	757,600	1184	28,410	0.78	3.75
Ararat	347	277,600	1,041,000	1301	25,157	0.47	2.42
Gippsland	484	145,200	793,760	1210	12,100	0.83	1.52
Victoria Total for 1868–1888		2,340,360	10,017,320	7395	119,534	0.31	1.19

Table 2: Calculated values showing mercury (lbs) use and loss for the years 1868 to 1888 in each mining district.

Mining District	Tons of quartz crushed per year (median)	Minimum mercury (oz) lost per year (median)	Maximum mercury (oz) lost per year (median)	Minimum mercury (oz) lost per ton crushed per year (median)	Maximum mercury (oz) lost per ton crushed per year (median)
Ballarat	307,830	12,688	253,792	0.04	0.82
Beechworth	55,092	10,352	207,200	0.19	3.76
Bendigo	296,860	7680	59,120	0.02	0.2
Maryborough	40,409	28,480	341,760	0.70	8.46
Castlemaine	101,966	18,944	454,560	0.18	4.46
Ararat	70,201	20,816	402,512	0.29	5.73
Gippsland	35,518	19,360	193,600	0.54	5.45

Table 3: Calculated estimates of mercury loss (in ounces) per ton of quartz crushed per year in each mining district for the years 1868 to 1888.

ore crushed each year from 1868 to 1888, derived from data published in MSR, and the minimum and maximum amounts of mercury lost per year, reduced to ounces. We divided this tonnage by minimum and maximum amounts of mercury lost each year to calculate annual rates of mercury loss per ton crushed.

Between 1868 and 1888, miners in Victoria processed a total of 19,163,502 tons of quartz. In Table 4, we multiplied the total tonnage of quartz crushed in each of the seven mining districts by the minimum rate of mercury lost to calculate the minimum quantity of mercury discharged from the stamp batteries between 1868 and 1888. The total amount for the study period is almost 70 tons of mercury. This is a minimum value and the actual historical rate was likely to have been somewhat higher. We also note that this rate is in the same order of magnitude as estimates in Californian hard rock mining for the same period. During the 1860s, for example, mining engineer J. Arthur Phillips reported that mercury loss for the principal 29 quartz mills in California ranged from 0.0027 oz to 1.12 oz per ton of ore crushed, with a median rate of 0.044 oz (Phillips 1867). In the 1880s, engineer John H. Hammond reported that 0.5 ounces of mercury were lost per ton of ore crushed, 'about the mean quicksilver loss for the mills of the State [of California]' (Hammond 1889). This low rate of mercury loss was similar to the situation in Victoria and suggests that comparable efficiencies were achieved in the two mining regions.

Taking the minimum of 69.7 tons of mercury lost (Table 4) and adding 51.3 tons lost in processing pyrite ores between 1869 and 1886 (see above), we estimate that at least 121 tons of mercury were discharged from stamp batteries in Victoria between 1868 and 1888, an average of 5.7 tons per year.

Some companies reported their holdings of mercury as an asset. The Black Hill Company at Ballarat, for example, listed assets of £186 4s 10d in quicksilver in 1866 (Dicker 1866). Assuming a cost of 2s 6p per pound this amounted

Mining District	Total tons quartz crushed 1868–1888	Minimum mercury (oz) lost per ton crushed per year (median)	Minimum mercury (oz) lost 1868–1888	Minimum mercury (tons) lost 1868–1888
Ballarat	6,625,485	0.04	265 019	7.394
Beechworth	1,289,457	0.19	244 997	6.83
Bendigo	6,003,182	0.02	120 063	3.35
Maryborough	980,231	0.70	686 162	19.14
Castlemaine	2,222,426	0.18	400 037	11.16
Ararat	1,280,841	0.29	371 444	10.36
Gippsland	761,880	0.54	411 415	11.48
Victoria	19,163,502 tons		2,499,137 oz	69.71 tons

Table 4: Calculated minimum quantities of mercury lost to the environment from 1868 to 1888 (where 1 ton avoirdupois = 35,840 ounces).

to 1491 lbs (675 kg) of mercury on hand. The Prince of Wales Company, also of Ballarat, spent £479 on 3832 lbs (1736 kg) of quicksilver in the seven years of operation up to 1865 (Dicker 1866: 34). This suggests that there were large volumes of mercury available for re-sale and transfer when companies went out of business. Much of the mercury imported during this period may have been used to replace mercury lost during amalgamation and retorting.

Year	Quicksilver (lbs)
1868	110,048
1869	90,516
1870	46,968
1871	104,956
1872	76,000
1873	73,264
1874	27,740
1875	76,988
1876	102,765
1877	109,353
1878	36,537
1879	57,887
1880	73,916
1881	51,992
1882	55,420
1883	109,390
1884	40,708
1885	101,750
1886	13,383
1887	73,236
1888	57,357
Total	**1,490,174 lbs (665 tons) (179,543 lbs (80.1 tons) re-exported)**

Table 5: Mercury (quicksilver) imports into Victoria between 1868 and 1888 (source: MSV).

Victoria imported more than 1.4 million lbs of mercury between 1868 and 1888 (Table 5). Annual totals fluctuated widely but the mean annual quantity was 70,960 lbs (31.7 tons). Out of this total, more than 80 tons was also re-exported to other colonies, while some was stockpiled and some was used in non-mining industrial applications. Small quantities, for example, were used in the medical treatment of syphilis and as an ingredient in numerous patent and proprietary medicines, along with dental amalgams for filling teeth. Mercury was also used in the hat-making industry to process animal hairs into felt, although it is uncertain how common this was in colonial Australia. The manufacture of mirrors, thermometers and barometers, and batteries and other electrical items, also used small amounts of mercury (Goldwater 1972; Tepper 2010).

It is likely that the total volume of mercury lost in Victoria from 1868 to 1888 ranged between the calculated minimum of 121 tons and the 585 tons of reported imports.

ENVIRONMENTAL IMPLICATIONS

The figures presented here have implications for current management of waterways and catchments. The toxicity of mercury in freshwater environments means that mercury contamination from historical mining activity has ongoing impacts on the health of rivers and aquatic systems. Mercury adversely affects surface and ground waters and sediments, and accumulates in aquatic plants and animals. Mercury contamination from mining within a catchment continues long after mining operations have ceased, and natural decontamination of mercury from polluted environments may take centuries (Churchill et al. 2004: 356). Numerous studies have assessed mercury contamination in catchments in historical mining areas around Victoria, including the Lerderderg River (Bycroft et al. 1982), Reedy Creek (Churchill et al. 2004), Raspberry Creek (Ealey et al. 1982), the Upper Goulburn (McRedie 1982) and Lake Wellington (Fabris 2012). These have identified elevated levels of mercury in water, sediments, plants and fish downstream from old gold workings. In some cases tailings and tailings dams in the vicinity of old mining areas also show elevated mercury levels and these have remained a long-term source of mercury contamination (Tiller 1990: 25).

Past estimates of mercury released to the environment from mining operations in Victoria show wide variation. Bycroft et al. (1982) calculated that the weight of mercury consumed in the amalgamation process was of the same order as the weight of gold recovered, following an earlier claim by Wise (1966). This would mean that at Bendigo, for example, around 900 tons of mercury were released, in proportion to the same weight of gold recovered. Glover et al. (1980) used a rate of 0.75 troy oz (about 23 g) of mercury per metric tonne of ore crushed to calculate that a minimum of 63 to 76 tonnes of mercury entered the Gippsland Lakes from mining operations in the region. McCredie (1982) based his calculations of mercury pollution in the Upper Goulburn River on a rate of 0.6 troy oz (18.6 g) of mercury per ton of rock crushed. In each of these cases, however, the method for establishing rates of mercury loss was not explained.

Identifying the likely quantities and sources of mercury contamination can provide an indication of where mercury may remain in today's environment. The next step for this research is to develop spatial models that combine the information presented here with evidence for the distribution of mining operations relative to catchments and on the topography and hydrology of relevant rivers and streams. Given the widespread nature of historic mining activity it is likely that many of Victoria's river systems will have been impacted by mining, particularly through the discharge of tailings (Lawrence & Davies 2014). Not all waterways will have been affected in the same way, however, as tailings and contaminants differed between quartz and surface alluvial operations and as hydrological regimes differed. Tailings from hilly areas, for example, flowed readily into nearby streams and mercury quickly entered aquatic systems. Where tailings were discharged or retained on more level ground, however, less mercury would have been washed into waterways. Historical mercury-flows into creeks and rivers have thus varied from region to region, with most studies conducted to date focusing on areas with steeper terrain. While previous research has highlighted mining-related changes to individual rivers and locales (e.g. Beard 1979; McCredie 1982; Jobling 1984; Paxton 1984; Underwood 1985; Peterson 1996; Davis et al. 1997; McGowan 2001; Cargill 2005) the full extent of how mining re-shaped Victoria's landscape and the accompanying distribution of contaminants have yet to be traced.

CONCLUSION

This paper presents a preliminary assessment of mercury use and loss from gold mining and amalgamation across Victoria for the period 1868 to 1888, based on contemporary sources. Figures given are broadly indicative, providing an index of probable mercury discharge into waterways in the seven mining districts of the colony over a 21-year period. Mercury loss meant gold loss, so miners worked hard to minimise the loss of mercury and maximise the rate of gold recovery. Nevertheless, the total extent of mercury lost during this period was at least 121 tons. This is comparable to the reported rate of mercury loss in Californian stamp mills from the same period. It is important to note that mercury amalgamation continued in use on the Victorian goldfields before and after the study period, resulting in an extended period of mercury contamination over a number of decades.

Acknowledgements

This research was carried out at La Trobe University as part of a project funded by the Australian Research Council, 'Cultural landscapes of colonial water management in Victoria's Central Highlands' (DP110100437). We thank Chris Davey, Ian Rutherfurd and two anonymous reviewers for critical comments on earlier versions of this paper.

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