Reconstruction of historical riverine sediment production on the goldfields of Victoria, Australia

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1. Introduction

There has been a strong trend to move from general descriptions of human impacts on landscapes to interdisciplinary, quantitative reconstructions (Gillson and Willis, 2004). These detailed reconstructions can be regional (Butzer and Helgern, 2005) or thematic (Bradshaw, 2012). In Australia there are good examples of thematic quantitative reconstructions of vegetation and land use change since first European settlement (Bowman, 2001; Lunt, 2002). Indicators such as diatoms (Reid et al., 1995) have been used to extend the water quality record to the period before routine measurements and back to first European settlement. Detailed knowledge of changes wrought by humans is of great assistance, not only in understanding our landscapes but also in defining targets for management and restoration.

Forensic analysis of historical records is a major source of quantitative information about the period between first European colonisation and routine environmental monitoring. One spectacular period of human impact in Australia was gold mining in the 19th century. In this paper we interrogate the remarkably detailed historical records of this period to reconstruct the temporal and spatial distribution of sediment released by historical gold mining. We also consider how the sediment was dispersed by river systems in the then colony (now state) of Victoria. While there have been reconstructions of mining sediment in specific rivers (Knighton, 1989; Locher, 1996; Boggs et al., 2000) this is the first regional reconstruction of legacy sediments from mining in Australia.
Gold mining mobilised large quantities of sediment and sludge in 19th-century Victoria, much of which flowed into and polluted local river systems (Lawrence and Davies, 2014). For more than half a century, miners diverted great volumes of water to separate gold from alluvial washdirt and produced huge amounts of mining waste in the process. In addition, smaller but significant volumes of tailings resulted from the crushing of auriferous ore in stamp batteries. The semi-liquid waste from these processes was known generally as ‘sludge’ and ranged in composition from fine silty-clays to coarse sands and gravels. Numerous contemporary accounts and government inquiries reported sediments that filled creeks and water holes and inundated farmland for tens of kilometres downstream (e.g. Royal Commission, 1859; Board, 1887; Committee, 1887). These historical sources indicate that disruption to river systems was significant and widespread. Mining activity was widely distributed across Victoria, extending from the north-eastern border with New South Wales to within 150 kilometres of the border with South Australia in the west. It was concentrated in the uplands along the continental divide that provide the primary source of Victoria’s main rivers, so the rivers carried mining waste both north and south across Victoria.

In this paper we use historical research to estimate the volumes of mining sediment produced, based on the detailed analysis of 19th-century documentary records. This research is part of an ongoing multi-disciplinary project to assess the scale and lasting impact of historical mining sediment across the state of Victoria. The goal is to determine the ongoing implications for stream health and land use today. In subsequent research these historical figures will be integrated with geomorphological analysis to derive the production of mining sediment that can be compared with other regions. In this paper we are not producing a full sediment budget, as we do not consider storage and end of valley delivery of sediment. Instead we estimate the volume of sediment delivered to streams by historical gold mining. Neither are we considering the chemical contaminants associated with the sediments. Future research will report full mining sediment budgets for Victorian catchments (including comparisons with other sources of anthropogenic sediment such as gullying and agriculture), as well as levels of contamination. While there is some knowledge of mercury use in Victoria based on historical records (Davies et al., 2015) and localised catchment studies (e.g. Bycroft et al., 1982; Churchill et al., 2004; McCredie, 1982) its relationship with sediment distribution and its impact regionally are yet to be determined. The scope of the present study is deliberately limited to 19th-century mining as this period experienced the greatest gold-mining activity, production and environmental impact. While there are many contemporary examples of uncontrolled sediment release in developing countries (e.g. Appleton et al., 2001; Day et al., 2009; Donkor et al., 2005), we are concerned here with a setting where we can observe more than a century of changes following a relatively short period of intense mining.

Our primary data in this paper relate to the years 1859–1891, which overlap all but the first eight years of the main gold rush period. We begin by reviewing the history and geology of Victoria’s gold province and the development of mining techniques used to recover gold from primary (quartz ore) and secondary (placer or alluvial) deposits. Drawing on records published in the Mining Department’s annual series Mineral Statistics of Victoria (MSV), we calculate sediment volumes for the main alluvial mining technologies, including puddlers, compound cradles, ground and box sluicing, and hydraulic sluicing. These data are arranged by the seven Mining Districts of Victoria: Ballarat, Beechworth, Sandhurst [Bendigo], Maryborough, Castlemaine, Ararat and (from 1867) Gippsland (Fig. 1). We also use MSV data to determine volumes of quartz ore processed in stamp batteries and track gold yields and mining populations against the volumes of alluvium processed.

![Fig. 1. Map of Victoria showing boundaries of Mining Districts and principal mining centres.](image)
MSV data are mapped by Mining District and major river catchment to indicate the geographic distribution of sediment production across the colony. We then examine contemporary documentary sources to explore the effects of mining sludge on downstream communities and official responses to the problem. These figures will allow the quantity of alluvial mining sediments mobilised in Victoria to be compared with other anthropogenic sources of erosion in future work and for their management implications to be assessed.

2. Historical context

Payable quantities of gold were first discovered in Victoria in 1851, only three years after similar finds were made in California and 16 years after the first permanent European settlement of the colony. Hundreds of thousands of migrants arrived in Victoria from around the world, increasing the colony’s population from 77,000 in 1851 to 540,000 just ten years later (Serle, 1968, p.382). By the time the gold rush had dwindled around the period of the First World War, the Victorian gold province had produced 80 million troy ounces of gold, approximately 2570 t or around 2% of all the gold ever mined globally. The 1500 t or more of alluvial gold from Victoria ranks the region as one of the world’s most important shallow alluvial goldfields, along with Siberia, California, the Yukon/Klondike and Otago, New Zealand (Phillips et al., 2003, pp. 377–380, 414).

Gold mining also had a dramatic impact on the natural environment. Miners dug up and polluted hundreds of creeks and gullies in their relentless search for gold. They diverted huge volumes of water to sluice their claims and flushed the resulting sludge into the nearest waterway. Much of this material flowed downstream to inundate and damage productive farmland (Peterson, 1996). Significant volumes of mercury used in gold amalgamation were washed into creeks and rivers (Davies et al., 2015). Miners also had a voracious appetite for timber and firewood, decimating forests and woodlands in the vicinity of the goldfields (Howitt, 1972, p.254; Ligart et al., 1865, p.4; Smyth, 1980, p.28). This was part of the wider pattern of broad-scale land clearance for agriculture during and after this period. The scale and impact of deforestation by mining on erosion and sediment yields, however, remains poorly understood (Dodson and Mooney, 2002; Lunt, 2002).

The geographic distribution of mining centres reflects the geological emplacement of gold-bearing strata. Primary or hard rock deposits of gold in quartz veins were formed in the Palaeozoic Era, ending with the Devonian Period around 350 million years ago. Existing basalts and the overlying sedimentary rocks were fractured during an intense period of volcanism and mountain building which allowed mineral-enriched water to flow into the cracks and precipitate-out to form gold-bearing quartz veins. Later, during the Cainozoic Era beginning some 65 million years ago, weathering and erosion liberated some of the gold and redeposited it in valleys and stream beds (Phillips et al., 2003, pp. 381–383). Some of these alluvial deposits were themselves subsequently re-buried by later deposition and by volcanic activity that began around 3 million years ago, forming ‘deep lead’ gold deposits (Hughes and Phillips, 2001). Palaeozoic outcrops in Victoria form the southern end of the Lachlan Fold Belt, part of the Great Dividing Range that stretches from the high country in eastern Victoria near Omeo and Buchan through central Victoria to Stawell in the west. Gold has been found throughout these upland regions in both hard rock and alluvial deposits. Quartz reefs are oriented north-south as a result of the east–west orientation of the Palaeozoic compression. Shallow alluvial deposits are found across the uplands while the buried deep leads follow the Cainozoic rivers that flowed out of the highlands either south towards Bass Strait (the deep lead mines at Ballarat) or north towards the Murray Basin (the mines around Creswick, Maryborough and Rushworth (Phillips and Hughes, 1996; Phillips et al., 2003)).

Gold deposits in Victoria are frequently located in the interfluves between the larger north-flowing rivers. This meant that securing adequate water supplies for mining and domestic purposes was often difficult. Miners quickly adapted to the low and variable runoff conditions by constructing extensive networks of artificial channels (known as races) and dams. By 1869 there were some 3900 km of races in operation, along with hundreds of reservoirs to store water for processing auriferous washdirt (Smyth, 1980, p. 547).

3. Mining technology

The kind of sediment produced is closely related to the type of technology used and the nature of the deposit being worked. Miners adopted a range of techniques to recover gold in response to the deposits they encountered, with technologies progressing through distinct stages. Each method required large volumes of water to separate gold from the surrounding matrix and all produced some form of sludge. The gold rush began with the treatment of shallow alluvial sands and gravels using primitive equipment such as pans and cradles (Fig. 2). By the mid–1850s miners had introduced more efficient ways of washing shallow deposits using ground sluices and panning machines (Davey, 1996; Smyth, 1980). Ground sluices channelled water through a series of races or ditches and over a bank into a creek or gully to loosen the overburden and washdirt, which was directed into a sluice-box or tail-race to retrieve the gold (Fig. 3). Ground sluices, long toms and sluice boxes have been aggregated in the published historical sources because each operated on similar principles of processing washdirt with running water through a channel lined with apparatus to catch the gold particles.

Puddling machines were ring-shaped troughs in the ground in which clays and gravels were mixed with water (Fig. 4). Paddles or harrows suspended from a rotating central arm were then dragged

Fig. 2. Cradling for alluvial gold, watercolour by S. Gill, 1869 (source: State Library of Victoria H86.7/8).
through the mud to break up the soil. Gold settled to the bottom and was recovered when the muddy water was released. Quicksilver or compound cradles were gold-washing machines that used a water wheel or other power source to drive a pudding shaft, with mercury used for amalgamating gold particles in a series of cradles or sluice-boxes (Fig. 5). Paddocking was another important alluvial mining technique that involved stripping an area of up to half a hectare down to bedrock. The method was commonly practised by Chinese miners but it was not reported in official sources and has been excluded from our analysis. ‘Washdirt’ was auriferous gravel, sand or clay in which the greatest proportion of gold was found, while ‘alluvium’ referred more broadly to the gold-bearing soils, clays and gravels found in watercourses, creek flats and adjacent slopes and terraces. ‘Tailings’ were the waste sand fraction that resulted from crushing ore, while ‘mullock’ was the barren waste rock extracted from mine shafts and adits (Ritchie and Hooker, 1997).

Hard rock mining developed from the mid-1850s to extract the gold visible in quartz reefs. Blasting the rock, hauling it to the surface and draining and shoring the shafts and tunnels required significant capital investment and labour, resulting in the development of company mining where miners worked as employees (Woodland, 2014). Further investment was needed for steam engines and stamp batteries to process the ore. Crushing batteries with heavy cast iron stamp heads were used to pulverise the rock into fine sands. Refractory pyritic ores required roasting and, by the end of the century, chemical treatment. In each stage except roasting, water was used to carry the ore through the sequence of treatments and provided the means of washing out the gold.

Deep lead mining combined characteristics of both shallow alluvial and hard rock mining. Where ancient gold-bearing rivers had been capped by subsequent volcanic deposits, the alluvial sands and gravels could occur at considerable depths. By the 1870s some deep lead mines were up to 166 m below the surface (Fahey, 1986, p. 50). These underground workings were much like those of hard rock mines and required capital and equipment for tunnelling, blasting, hauling out waste rock and ore, and for draining the mines. The ore treatment process was similar to that of surface alluvial workings. Washdirt was treated in puddlers to separate gold from the sands, gravels and clays, while stamp
batteries were used where it was necessary to crush conglomerate deposits of cemented gravels.

Hydraulic sluicing was developed in California in the early 1850s and introduced to Victoria by 1860 (Smyth, 1980, p. 131, 519). The technique relied on piping water under pressure through a nozzle (known as a ‘monitor’) and directing the high-powered stream at the working face of a claim (Fig. 6). The water undercut the hillside and washed the deposit into sluice boxes where the gold was recovered. The residual sludge was then released into nearby waterways. By the late 1880s ‘giant monitors’ were being used in north-east Victoria that were capable collectively of washing out up to 1.5 million m³ of washdirt per year (MSV, 1888, p. 29; Sludge Board, 1887, p. xxvi, 17). Dredges were introduced from New Zealand in the late 1890s (Davey and McCarthy, 2002, pp. 84-85). These were treatment plants built on a pontoon that floated on a pond or river and used a chain of buckets to scrape up the washdirt, passing it through a series of screens and separators to extract the gold, and releasing the sludge back into the pond. As they were mostly a 20th-century technology we have excluded them from our current analysis.

There was considerable overlap in the distribution of different branches of mining, with most methods used in most districts at some time. Inevitably, however, local conditions favoured certain techniques over others. Deep lead mines were concentrated in the area between Ballarat, Creswick and Maryborough and in the north around Chiltern and Rutherford. Bendigo was the centre for puddling, with up to 2000 machines in operation at the height of the industry in 1859, and the district was later renowned for its rich quartz reefs in the 1870s and 1880s. The hilly, well-watered country in the north-east of the state around Beechworth, Yackandandah and Mitta Mitta was well suited to the adoption of hydraulic sluicing for working the deep alluvial deposits.

4. Methods

We have reconstructed the volume of sediment liberated by different mining methods from detailed historical records. Our approach has been to identify the number of different types of mining machines on the various gold fields at different times, and then estimate the typical sediment yield from these machines.

5. Data sources

The Mining Department recorded details of mineral production, mining leases and associated information from 1859, based on quarterly reports provided by District Mining Surveyors and Registrars. This was summarised in the annual series Gold Fields Statistics (1860–1863), Mineral Statistics of Victoria (1864–1888) and thereafter the Annual Report of the Secretary for Mines and the Statistical Register of Victoria. These reports included tables of ‘Machinery on the Gold Fields’ for alluvial and quartz mining, with breakdowns by each of the seven Mining Districts and the divisions and subdivisions they contained. The final year for which details of ‘Machinery on the Gold Fields’ was published was 1891. In many cases, however, miners, mining companies and mining surveyors neglected to supply information to the department. These missing data reduce the reported quantities of machinery, and thus alluvium processed, by an unknown but significant factor. Alluvial mining production was also poorly recorded during the depression years of the 1890s and thus we limit our formal analysis to the period ending in 1891.

We have developed a set of scale factors to calculate the amount of washdirt processed by miners using different alluvial mining techniques, including puddlers, compound cradles, ground and box sluicing, and hydraulic sluicing. These are based on
descriptions in contemporary historical sources, including the 1859 Royal Commission into the Sludge Question. Robert Brough Smyth’s Gold Fields and Mineral Districts of Victoria (1869 [1980]), quarterly Reports of the Mining Surveyors and Registrars and the report of the Sludge Board (1887). Historical estimates of washdirt volumes were recorded as cubic yards, which we convert into cubic metres by a multiple of 0.765.

In 1859 the Royal Commission into the Sludge Question reported that puddlers processed 10 cubic yards per day, and each puddler on average worked 200 days during the year, or about eight months (Royal Commission, 1859, p.20). This limit was determined by available water supplies. References to steam and horse-powered puddlers have been aggregated. We calculate 10 cubic yards per day for each puddler, or 2000 cubic yards per mill per year.

Compound cradles were first recorded on the goldfields in 1866 and were used most commonly in the Maryborough, Castlemaine and Ararat Mining Districts. We estimate that each device was used to process a minimum of 10 cubic yards per day, with an average of 200 days worked during the year, thus giving a total of 2000 cubic yards per compound cradle per year (Smyth, 1980, pp.618–619).

In ground and box sluicing, the volume of material a miner could process varied according to the amount of water available and the nature of the washdirt itself. While up to 150 cubic yards in a short winter’s day at Yackandandah was ‘not uncommon’, for example, a more typical amount was for two or three men to wash 20–50 cubic yards each per day in a ground sluice (Smyth, 1980, pp.131–132). In some cases, miners joined multiple sluice boxes into lengthy tail races to process larger volumes of material. We have thus applied a conservative multiplier of 5 cubic yards per sluice box per day, operating for 200 days per year, meaning each sluice could process at least 1000 cubic yards per year. This is a conservative estimate and in many cases much greater volumes were washed (Smyth, 1980, pp.126–131).

Hydraulic sluicing was generally confined to the Beechworth Mining District in north-eastern Victoria, with most operations capable of mobilising thousands of cubic yards of alluvium every week. We use a multiplier of 500 cubic yards per day for each sluicing plant, operating for 200 days per year, or 100,000 cubic yards per annum.

Historical sources, including Mineral Statistics of Victoria, also provide estimates of the annual tonnage of quartz crushed in stamp batteries for each Mining District. These are summarised in Table 1. An alternative but parallel source of historical data is the ‘VicProd’ database, produced by Geoscience Victoria (Department of Primary Industries c.2002). VicProd captures historical data on various aspects of gold production, including quartz tailings, for the period 1864–1960, based on published historical reports. Metadata from Geoscience Victoria indicate, however, that data capture for our study period, especially Bendigo/Sandhurst, was

<table>
<thead>
<tr>
<th>Mine</th>
<th>Puddlers</th>
<th>Compound cradle</th>
<th>Sluice box</th>
<th>Hydraulic sluice</th>
<th>Quartz tailings</th>
<th>Percentage of statewide yield</th>
<th>Totals (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballarat</td>
<td>16,850,000</td>
<td>179,000</td>
<td>21,027,000</td>
<td>994,000</td>
<td>7,099,000</td>
<td>9.4%</td>
<td>46,149,000</td>
</tr>
<tr>
<td>Beechworth</td>
<td>3,184,000</td>
<td>78,000</td>
<td>247,327,000</td>
<td>37,485,000</td>
<td>1,442,000</td>
<td>58.8%</td>
<td>289,536,000</td>
</tr>
<tr>
<td>Sandhurst</td>
<td>20,224,000</td>
<td>112,000</td>
<td>3,311,000</td>
<td>1,989,000</td>
<td>5,954,000</td>
<td>6.4%</td>
<td>31,590,000</td>
</tr>
<tr>
<td>Maryborough</td>
<td>25,696,000</td>
<td>3,023,000</td>
<td>2,354,000</td>
<td>1,300,000</td>
<td>1,224,000</td>
<td>6.8%</td>
<td>33,597,000</td>
</tr>
<tr>
<td>Castlemaine</td>
<td>18,245,000</td>
<td>1,567,000</td>
<td>10,575,000</td>
<td>16,830,000</td>
<td>2,456,000</td>
<td>10%</td>
<td>49,673,000</td>
</tr>
<tr>
<td>Ararat</td>
<td>3,791,000</td>
<td>828,000</td>
<td>2,773,000</td>
<td>0</td>
<td>1,298,000</td>
<td>1.8%</td>
<td>8,090,000</td>
</tr>
<tr>
<td>Gippsland</td>
<td>234,000</td>
<td>28,000</td>
<td>26,671,000</td>
<td>5,661,000</td>
<td>673,000</td>
<td>6.3%</td>
<td>33,267,000</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>88,224,000</strong></td>
<td><strong>5,815,000</strong></td>
<td><strong>314,038,000</strong></td>
<td><strong>64,259,000</strong></td>
<td><strong>20,146,000</strong></td>
<td><strong>100%</strong></td>
<td><strong>492,482,000</strong></td>
</tr>
</tbody>
</table>

Fig. 6. Hydraulic sluicing nozzle c.1880–1884 (source: State Library of Victoria).
very uneven and thus underestimates volumes of treated quartz by, in some cases, an order of magnitude or more. For this reason we use MSV historical data instead, as more complete, consistent and reliable, for our analysis of quartz volumes.

6. Results

The total volume of alluvial washdirt and quartz tailings mobilised by Victorian gold miners in the period 1859–1891 is estimated to be 644 million cubic yards or almost half a billion cubic metres (Table 1). Specific volumes for each of the seven Mining Districts are provided in Table 1. We can also extrapolate volumes of alluvial sediment mobilised during the 1890s on the basis of similar industrial activity in the 1880s, which gives an additional 145 million m³ (e.g. Howitt, 1895, pp.12–13). Simple panning and cradling in the first few years of the gold rush likely produced another 20 million m³, along with puddling and ground and box sluicing that was poorly recorded for this period (Smyth, 1980, pp.79–80). A probable historical range for the period 1851 to 1900 is thus somewhat greater than 850 million cubic yards (650 million m³) of mobilised alluvium and quartz ore. It is also worth noting that for the period 1900–1915, mining by hydraulic dredges across Victoria processed a total of 174 million m³ of washdirt, most of which was returned directly to the streams (Secretary for Mines, 1915, p.36).

Hydraulic sluicing with high-pressure nozzles represents a relatively small proportion of alluvium from the period 1859 to 1891, around 13% of the total (Fig. 7). Puddlers represent a slightly larger proportion from the same period, at 17.9%, with compound cradles another 1.2%. Ground sluicing and sluice boxes account for the majority of alluvium mobilised, at 63.8%. The 20 million m³ of quartz tailings produced by ore crushing was about 4%, a relatively small proportion, of all the material mobilised by the gold mining industry in this period (Fig. 8).

6.1. Sludge production by catchment

The sludge volumes above are produced by mining district, but in this section we estimate volumes of historical mining sediment for Victoria’s major river catchments to put the sediment supply in perspective with other mining regions (Table 2; Fig. 9). We base this analysis on the ‘VicMine’ database created by Geoscience Victoria which captures historical mine locations, production volumes and spatial data for over 16,000 gold mines (Department of Primary Industries c.2002). While the production data are far from complete, these data provide a solid basis for spatial analysis. Based on the total volume of alluvium and quartz ore mobilised for
Table 2
Volumes of alluvium and quartz tailings mobilised (converted into m$^3$) between 1859 and 1891 per major river catchment (rounded to nearest 1000) and compared with background pre-European sediment yields.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Ore m$^3$</th>
<th>a Ore Kt.a$^{-1}$</th>
<th>b Background sediment yield (Kt.a$^{-1}$)</th>
<th>Ratio sludge to background annual yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoca River</td>
<td>7,783,000</td>
<td>389</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>Avon River-Tyrell Lake</td>
<td>897,000</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barwon River-Lake Corangamite</td>
<td>38,132,000</td>
<td>1907</td>
<td>3</td>
<td>636</td>
</tr>
<tr>
<td>Broken River</td>
<td>4,374,000</td>
<td>219</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Campaspe River</td>
<td>13,503,000</td>
<td>675</td>
<td>19.3</td>
<td>35</td>
</tr>
<tr>
<td>East Gippsland</td>
<td>1,834,000</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glenelg River</td>
<td>265,000</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goulburn River</td>
<td>41,932,000</td>
<td>2097</td>
<td>88</td>
<td>24</td>
</tr>
<tr>
<td>Hopkins River</td>
<td>6,081,000</td>
<td>304</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiewa River</td>
<td>21,598,000</td>
<td>1080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loddon River</td>
<td>80,142,000</td>
<td>4007</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Mitchell-Thomson Rivers</td>
<td>28,978,000</td>
<td>1449</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Murray Riverina</td>
<td>47,643,000</td>
<td>2392</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owens River</td>
<td>90,081,000</td>
<td>4504</td>
<td>17.5</td>
<td>257</td>
</tr>
<tr>
<td>Snowy River</td>
<td>2,718,000</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Murray River</td>
<td>96,434,000</td>
<td>4822</td>
<td>96</td>
<td>50</td>
</tr>
<tr>
<td>Werribee River</td>
<td>2,712,000</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wimmera River</td>
<td>5,517,000</td>
<td>276</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yarra River</td>
<td>1,658,000</td>
<td>83</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>492,482,000</td>
<td>83</td>
<td></td>
<td>AVE. 142</td>
</tr>
</tbody>
</table>

Notes: (a) value converts m$^3$ to tonnes by multiplying by density of 1.6; (b) NLWRA (2001) estimated background sediment yield for a selection of Victorian catchments using the Sednet model.

each of the seven Mining Districts, we divide these by the count of mines for each district to establish proxy volumes for each mined area and approximate volumes per mine. We then use spatial data provided by the Australian Hydrological Geospatial Fabric (AHGF) river regions to estimate volumes of mining sediment per catchment.

These data reveal that the largest volumes of mining-related sediment in 19th-century Victoria flowed into the Ovens River, Goulburn River, Loddon River, Barwon River tributaries and Upper Murray waterways including the Mitta Mitta. This distribution is consistent with our understanding of the production of major sources of historical mining sediment. Sludge affected around three-quarters of river catchments in Victoria (Fig. 10), and the only major river catchments not affected by sludge were the Glenelg and the Wimmera in the west, the Broken River in the north, and most streams east of the Tambo in Gippsland in the east of the state. Comparing the sediment released by sludge with estimates of pre-European sediment yield (Table 2) suggests that the volume of sludge released into rivers exceeded the background rate by an
average of 140 times, with the Yarra being the lowest, with four times, and the Barwon being the highest, exceeding the background rates by over 600 times. A later paper will compare

the sludge yield with other anthropogenic sources of sediment such as gullying.

The VicMine data suggest that most historical gold mining (and sludge production) took place in the upper reaches of each of the 19 mined catchments. Mined sub-catchments had an average size of 73 km$^2$ and were most common on 2nd order streams. This means that mines were on average 12 km from the river headwater and 714 km from the river outlet. Considering just the major trunk streams in the state, there are about 11,900 km of trunk streams, of which about 2800 (23%) were recognised to have been affected by sludge in the sludge enquiry of 1887 (Fig. 10). Thus one quarter of the length of major streams in the state have been affected by sludge.

6.2. Character of the sediment released

Each branch of gold mining in Victoria produced sludge with distinct characteristics, based on the kinds of deposits being worked and the treatment processes used (Sludge Board, 1887, pp. vii–xiii; Table 3). Puddlers were favoured for working stiff clay soils and produced sludge high in clay and silt that remained in suspension to be carried long distances downstream. When retained in settling ponds, sludge from puddlers formed a hard crust on top but remained liquid underneath. After being deposited on flood plains it formed an impermeable layer that reformed in the first rain after ploughing (Peterson, 1996, pp.44–45). Stamp batteries reduced quartz and gravels to a fine sand that settled out in treatment ponds, but the sand could be carried long distances in floodwaters and when settling dams were not used. The mesh sizes used in stamp batteries suggest that quartz tailing sands generally ranged between 1 mm and 2 mm across (e.g. MSV, 1870, p.43). Ground sluicing and hydraulic sluicing produced a combination of large cobbles, small gravels, and fine sands and silts. The cobbles were generally forked out of the tail races and stacked on site while the gravels, sands and silts were flushed downstream. Waste material from dredging was also produced in a range of sizes, all of which was released in the waste water. From 1904, however, dredges were required to work in self-contained ponds, with the tailings returned to the work site (Dredging and Sluicing Inquiry Board, 1914, p.12).

7. Contemporary descriptions of the fate of mining sediment

Mining waste in waterways was a major problem for farmers and communities downstream from mining areas for at least half a century. The physical impacts of the sludge are fully described in Lawrence and Davies (2014), which we paraphrase here. The first complaints about sludge emerged within a few years of the start of the gold rush. The Bendigo Advertiser alone carried over 4000 sludge-related stories between 1855 and 1901, demonstrating the extent of contemporary concern. Sediment-choked waterways raised the level of creek beds and covered adjacent land after floods. The creeks and waterholes became unsuitable for watering stock, for human consumption, and for watering gardens and orchards. Severe damage from sludge was reported up to 64 kilometres below the mining town of Ballarat. Laanecoorie Reservoir, built in 1891 downstream of major goldfields on the Loddon River, had already accumulated 3 m of silt in its basin by 1908. Although multiple public enquiries, beginning as early as 1856, investigated the ‘sludge problem’ it was accepted as the inevitable consequence of gold mining and the price of progress and development (Figs. 11 and 12). Initially the response was to divert sludge away from mining centres via sludge channels and drains, and it was only after 1900 that serious attempts were made to control and retain sludge at the point of generation.

Fig. 10. Victorian rivers affected by mining sludge in 1886, reconstructed from evidence in Sludge Board (1887).
8. Discussion

Most catchments in Victoria, and many major streams, have been affected by the 0.65 billion cubic metres of sludge produced by historical gold mining. In the following discussion we compare the scale of effect in Victoria with that experienced elsewhere, then explain the spatial and temporal patterns of sludge, and finally comment on its present effects.

8.1. Comparison with background sediment supply

Several studies have estimated the effect of European land-uses changes on erosion rates and sediment supply in Victoria. None of these studies, however, have considered the effect of mining sediments.

8.2. Comparison with other mining areas

The volumes of sediment delivered to streams by gold mining in Victoria in the 19th century are comparable with yields from contemporary mining regions in similar mining booms elsewhere, including England, California, New Zealand and Tasmania. In making these comparisons we need to distinguish between production and delivery of sediment, and the storage of that sediment. Our analysis here is about sediment delivered to waterways from mines and does not consider storage (the subject of a later paper). Dennis and others (2009), for example, have determined that approximately 550,000 tonnes of Pb were extracted from mines in the Swale catchment in the UK during the 18th and 19th centuries, with up to 155,000 tonnes of Pb-contaminated sediment remaining in storage in the catchment (Dennis 2005, p.267; Dennis et al., 2009, p.463). Similar volumes of arsenic contaminated sediments (85,000 m$^3$) were delivered to the Shag River in New Zealand (Black et al., 2004).

Gold mining in 19th-century California was dominated by hydraulic sluicing, with about 400 hydraulic mines operating throughout the Sierra Nevada by 1880 (Isenberg, 2005, p.256). The greatest volumes of excavated sediment were on the Yuba, American, Feather and Bear Rivers which drain into the Sacramento River, a region that encompassed the principal hydraulic mines in California (Greenland, 2001, p.14). Several attempts have been made to calculate the volumes of material mobilised by hydraulic sluicing. Lindgren (1911, p.20-21), for example, determined that 990 million m$^3$ of material came from hydraulic mining on the four main rivers, while Gilbert, 1917, p.43; Rohe, 1986) estimated that 1.27 billion m$^3$ of debris had been washed into San Francisco Bay. More recently, Wohl estimates that 990 million m$^3$ of material accumulated in the four main mining waterways (Wohl, 2004, pp.81–83).

Attempts have also been made to calculate sediment budgets for historical mining operations on several rivers in the island of Tasmania, Australia. Tin mining on the Ringarooma River in northeast Tasmania, for example, began in 1875 using hydraulic methods and, with the introduction of dredging, continued until c.1980. Knighton (1989, p.95) used historical records to estimate that numerous mines delivered 40 million m$^3$ of tailings to the

<table>
<thead>
<tr>
<th>Processing type</th>
<th>Location</th>
<th>Date range</th>
<th>Sediments</th>
<th>Fate of sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puddlers</td>
<td>Ballarat, Bendigo, Creswick, Maryborough, Castlemaine</td>
<td>1850s–1870s</td>
<td>clay, silt</td>
<td>Suspended load, overbank deposition</td>
</tr>
<tr>
<td>Stamp batteries</td>
<td>Bendigo, Ballarat, Castlemaine</td>
<td>1860s–1900s</td>
<td>silt, sand</td>
<td>Suspended load, channel bedload, overbank deposition, local storage</td>
</tr>
<tr>
<td>Sluicing and dredging</td>
<td>North-east Victoria</td>
<td>1860s–1900s</td>
<td>clay, silt, sand, gravel</td>
<td>Suspended load, channel bedload, overbank deposition, local storage</td>
</tr>
</tbody>
</table>

Fig. 11. Sludge choking Spring Creek near Daylesford in central Victoria, c.1858 (source: State Library Victoria H84.167/31).
Ringrooma. On the west coast, the Mount Lyell Copper Mine at Queenstown operated for almost a century from 1896 (Blainey, 1993), and Locher (1996) estimated that 97 million tonnes of mining sediment were discharged down the Queen and King Rivers in that period, with around 10% of the total held in river storages and the remainder stored in the delta at the river mouth.

When summarised in terms of sediment yield per unit catchment area (Table 4), the average sludge production from Victorian catchments is not large compared to the examples described above. All these examples, however, are from production in a small number of river basins. By contrast, on the Victorian goldfields a large number of smaller mining operations were spread out over multiple catchments across much of the state, resulting in more widespread environmental impact to a quarter of the major streams in the state.

8.3. Explaining the distribution of sediment

The spatial distribution of alluvium is structured by the diverse nature of mineralogical deposits across Victoria, by rainfall and by the various technologies used by miners to extract gold. The Beechworth Mining District, for example, accounts for 58.8% of all the alluvium mobilised in Victoria during our study period (Table 1). The bulk of this (247 million m$^3$) derives from ground sluicing and box sluicing, which in turn relates to the nature of gold deposits in the region and its relatively high rainfall (Fig. 8). Most gold in the area was in the form of very fine grains distributed through placer deposits. Recovering the gold required abundant supplies of water to sluice large areas of auriferous washdirt.

Some of the distribution of mining sediments can be explained by the pattern of rainfall (Fig. 8). Wetter areas generated both more sludge, through more hydraulic mining, and also washed more sludge into streams. Hence, the greatest volume of mining sediment was generated in the Ovens, Kiewa and Mitta Mitta river basins in the Beechworth region (Fig. 9). This area of north-east Victoria receives almost 1000 mm of rain on average per annum, which meant that surface and ground water for sluicing was available for much of the year (Davies et al., 2016). Rainfall generally declines to the west in Victoria to around 750 mm per year along the Great Dividing Range in central Victoria, and is even lower further to the north of the divide in the mining centres of Bendigo and Maryborough, with average rainfall of around 550 mm per year (Bureau of Meteorology).

Five other Mining Districts (Ballarat, Sandhurst/Bendigo, Maryborough, Castlemaine and Gippsland) each accounted for between 6% and 10% of the total sediment production, which reflects the diverse nature of the mining geology and technologies applied in each region, along with the lower volumes of water available for sluicing. Large volumes of quartz debris from the Ballarat and Sandhurst/Bendigo districts reflects the special place of this region as the largest underground auriferous quartz province in the world at the time (Phillips et al., 2003, p.380). Puddling of stiff gold-bearing clays was most common in the Castlemaine, Maryborough, Ballarat and Sandhurst/Bendigo districts and less frequent in the eastern part of Victoria including the Beechworth and Gippsland districts. The lower overall proportion of material at Ararat (1.8%) reflects the smaller scale of mining and poorer quality of gold deposits in this westerly region.

8.4. Explaining the timing of sludge delivery

The timing of sludge releases to streams is controlled by economic factors and by the availability of water. The total annual volume of alluvium released by gold mining in Victoria rose to a peak in 1867 at 19.4 million m$^3$ (Fig. 13a). Thereafter, there was a progressive decline in washdirt volumes, down to 10.9 million m$^3$ by 1891. This decline was closely associated with reductions in both the population of alluvial miners and alluvial gold yields (Fig. 13b and c). The broad pattern was that declining numbers of miners were using, overall, less water and recovering smaller amounts of gold.

The peak in washdirt volumes in 1867 can be explained by several factors. The 1865–66 drought, which was the worst known by Europeans in Victoria to that time, had eased and stream flows were improving (Keating, 1992, pp.33–39). This provided more water for sluicing and resulted in more washdirt being processed. Good rains in the early 1870s meant totals remained high. This period also corresponds to the effective introduction of water-right licences under the 1865 Mining Statute. These licences, issued for up to 15 years, provided greater certainty for miners investing thousands of pounds in the construction of races and other water infrastructure for mining (Davies and Lawrence, 2014, p.180). More
water led to more gold mining (both alluvial and quartz) and more mobilised sediment. Improved recording and reporting of alluvial mining machinery by district mining surveyors in this period (late 1860s–early 1870s) also appears to have been a factor in the increase.

A second, lesser peak occurred in 1879, at 18 million m³. This peak may relate to the ending, transfer, and renewal, of 10 and 15 year water-right licences issued in the 1860s, with alluvial miners keen to maximise their water entitlements (Board, 1879–80, pp.37–42). A return to dry conditions in the early 1880s, however, contributed to the overall decline in washdirt volumes thereafter (Keating, 1992, p.51).

8.5. The relationship between gold and sludge production

There are interesting relationships between the number of miners employed on the gold fields and the production of gold and production of sludge. Alluvial gold production peaked in Victoria at the very beginning of the gold rush in 1852, when around 4 million troy ounces (approximately 128 t) were recovered Gold Fields' Commission of Enquiry, 1854–5, pp.iii–lii; Serle, 1968, pp.390–391). This was when surface gold was at its easiest to find. Official figures may even understate the total, however, as many miners left the colony with gold dust and nuggets in their personal possession. Alluvial gold yields remained above 1 million ounces per year until 1865 but there was a steady decline in yields over the following decades, until by the end of our study period in 1891, annual alluvial gold yields had declined to less than 200,000 ounces (Government Statist, 1892, p.70). Fig. 13a and b reveal that the recovery of alluvial gold declined over the years as volumes of alluvium were yielding less gold. It is interesting to note that this period of highest gold production coincided with comparatively modest volumes of mobilised sediment.

A similar pattern is evident in relation to the population of alluvial miners. Numbers were at their highest in 1858, when 147,358 adult males were reported on the goldfields, the great majority of whom were engaged in alluvial mining (Serle, 1968, p.388; Smyth, 1980, p.511). Totals declined over the years, however, as many took up employment elsewhere or left Victoria altogether. By the end of our study period in 1891, the number of alluvial miners had shrunk to 10,520, including 2590 Chinese (Government Statist, 1892[Part II]:28). Fig. 13c indicates that the amount of alluvial gold per miner varied on average between 12 and 22 ounces per year, but declining numbers of active miners reduced overall yields.

9. The present impact of sludge on victorian rivers

Victorian waterways have been altered by more than 160 years of European-settler activity but changes are conventionally attributed to agriculture and land clearance. The legacy impacts of gold mining on waterways in Victoria has not been recognised and remains under-researched, unlike other mining regions where impacts have been better-documented (e.g. Alpers et al., 2005; Morse, 2003; Rohe, 1983). This study is part of a larger investigation that is reconstructing the impact of historical gold mining on past and present rivers. Subsequent articles will therefore discuss the legacy effects of historical sludge loads on modern rivers, so we make just a few observations here. The most remarkable aspect of the sludge story in Victorian rivers is the extent to which these historically devastating impacts are now all but forgotten. The major visible legacy of the sludge are sheets of buff-coloured fine sands and silts that blanket river floodplains (Fig. 14). These sheets can be up to 2 m thick and are most prominent on the Loddon, Ovens and Campaspe Rivers. It is often difficult to distinguish sediment from mining, from sediment from gullying and other accelerated erosion processes that occurred at similar times in these catchments. Coarser sediment from mining still remains in many channels, forming ‘sand slugs’. These coarse pulses of sediment have been implicated in triggering river avulsions. A secondary consequence of gold mining was the wholesale clearing of forest from catchments. Although many of these forests have regrown, it is likely that this clearing led to accelerated catchment erosion. Neither mining sludge nor catchment clearing have been factored into modelled estimates of post-settlement sediment loads (e.g. National Land and Water Resources Audit, 2001; Prosser et al., 2001).

Sediments derived from historical mining can also be contaminated with mercury. Our preliminary research estimates that a minimum of 119 t of mercury were discharged from Victorian quartz mines in the 19th century, with minor additional amounts from alluvial sluicing activity (Davies et al., 2015). Several 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. Our current research is examining mercury levels in mining legacy sediments.

Sediment mobilisation, measured as turbidity or total suspended solids, is seen as a major threat to many inland waterways in Australia and elsewhere (e.g. National Land and Water Resources Audit, 2011). The current paradigm is that, particularly in Victoria, most of the sediment is derived from gully and riverbank erosion, with concomitant management activities focused on minimising these sources (e.g. Moran et al., 2005). We contend, however, that without accounting for large historical loads of anthropogenic alluvium (Macklin et al., 2014) generated and redistributed through historical mining activities it will be difficult to mitigate the threat of increased sediment loads to lowland rivers.

One important implication is in the areas of conservation ecology and environmental restoration, where conservation relies on the accurate identification of conditions prior to disturbance. The status of a target species (in conservation ecology) or environmental condition (in restoration ecology) is assessed against a reference condition (baseline). The reference condition, however, may be substantially different than an even earlier state of the system. Pauly (1995) asserted that in fisheries conservation, scientists used the stock size of a target species at the beginning of

Table 4

<table>
<thead>
<tr>
<th>Area of catchment affected (km²)</th>
<th>Delivery (m³ x 10⁶)</th>
<th>Sludge m² per km² of catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ringarooma R. (Tas. Aust.)</td>
<td>1190</td>
<td>40</td>
</tr>
<tr>
<td>Queen R. (Tas. Aust.)</td>
<td>80</td>
<td>97</td>
</tr>
<tr>
<td>R. Swale (UK)</td>
<td>80</td>
<td>0.15</td>
</tr>
<tr>
<td>Sacramento R. (USA)</td>
<td>18,000</td>
<td>990</td>
</tr>
<tr>
<td>Shag R. (NZ)</td>
<td>550</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Victoria (all affected rivers)/average</strong></td>
<td><strong>205,000</strong></td>
<td><strong>644</strong></td>
</tr>
<tr>
<td><strong>Ovens R. (max.)</strong></td>
<td>6360</td>
<td>90</td>
</tr>
</tbody>
</table>
their career as the baseline for that species; and used that baseline to determine the decline in that species. When the next generation of scientists start, their baseline is lower than their predecessors. Shifting baselines confound targeting setting. As Humphries and Winemiller (2008) note ‘[t]he passage of time and lack of data about conditions before these disturbances [mining in this instance] commenced obscures our perception of historic conditions, making it difficult to establish accurate restoration targets.’ A clear example of this is the restoration of mid-Atlantic US streams (Walter and Merrits, 2008). It was originally believed that, prior to European settlement, gravel bed streams had a meandering form and were bordered by floodplains of fine silt. It was later shown, however, that these landforms were actually created by sedimentation behind 17th to 19th-century mill dams. Prior to European settlement the streams were actually small anabranching channels in large vegetated wetlands. Multi-billion-dollar restoration activities were focussing on the wrong target conditions (Walter and Merrits, 2008).

Fine-grained analysis of historical records provides enough information to reconstruct the first regional-scale assessment of

Fig. 13. Fig. 13a plots the annual volume of alluvium production (m$^3$), the annual alluvial gold yield and the population of alluvial miners from 1859 to 1891. Fig. 13b shows the increase through time in the volume of alluvium per ounce of gold recovered, and Fig. 13c shows the annual change in alluvial gold yield per person.
the volumes and distribution of sediment (sludge) from historical gold mining in Victoria. The mining methods used throughout the Victorian goldfields during the 19th century were very effective at delivering sediment directly into streams. Our study reveals that, unlike more spatially concentrated mining in other parts of the world at the time, widespread mining activity in Victoria delivered sediment into the headwaters of several large catchments. The input of sediment was almost simultaneous across the state, during a relatively short period of time. The nature of the low gradient and wide floodplains in most large streams in Victoria means that conditions were optimal for fine grain deposition from these upstream sources.

Alluvial gold mining was widespread throughout eastern Australia in the 19th century. Other mining areas in the states of New South Wales and Queensland could also be expected to have had high historical sediment yields from this source. These yields have yet to be recognised in sediment budgets from anthropogenic sources. In addition, gold miners decimated forests in the vicinity of the goldfields for fuel and other purposes (Frost, 2013). This deforestation would also have increased the sediment yield from hillslopes during this time. Many of these areas have since reforested, disguising the extent and severity of disturbance.

Contemporary descriptions reveal that gold mining sediment in the form of sludge transformed entire landscapes, degraded one-quarter of Victoria’s major rivers and damaged large areas of farmland across the colony. Debate and discussion on the problem filled newspapers for more than 50 years and generated numerous parliamentary inquiries. One quarter of the length of major streams in the state have been affected by sludge. The physical impact of this mining, however, is now largely forgotten and unrecognised, as is the degree to which rivers might have recovered and readjusted from significant increases, and later decreases, in sediment supply. The long-term impacts of historical gold mining on streams still needs to be determined.

Using historical records we estimate the volume of sediment delivered to Victorian streams by alluvial and quartz gold mining was at least 650 million m³ between 1851 and 1900. This estimate excludes several major mining methods and does not take into account the large volumes of material mobilised by bucket dredging and hydraulic sluice mining in the 20th century. Historical gold mining sediments have not been included in estimates of anthropogenic sediment used for national catchment management, and this should be done. Much of this mined sediment is now stored in floodplains and as slugs of coarse sediment in stream beds. Understanding these historical sources allows us to explore how our streams respond, and potentially, recover from human disturbance.

Acknowledgement

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