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REPORT

Groundwater extraction on the goldfields of Victoria, Australia

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Abstract
Groundwater supply systems constructed by gold miners in Victoria during the nineteenth century were highly significant in the historical development of water law and water licensing in Australia. Alluvial gold mining required large volumes of water to separate gold from washdirt, but surface flows often failed in seasonally dry conditions. Drought in the mid-1860s prompted miners on the Ovens goldfield in north-east Victoria to exploit groundwater to increase supplies, despite limited scientific understanding of this resource at the time. Analysis of historical plans held by Public Records Office Victoria has revealed numerous 'source of supply' tunnels dug by miners to extract groundwater in the area. By the early 1880s, miners were using up to 31 ML of groundwater per day, with much of the water transferred between creek and river catchments. These activities represent an early, large-scale and significant intervention in the hydrogeological environment, several decades prior to economic development of the Great Artesian Basin in northern Australia. Understanding the nature and scale of groundwater use in this period provides vital social and historical context for modern debates about groundwater modelling, extraction and management.

Keywords Australia · Groundwater development · Mining · Water supply · History of hydrogeology

Introduction

Exploitation of groundwater in Australia has played a vital role in supporting irrigated agriculture and domestic water supply since the end of the nineteenth century. For many years prior to this, however, gold miners were extracting large volumes of groundwater for washing auriferous alluvium. In the early 1860s, miners on the Ovens goldfield in north-east Victoria began tapping large volumes of groundwater and diverting it between creek and river catchments to their sluicing claims. This capture and transfer of groundwater was part of the wider development of water sources in colonial Victoria during the gold rush for mining, industrial, commercial and domestic uses. While drilling of the Great Artesian Basin from the 1880s is generally cited as the beginning of large-scale exploitation of groundwater in Australia (Blackburn 1999; Habermehl 2020; Lloyd 1988; Muir 2014; Murray 2018; O'Gorman 2012; Robertson 2020), extraction of groundwater by gold miners from the 1860s represents an earlier, significant and largely unknown intervention in the hydrogeological environment.

International research on the history of groundwater has focused on a range of issues, including the widespread use of subterranean galleries (*qanats* in Iran) to distribute water in arid environments (Angelakis et al. 2016; Charbonnier and

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Hopper 2018; Khaneiki 2019; Martínez-Medina et al. 2018), and the spiritual values of springs to ancient societies (Håland 2009; Strang 2004). The development of groundwater supplies for irrigation (Berry 2009; Wolfe 2017) and histories of urban groundwater use have also been widely documented (Blomquist 1992; Foster et al. 2018; Winiwarter et al. 2016), along with the emerging environmental consequences of over-extraction for urban land subsidence (Goh 2019; Shi et al. 2008; Yin et al. 2016). This report examines the early industrial development of groundwater resources on Victoria's goldfields, with a focus on extraction and interbasin transfers on the Ovens goldfield at Beechworth and Stanley during the nineteenth century (Fig. 1). This is part of broader research into the environmental effects of historical gold mining on Victoria's waterways, including sedimentation, changes to stream morphology and chemical contamination of floodplain deposits (Davies et al. 2018, 2020; Lawrence and Davies 2019; Lawrence et al. 2016; Rutherfurd et al. 2020).

Groundwater was valuable to miners because it extended surface-water supplies and improved reliability, especially in dry periods. Groundwater extraction and diversion represented, in effect, another form of mining. Alluvial miners on the Ovens goldfield developed extensive networks of tunnels and channels (known as races) to transfer groundwater and surface water to their claims. Many of these systems are recorded in a series of highly detailed, large-scale plans of water-right licence applications held by the Public Records Office Victoria (Fig. 2). Twenty-six application plans include numerous 'source of supply' tunnels excavated to extract groundwater. These tunnels often extended for hundreds of metres under hillsides. Daily water extraction volumes recorded on each plan are used here to calculate total groundwater transfers within and between the catchments of Spring Creek, Three Mile Creek, Burgoigee Creek and Upper Nine Mile Creek. Miners in the area began capturing groundwater in the mid-1860s and by the early 1880s they were using more than 30 ML of groundwater per day. They continued in this way for several decades thereafter. Alluvial mining in the district represents the earliest evidence for industrial-scale groundwater extraction and interbasin transfer in colonial Australia.

Groundwater in colonial Victoria

Springs and soaks were of great practical and spiritual value to Indigenous people throughout Australia for millennia (Jackson and Barber 2016). With the arrival of Europeans, springs were routinely noted and mapped by early explorers (e.g. Lhotsky 1979, pp. 20–25; Mitchell 1839) and well-sinking provided stock and domestic water for inland pastoral

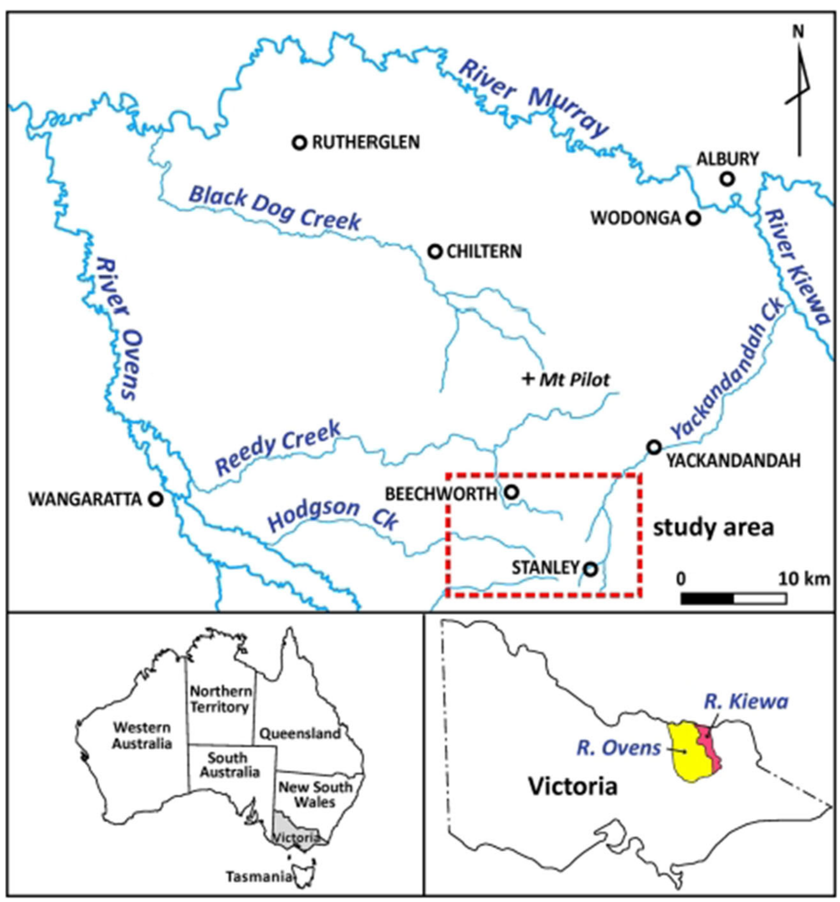

Fig. 1 Location of study area in north-east Victoria, Australia

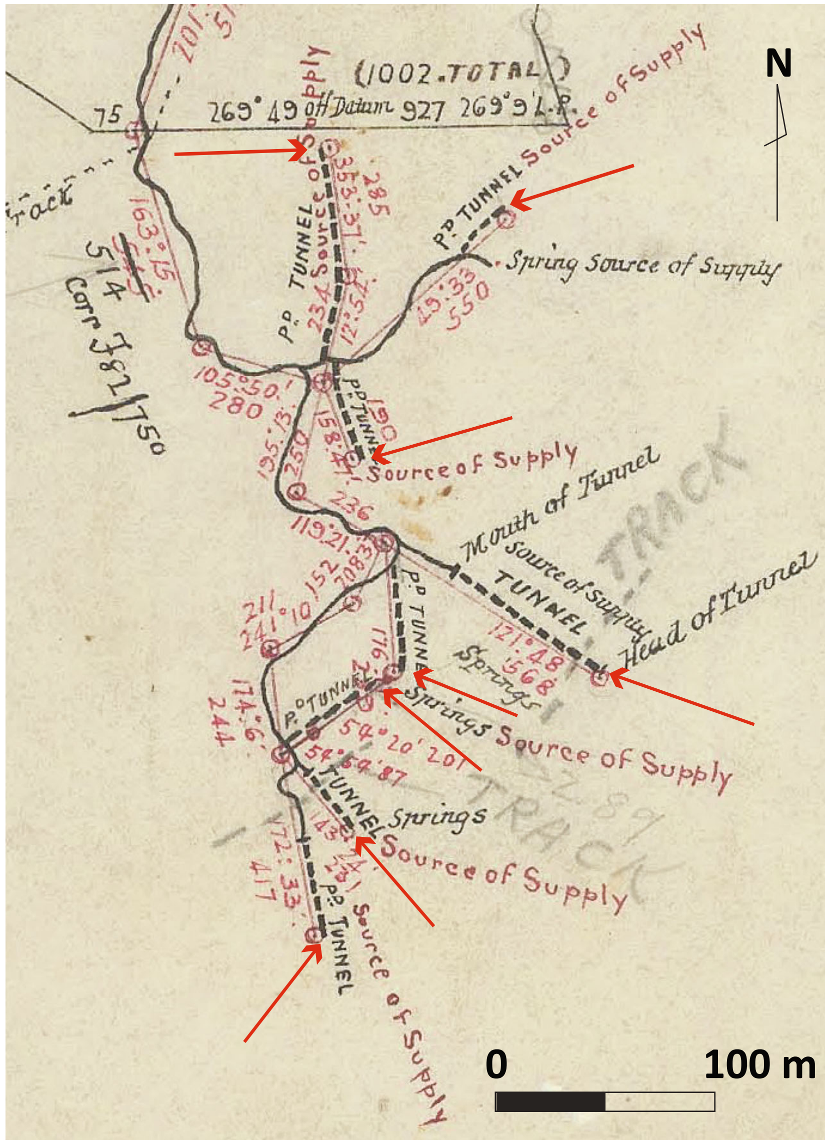

Fig. 2 'Source of supply' groundwater tunnels highlighted with red arrows on plan of application for water-right licence by Friedrich Kassebaum in 1881 (Kassebaum 1881). Tunnels were surveyed by local mining surveyors using chain and compass methods, with bearings recorded from magnetic north and distances measured in links of 7.92 in. (0.2 m). Surveyors also recorded the head and mouth (opening) of each tunnel on plans

stations (Lloyd 1988, pp. 60–61). Despite this early awareness, however, scientific knowledge of groundwater in Victoria during the nineteenth century was limited, even though recurring droughts highlighted a growing need for reliable water supplies. Springs of mineral water were identified around Daylesford in the 1840s, and these were analysed for their medicinal properties in 1855 (Wishart et al. 2010). Artesian water was also tapped near a Melbourne beach in 1856 by engineer John Benger, but the wider use of groundwater in Victoria focussed mainly on shallow wells for domestic supply (Lloyd 1988, p. 105). Director of the Geological Survey, Alfred Selwyn, was convinced that the purity and volume of surface water in Victoria would always be greater than that from groundwater springs (Selwyn 1857).

British engineers made rapid advances in supplying English towns and cities with groundwater during the nineteenth century, but there remained a widespread view in Victoria that artesian supplies in the colony were very limited. Civil engineer Frederick Acheson argued in a prize-winning essay in 1860 that despite widespread and reliable rainfall across much of the colony, 'the impervious nature of the surface of Victoria' meant that rain rapidly drained from the surface and passed rapidly to the sea, depriving rivers and springs of consistent flows (Acheson 1861). Despite official scepticism, farmers began using steel windmills in the 1880s to pump groundwater (Baker 2017), around the same time the Victorian government began a program of diamond drill boring to discover mineral deposits and groundwater supplies, recording of which continued until 1965 (Dahlhaus et al. 2016; Gill et al. 2017; Langtree 1885). Artesian wells drilled in the Wimmera in western Victoria during the 1880s encouraged the expansion of pastoralism in the district (Royal Commission 1885, p. iv).

There were at least 15 references to 'spring' in the naming of creeks, gullies, hills and leads on Victoria's early goldfields, indicating the extent to which miners recognised that waterways flowed from groundwater sources (Flett 1970). Environmental historian Erica Nathan has described a typical goldfields spring as 'a concentrated dribble that oozes, and sometimes gurgles, its way into a stream from strategic points in the landscape' (Nathan 2007, p. 109). During the 1850s at Ballarat, springs attracted various industries in support of mining communities. These included several sawmills, an aerated waters factory, two breweries and a distillery. Geological maps of the area from 1870 and 1871 record more than 30 springs discharging groundwater (Dahlhaus et al. 2010). The Lands Department subsequently reserved several springs for public watering purposes, while springs were also prized by small landholders as reliable sources of high-quality groundwater. Surveyors created irregularly shaped allotments to accommodate the competing water needs of selectors, with around 50 public reserves associated with springs established in the West Moorabool catchment near Ballarat during the 1860s and 1870s. Spring reserves created a more democratic water resource than Crown frontage of creeks and rivers and became a valued part of small farm geography during this period (Nathan 2007, pp. 110–128).

Gold miners also encountered groundwater as soon as they began working on deep leads (paleo-placers) at the beginning of the gold rush. As early as 1853 at Ballarat, miners deep-sinking shafts to depths of 30 m or more encountered 'drifts' of sand and gravel that were full of water. The situation was exacerbated when leads were traced deeper beneath caps of Plio-Pleistocene basalt that covered ancient river systems. Steam engines were introduced to pump out the shafts and cooperation was needed to lower the water table along deep leads and quartz reefs (Bate 1988; Birrell 1998; Canavan 1988). In 1864, for example, the Great Southern Company began pumping almost 10 ML/ day, while 14 deep lead mining operations on the Sebastopol plateau at Ballarat were pumping a total of 35 ML/day from depths of up to 140 m by the late 1870s (Parliament of Victoria 1879−1880, p. 18). Groundwater was such a problem in this area that plans were drawn up to cut a tunnel 7.3 km long to dewater the mines (Plan 1870). The Smeaton Reserve United Company was pumping 36 ML of groundwater each week in 1886, with excess groundwater preventing access to the auriferous wash (Shakespear et al. 1887, p. 32). Poor gold returns and rising groundwater in underground workings caused some mines to close. In other cases, the water pumped from deep mine shafts was used in surface operations. The Port Phillip Company at Clunes used water drawn from its north shaft in a stamp battery and in steam engines for pumping and winding (Woodland 2001, pp. 53–54). Farmers also depended on this supply to water their stock in summer (Shakespear et al. 1887, p. 31). Groundwater was also responsible for one of Australia's worst mining disasters, at the New Australasian Mine at Creswick in 1882, when groundwater flooded the No. 2 shaft and drowned 22 men (Penney 2001).

Regulating groundwater

Despite these practical responses to dewatering mines, nineteenth-century laws concerning the use of groundwater resources were poorly developed, hampered by technical ignorance of hydrological processes and the nature of subterranean reserves. The connection between surface flows and groundwater was far from clear, but the rights of landholders to extract water from wells and springs on their land was generally upheld by the courts (Clark 1971, pp. 112–119; Getzler 2004, pp. 296–300; Stoeckel et al. 2012, pp. 15–17). On the Victorian goldfields, however, where most land was held by the Crown, groundwater effectively came under government control. The first legislation referring specifically to groundwater extraction on the goldfields was the 1862 *Leases of Auriferous Lands Act*, which authorised the government to issue 15-year licences for miners to construct water races, dams and reservoirs for mining purposes and 'take or divert water from any *spring* lake pool or stream' on Crown land (emphasis added). These licences were confirmed in the 1865 *Mining Statute*. The Beechworth Mining Board responded in 1866 by issuing a by-law ('Protection to Springs') that regulated miners' access to groundwater and ensured that each tunnel or drain tapping a spring had to be at least 100 yards (91 m) from previously opened tunnels (VGG 1866). The intention was to prevent conflict between mining parties and ensure a roughly equal distribution of groundwater for those who took the trouble to extract it.

There was a widespread view in the nineteenth century that miners digging tunnels for groundwater were creating 'new' water supplies, based on the idea that surface and subterranean water were unrelated. Their work was thus understood to benefit not only the mining industry but increase natural flows in waterways as well. Mining entrepreneur John Alston Wallace, for example, believed that by drilling 'deep tunnels into the ranges', the flow of rivers such as the Ovens could be increased almost indefinitely (Royal Mining Commission 1862–1863, p. 345). As late as 1892, Beechworth mining surveyor Henry Davidson referred to 'vagrant' water in a race that was drawn from underground sources. This water had, he thought, no relation to surface water flows (Davidson 1892). Miners believed that extra water should be held as private property as reward for the time and money spent securing the supply. At the same time, however, there was growing recognition that groundwater flows were declining, as sluicing operations removed entire creek beds and altered recharge patterns and processes.

Regulations were designed to maintain a distance between source of supply tunnels, but miners continued to dig tunnels at levels that disrupted the supply of neighbouring parties. The small size of most mining claims also increased competition for available water supplies, which resulted in frequent disputes, litigation and sometimes hostilities (Lawrence and Davies 2019).

A legal hierarchy of water rights was recognised in the Beechworth mining district during this period, with an order of priority imposed in times of water shortage (Royal Mining Commission 1862–1863, p. 348). In the first place were creek rights, which meant a sluice-head of water, roughly 1 ML/day, had to remain flowing in a creek to supply miners working with pans and cradles. Next in order of precedence were bank rights, where miners could divert water away from the channel to their claims for ground sluicing. Motive power rights, which used water wheels to drive machinery, were third in line and had to make do with whatever water was left. 'Spring rights', however, which conveyed the right to extract groundwater, were not part of this sequence of priority. These rights entitled their owners to all the groundwater they could obtain from springs and underground sources and no order of priority was recognised (Royal Mining Commission 1862–1863, p. 350; Parliament of Victoria 1879–1880, p. 41). This made spring rights popular among alluvial miners, who could extract groundwater without reference to preexisting creek, bank and motive power rights (Royal Mining Commission 1862–1863, pp. 348–349).

Physical landscape

The Beechworth-Stanley area is an elevated, hilly plateau located in north-east Victoria. The terrain generally falls from Stanley in the south-east, at an elevation of 720 m AHD (Australian Height Datum), down to Beechworth and beyond, at 550 m AHD. The landscape today is a mix of grazing pasture, orchards, native forests and pine plantations (Fig. 3). The geology of the area is dominated by Ordovician-era sandstone, siltstone, shale, mudstone and slate, steeply folded into a series of synclines and anti-synclines. A fault extending through Beechworth separates these minerals from subsequent Devonian-era granitic intrusions to the north and west. Granite plutons dominate the Mt Pilot range to the north-west, with a further outcropping at Mt Stanley to the south-east. Gold mineralisation post-dates the granite intrusion, with subsequent erosion leading to the accumulation of gold-rich placers in Tertiary and Quaternary alluvium in creek beds. A mix of friable and hard reddish and brownish gradational soils occur on the Stanley plateau (LCC 1974; O'Shea 1981; Phillips et al. 2003).

The climate of the area is mild temperate, with average mean maximum temperatures ranging from 27 °C in summer to 10 °C in winter. Average annual rainfall at Beechworth is 950 mm/year, increasing to 1,200 mm at Stanley, with heaviest falls occurring from April to October (BOM 2019). Occasional snow falls are recorded in winter. The Beechworth-Stanley goldfield includes the upper tributaries of four creek systems: Upper Nine Mile Creek, which drains into the Kiewa River; and Spring Creek,

Fig. 3 Spring at Stanley in 2018 (photo: Susan Lawrence)

Three Mile Creek and Burgoigee Creek, which form part of the Ovens River basin.

The Beechworth-Stanley area is part of the Eastern Highlands groundwater province. Catchment management authorities have identified eight groundwater flow systems (GFS) in north-east Victoria for managing on-ground salinity control works (DPI 2007). These systems are based on a range of geological and geomorphological characteristics and are summarised in Table 1. Groundwater extraction by goldminers at Stanley and Beechworth occurred in a local GFS of fractured sedimentary and fine-grained metamorphic rocks. Fractured rock aquifers occur in catchments confined by hillslopes with moderate to high relief, where groundwater migrates from mid and upper slope regions and converges on adjacent valley floors. Groundwater flow occurs through a network of geological fractures open to depths of 50 m or more.

Groundwater continues to be an important, and often contested, resource at Beechworth and Stanley today (McDonald 2016; White and Nelson 2018). There are approximately 250 bores in the area, used for stock watering, domestic supply and observation of water quality. Most bores were drilled between the 1970s and 2000s, and generally range in depth from 25 to 70 m (VVG 2019).

Technology

The discovery of gold in Victoria in 1851 was part of a sequence of gold rushes around the Asia-Pacific region in the nineteenth century, with major discoveries in Siberia (1840s), California (1848), British Columbia (1858), New Zealand (1861) and the Klondike/Yukon (1896; Mountford and Tuffnell 2018). Victoria proved to be one of the richest shallow alluvial goldfields in the world, and mining brought dramatic changes to the society, economy and physical landscapes of the colony (Phillips et al. 2003; Serle 1963). Payable quantities of gold were first discovered on tributaries of the Ovens River in north-east Victoria in 1852, and by the following year there were up to 8,000 miners on the Ovens goldfield, centred on the town of Beechworth (Woods 1985). Gold was discovered nearby at Snake Gully (Stanley) around the same time (Flett 1970). Most gold in the area was in the form of small flakes distributed through Quaternary alluvium. This contrasted with other mining areas in Victoria where gold was often found as grains and nuggets in thin layers of pipeclay or embedded in quartz rock.

Miners on the Ovens Goldfield needed large volumes of water to wash out these very fine flakes of gold from the auriferous alluvium in the area. Initially they worked with pans and cradles, but from 1853 miners began excavating channels or races to divert water from creeks and springs to their sluicing claims. Ground sluices channelled water over a bank and into a creek or gully to loosen the overburden and washdirt, which was directed into a wooden sluice-box or tailrace to retrieve the gold (Fig. 4). Some races were short, only a few hundred metres in length, but others extended for many kilometres around the contours of hills, in some cases diverting water from one creek or river basin into another. The slope or fall of races was typically about 1:1000, with water flowing at roughly walking pace (Lawrence and Davies 2012). By the 1860s there were more than 1600 km of water races recorded in use across north-east Victoria (Smyth 1980, p. 548). Drought in the mid-1860s, however, severely reduced surface flows for sluicing, which encouraged miners to exploit groundwater (Mining Surveyor 1865).

The earliest recorded attempt to exploit groundwater in the Beechworth-Stanley district was carried out by the Ovens Gold Fields Water Company, a scheme established in 1858 by mining entrepreneur John Alston Wallace. The engineer for the company, Joseph Brady, proposed bringing water from springs and surface drainage in the headwaters of Nine Mile Creek and distributing it by race to mining parties on the Nine Mile, Hurdle Flat, Three Mile and Spring Creek goldfields. Brady identified 11 springs that he expected would yield 2500 l per minute or 3.5 ML/day for 10 months of the year

Table 1 Groundwater flow systems (GFS) identified in north-east Victoria (from DPI 2007). Miners extracted groundwater via tunnels from *fractured rock* GFS and by pumping from deep lead palaeoplacers in *riverine plains* GFS around Chiltern and Rutherglen (see Fig. 1)

Groundwater flow system	Geological and geomorphological settings
Granitic rocks	Massive weathered granitic and metamorphic rocks on steep hilly terrain
Fractured rocks	Fractured sedimentary and finer-grained metamorphic rocks in catchments with moderate to high relief
Glacial sediments	Sediments deposited by melting ancient glaciers on gently undulating terrain
Riverine plains	Gravel and sand aquifers within the trench of an ancient deep lead river system
Deeply weathered fractured rock	Fractured sedimentary and metamorphic rock, decomposed to pale kaolinite rich clays
Basaltic rocks	Highly fractured basalt on ridge tops over less permeable substrates
Lunettes	Dunes and lunettes along the floodplain of the River Murray
Upland alluvium	Alluvial sediments comprising valley floors and terraced floodplains in upland river valleys

Fig. 4 Chinese miners sluicing in a creekbed near Beechworth, Victoria, in ca. 1880 (source: State Library Victoria)

(OMA 1858). The company's prospectus stated that 'a large number of never-failing springs, yielding an enormous supply of water are at present running to waste' (Legislative Assembly 1867). Construction of tunnels to exploit the springs began in 1859 and by the following year the company employed 150 men to cut tunnels and races and build reservoirs (Parliament of Victoria 1860). One of the tunnels was 1.6-km long and more than 30 m below the surface at the deepest point (Mining Surveyor 1859). By 1866, however, the company had spent £40,000 to provide only a fraction of the promised water. Engineers had overestimated the flow rates of groundwater, underestimated the porosity of the gathering ground and lacked capital to complete vital sections of the scheme (Woods 1985, p. 100).

Tunnels were also cut to drain mining waste or tailings away from alluvial workings. In 1875, for example, the Rocky Mountain Extended Gold Sluicing Company began excavating a tunnel beneath the township of Beechworth to drain the company's alluvial tailings. The tunnel, which took three years to complete, was driven through granite and was almost 800 m long and measured 2 m × 1.5 m inside. The floor of the tunnel was lined with heavy timber sluice boxes, with wooden riffles and coir matting to catch the fine gold flakes that escaped the sluicing operations at the Spring Creek diggings. By the end of the century the company had produced more than 960 kg of gold (Lloyd 2006).

District mining surveyors conducted formal chain and compass surveys of each proposed mining water race and prepared a detailed plan for the Mines Department. Distances were originally recorded in links of 7.92 in. (0.2 m). Plans recorded the route of the race along with source-of-supply springs and tunnels, other races, roads and tracks, and nearby property boundaries (Fig. 5). Plans were drawn on large map sheets at a scale of eight chains (1:6336) or four chains (1:3168) to the inch, with summary information about the length of the race, the area of land reserved as gathering ground and the total daily volume of water to be diverted. By 1867 there were 39 water-right licences held on the Ovens goldfield at Beechworth, with an average daily entitlement of 2 ML per licence (Parliament of Victoria 1867, pp. 15–16). Beginning in 1880 there was a flurry of applications to the Mines Department to renew water-right licences that were about to expire after 15 years. Preserved plans from the early 1880s thus reveal mining water systems as they had developed since the 1860s, as well as proposals for expansion, including extra tunnels for groundwater extraction. Thereafter miners continued extracting groundwater for sluicing for several decades—GSG Amalgamated, for example, which had acquired the operation of Pund and Co in 1919, continued working Three Mile Creek with water drawn from Upper Nine Mile Creek until 1948 (Lloyd 2006).

Sources of supply: extracting and diverting groundwater

Twenty-six plans from water-right licence applications featuring groundwater tunnels in the Beechworth-Stanley area have

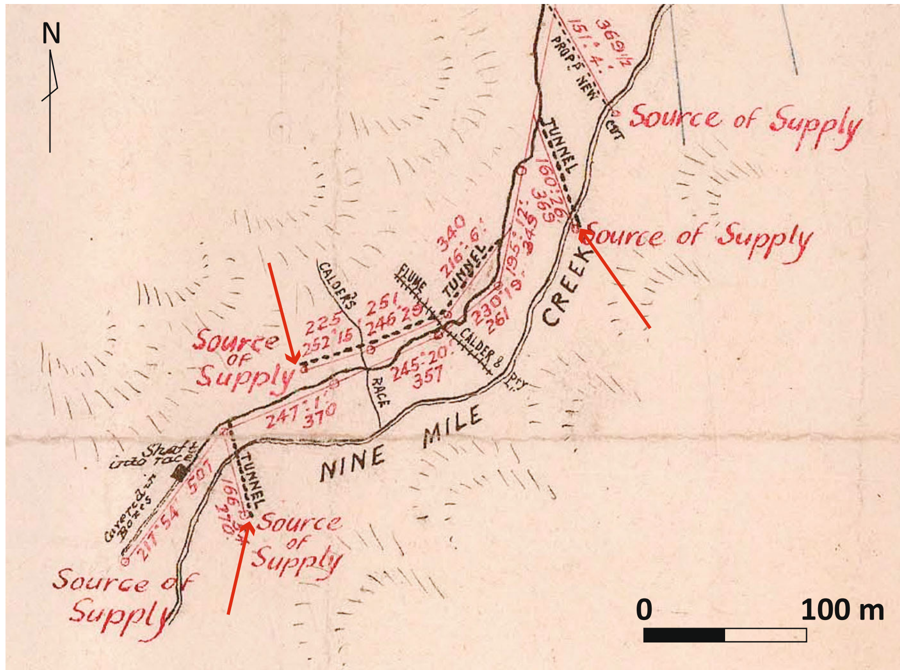

Fig. 5 Head of John Pund's water race in Nine Mile Creek, with three 'source of supply' groundwater tunnels indicated with red arrows on the plan of application for water-right licence in 1881 (Pund 1881)

been analysed here, dating mostly to the early 1880s. By this stage there were approximately 800 miners working the creeks of the area (Mining Surveyor 1881). Several mining parties held multiple licences (Table 2). The plans reveal a total of 57 source-of-supply tunnels excavated by miners to extract groundwater. By 1883, the aggregate length of these

Table 2 Water-right licence applications with 'source of supply' groundwater tunnels between Stanley and Beechworth in the early 1880s (with proposed additional tunnels). Totals are italicised

WRL No.	Name	Year of plan	No. of tunnels constructed	Aggregate tunnel length (m) constructed	No. of tunnels proposed	Aggregate tunnel length (m) proposed
404	J Lang	1877	1	230	–	–
420	John C Davies and Co	1880	1	281	–	–
422	Shand, Milne and Co	1880	–	–	4	283
423	J Pendergast	1880	1	207	–	–
424	Robert McAliece	1880	3	407	–	–
425	JD Law	1880	2	411	–	–
427	Thomas Booth	1880	2	432	–	795
428	Thomas Booth	1880	–	–	1	48
429	Alexander Calder	1880	2	311	–	–
435	Hambleton and Shand	1881	7	1204	–	–
436	Reed, Mateer and Co	1880	3	194	4	66
437	Thomas Little	1881	4	1168	–	–
439	Robert McAliece	1881	3	399	–	–
442	John Pund	1881	6	676	1	74
445	George Haworth	1881	8	1393	4	587
452	Friedrich Kassebaum	1881	4	208	5	310
455	William Hyndman	1881	1	402	1	85
475	Miehe and Basse	1882	–	–	2	240
478	J Turner	1883	2	145	–	–
482	Gillies, Rae and Co	1883	1	166	–	–
484	MacCarthy and Co	1883	2	605	–	–
488	W Orchard	1883	1	85	–	–
490	Donald Fletcher	1883	–	–	–	–
492	Donald Fletcher	1883	–	–	6	595
501	Charles Connolly	1883	2	104	4	341
521	Donald Fletcher	1883	1	68	2	369
		Totals	*57*	*9,096*	*34*	*3,793*

tunnels was more than 9 km, with the longest single example, cut by Thomas Booth in the headwaters of Nuggetty Gully, extending almost 650 m into the hillside. Shorter tunnels were generally 20–40 m long, with an average length of around 160 m. George Haworth's water system on the Upper Nine Mile Creek included eight tunnels with a total length of almost 2 km. At least two miners cut tunnels directly beneath the township of Stanley itself. The plans also reveal that 11 mining parties proposed cutting an additional 34 tunnels, with a total length of almost 3.8 km. Correspondence from the 1890s indicates that virtually all these tunnels were subsequently completed (Davidson 1893).

Tunnels were excavated horizontally into hillsides on a slight incline for water to drain out by gravity to the surface. This was a traditional mining technology and differed from the subsequent use of deep vertical drilling in the Great Artesian Basin to extract pressurised water. Tunnels were of sufficient height and width for one or two men to work side by side, and many also had vertical shafts to the surface for ventilation (Kennan 1859). Each tunnel normally took several months to build, with day and night

Table 3 Diversions of groundwater within and between watersheds at Stanley and Beechworth in the early 1880s, rounded to 0.1 ML. The delivered daily water volumes are 50% of the licensed daily water volumes. This represents our estimate of the amount of water miners actually used, based on preserved historical correspondence. Subtotals are italicised. *Ck* creek

WRL No.	Name	Watershed origin	Watershed delivery	Licensed daily water volume (ML)	Delivered daily water volume (ML)
404	J Lang	Nine Mile Ck	Nine Mile Ck	1.6	0.8
420	John C Davies and Co	Nine Mile Ck	Nine Mile Ck	0.7	0.3
422	Shand, Milne and Co	Nine Mile Ck	Nine Mile Ck	3.6	1.8
424	Robert McAliece	Nine Mile Ck	Nine Mile Ck	1.8	0.9
425	JD Law	Nine Mile Ck	Nine Mile Ck	1.9	1.0
436	Reed, Mateer and Co	Nine Mile Ck	Nine Mile Ck	2.3	1.1
445	George Haworth	Nine Mile Ck	Nine Mile Ck	4.5	2.3
482	Gillies, Rae and Co	Nine Mile Ck	Nine Mile Ck	0.4	0.2
484	MacCarthy and Co	Nine Mile Ck	Nine Mile Ck	1.4	0.7
Watershed group subtotal				*18.2*	*9.1*
423	J Pendergast	Nine Mile Ck	Spring Ck	2.2	1.1
427	Thomas Booth	Nine Mile Ck	Spring Ck	1.6	0.8
428	Thomas Booth	Nine Mile Ck	Spring Ck	1.9	1.0
429	Alexander Calder	Nine Mile Ck	Spring Ck	3.0	1.5
435	Hambleton and Shand	Nine Mile Ck	Spring Ck	1.8	0.9
437	Thomas Little	Nine Mile Ck	Spring Ck	3.1	1.6
439	Robert McAliece	Nine Mile Ck	Spring Ck	2.7	1.4
Watershed group subtotal				*16.3*	*8.3*
442	John Pund	Nine Mile Ck	Three Mile Ck	4.3	2.2
Watershed group subtotal				*4.3*	*2.2*
452	Friedrich Kassebaum	Burgoigee Ck	Three Mile Ck	2.4	1.2
Watershed group subtotal				*2.4*	*1.2*
455	William Hyndman	Three Mile Ck	Three Mile Ck	4.5	2.3
475	Miehe & Basse	Three Mile Ck	Three Mile Ck	3.6	1.8
488	W Orchard	Three Mile Ck	Three Mile Ck	0.9	0.4
Watershed group subtotal				*9.0*	*4.5*
478	J Turner	Spring Ck	Spring Ck	0.8	0.4
490	Donald Fletcher	Spring Ck	Spring Ck	3.4	1.7
492	Donald Fletcher	Spring Ck	Spring Ck	3.4	1.7
521	Donald Fletcher	Spring Ck	Spring Ck	1.7	0.8
Watershed group subtotal				*9.3*	*4.6*
501	Charles Connolly	Spring Ck	Three Mile Ck	2.3	1.1
Watershed group subtotal				*2.3*	*1.1*
Totals				61.8	31.1

shifts cutting through sandstone and slate. Longer tunnels of several hundred metres often included angled changes in orientation to avoid harder rock and to increase water flow. Steam-powered rock-drilling machines were in use on the goldfields by the 1860s (Smyth 1980, pp. 230–231).

Each mining party was licensed to use a specific volume of water per day. This ranged from 0.4 ML up to 4.5 ML, with an average of 2.4 ML (Table 3). The great majority of this was groundwater, with smaller additional amounts drawn from creeks and surface drainage or 'gathering ground' adjacent to water races. Other mining parties in the area diverted surface water directly from creeks and gullies. The total licensed water volume of the 26 operations analysed here was 61.8 ML/day. Historical sources indicate, however, that the volumes of water miners were licensed to extract were often exaggerated, and less was usually available. Supplies of groundwater and surface water dwindled in the summer months and the cutting of numerous supply tunnels gradually reduced creek flows (Parliament of Victoria 1867, p. 6). Extensive disturbance by ground sluicing in the heads of creeks and gullies also affected groundwater volumes. On this basis, it is expected that only around half of the licensed water was available for use by mining parties at Beechworth and Stanley. This means an average daily groundwater flow from source of supply tunnels of ca. 31 ML (Table 3).

Miners at Stanley extracted and channelled groundwater within and between the catchments of Nine Mile Creek, Spring Creek, Three Mile Creek and Burgoigee Creek (Fig. 6). The largest interbasin transfer was from Nine Mile Creek to Spring Creek, where the holders of seven water-right licences diverted up to 8.3 ML/day, representing a steady transfer of water out of the Kiewa River basin and into the Ovens River catchment (Fig. 7). John Pund's mining water system was more than 20 km long and captured 2.2 ML/day from Nine Mile Creek and diverted it across the Spring Creek catchment to Three Mile Creek, representing an additional transfer from the Kiewa to the Ovens River. Smaller volumes were also diverted by other miners from Burgoigee Creek (1.2 ML) and Spring Creek (1.1 ML) to Three Mile Creek. Up to 12.8 ML of groundwater may thus have been transferred per day between creek catchments by alluvial miners on the goldfield.

Groundwater extracted on the Beechworth-Stanley goldfield was often reused multiple times, with mining water systems developed and extended over many years. In 1892, for example, miner Richard Warren applied to reuse tunnels and trenches in Frenchman's Gully, part of the Kiewa watershed, that had been cut by Robert Shand up to 25 years earlier. These works diverted up to 3.6 ML of groundwater per day from several tributaries of Upper Nine Mile Creek and conveyed it by race and tunnel to a succession of five alluvial operations further downstream. The mining surveyor claimed that the water furnished employment to 77 men between its sources and Woolshed Creek (Davidson 1892).

Extraction of groundwater continued on the Stanley-Beechworth goldfield for many years. In several cases tunnels were used continuously as sources of supply over decades. In 1866, for example, Robert Shand's party applied for a water-right licence to divert water from Back Creek near Stanley to Spring Creek near Beechworth, with the spring water already described in 1869 as 'muddy from use' (Smyth 1980, p. 406).

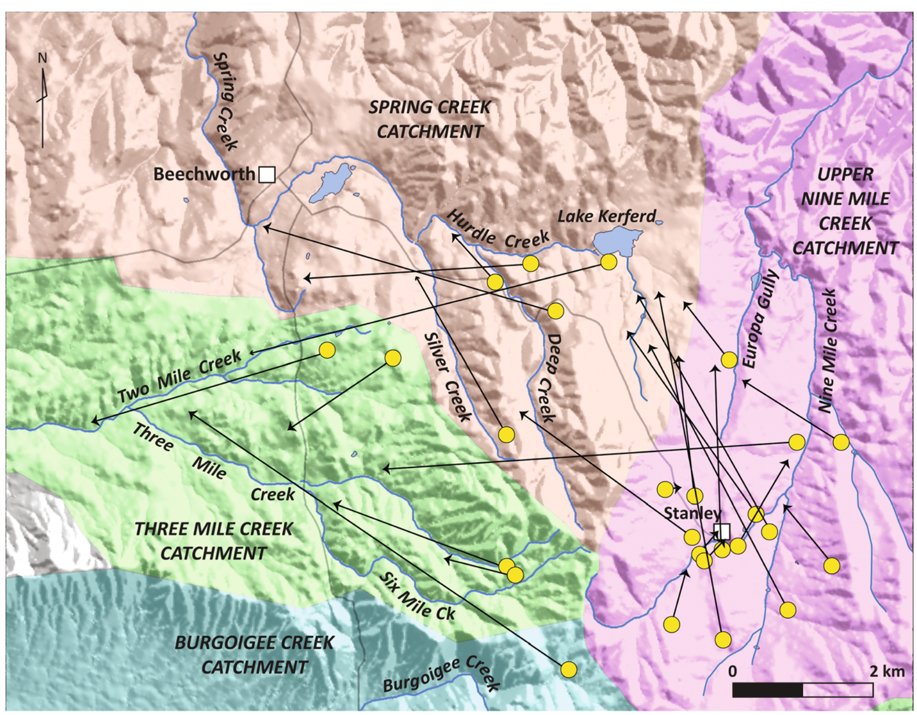

Fig. 6 Groundwater sources of supply (tunnels, yellow dots) and point of delivery to mining claims (arrowheads) for water licences in the early 1880s

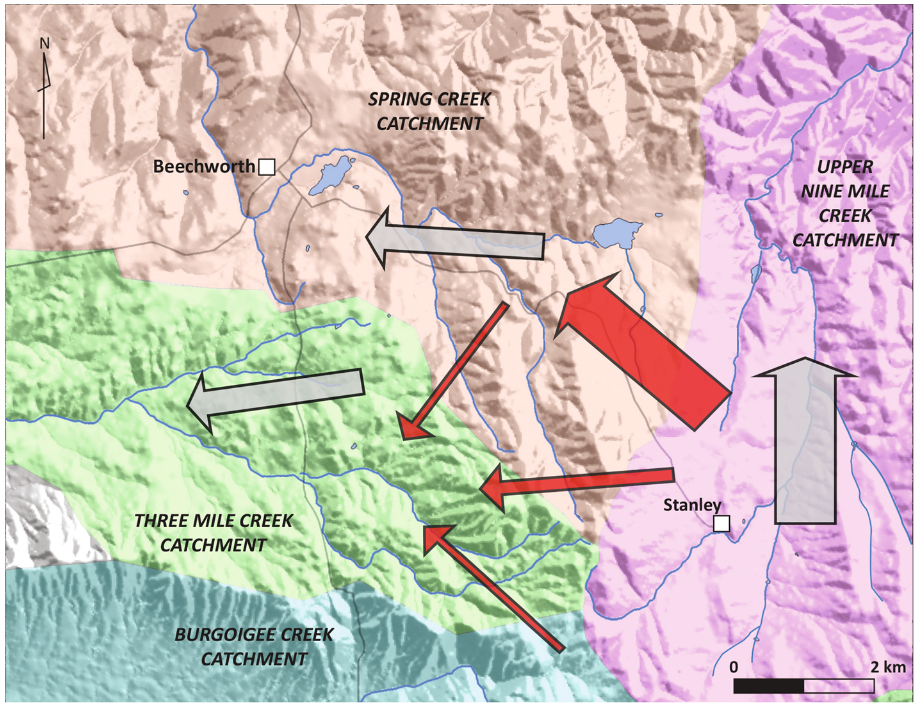

Fig. 7 Intrabasin groundwater transfers (grey arrows) and interbasin groundwater transfers (red arrows), width of arrows proportional to daily volumes

Shand renewed the licence in 1881 before it was taken over by the United Sluicing Company in 1895 (Davidson 1895). The race was realigned but the original seven groundwater tunnels remaining in operation. The water-right licence was renewed for a fifth time in 1910. By this stage miners in the area were trying to maintain and increase their groundwater supplies by yet further tunnelling. Residents at Stanley opposed the idea, however, as their domestic water drawn from wells was in decline.

Conclusion

Most research on the history of groundwater use in Australia has related to development of the Great Artesian Basin in Queensland, New South Wales and South Australia, with the first important flowing bore sunk in 1878 (Powell 1991). Miners at Stanley and Beechworth, however, identified significant groundwater resources on the Ovens goldfield from the mid-1860s and determined how it could be extracted and distributed. This represents one of the earliest recorded examples of large-scale exploitation of groundwater in Australian history. Research presented here also refocuses historical analysis of groundwater use away from the Great Artesian Basin to the Alpine regions of south-eastern Australia. It demonstrates that people on the goldfields were capable of extracting groundwater from shallow, fractured rock aquifers using traditional mining techniques. Miners also learned that groundwater was a resource that could be damaged and destroyed by mining, heavy groundworks and continued extraction. The Victorian government nationalised water supplies in the 1880s, continuing a process begun by the gold mining industry several decades earlier (Clark 1971, p. 153; Deakin 1885, p. 55; Powell 1989). Government management of water thus became increasingly important, especially for the newly emerging irrigation industry. The understanding earned by alluvial gold miners in north-east Victoria had begun to inform the wider management of Australia's groundwater resources.

The nature of groundwater was understood locally on individual goldfields during the nineteenth century but the science of hydrogeology was still in its infancy. Many miners regarded the groundwater they extracted as 'new' water, as separate from the surface water that flowed down creeks and gullies. Miners often applied for larger volumes of water than they generally received, 'hedging' their licence conditions to protect access to supplies in case of disputes with neighbouring parties. Extraction of groundwater at Beechworth and Stanley in the nineteenth century was thus a highly commercialised activity. Miners invested large sums to develop source of supply tunnels and distribution races, before leasing the water to downstream parties. This helped create a dynamic market in water supply and delivery systems that was widespread across the Victorian goldfields. Use of groundwater for mining persisted at Beechworth and Stanley well into the twentieth century. Extraction of groundwater on the goldfields was itself another form of mining.

Gold miners needed large volumes of water for alluvial sluicing during this period. This technology was very prominent on the Ovens goldfield at Beechworth and Stanley, where mining claims typically used several ML/day for washing auriferous alluvium. Miners in the area obtained a large proportion of their mining water supplies from groundwater tunnels cut into hillsides. In this context, groundwater was often more abundant and reliable, especially in drier periods, so miners went to great lengths to secure it. Historical evidence indicates that at least 90 tunnels were excavated in the area, with an aggregate length of almost 13 km. Increasing numbers of tunnels and levels of groundwater extraction, however, appear to have gradually reduced the overall volume of groundwater available. It is estimated that miners at Beechworth and Stanley could extract up to 31 ML of groundwater per day by the early 1880s, extending a process the industry had commenced in the 1860s. Of this total, more than one-third (12.8 ML) was transferred between local catchment basins.

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