Groundwater

Review Paper/

Managed Aquifer Recharge in Mining: A Review

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Abstract

Managed aquifer recharge (MAR) has been gaining adoption within the mining industry for managing surplus water volumes and reducing the groundwater impacts of dewatering. This paper reviews MAR for mining and includes an inventory of 27 mines using or considering MAR for current or future operations. Most mines using MAR are in arid or semi-arid regions and are implementing it through infiltration basins or bore injection to manage surplus water, preserve aquifers for environmental or human benefit, or adhere to licensing that requires zero surface discharge. Surplus water volumes, hydrogeological conditions, and economics play a pivotal role in the feasibility of MAR for mining. Groundwater mounding, well clogging, and interaction between adjacent mines are common challenges. Mitigation strategies include predictive groundwater modeling, extensive monitoring programs, rotation of infiltration or injection facilities, physical and chemical treatments for clogging, and careful location for MAR facilities in relation to adjacent operations. Should water availability alternate between shortage and excess, injection bores may be used for supply, thus reducing costs and risks associated with drilling new wells. MAR, if applied strategically, also has the potential to accelerate groundwater recovery post-mine closure. The success of MAR for mining is emphasized by mines opting to increase MAR capacity alongside dewatering expansions, as well as prospective mines proposing MAR for future water requirements. Upfront planning is the key to maximizing MAR benefits. Improved information sharing could help increase awareness and uptake of MAR as an effective and sustainable mine water management tool.

Introduction

Managed aquifer recharge (MAR) and aquifer re-injection are among the most innovative groundwater engineering solutions to water management problems (Drury 1998; Zhang et al. 2020). MAR is the deliberate replenishment of aquifers for later use or environmental benefit (Dillon et al. 2009; Gruetzmacher and Kumar 2012; Waterhouse et al. 2017). Historically, it has been implemented by collecting surface water runoff and facilitating infiltration into aquifers for future use, primarily for agriculture and urban water supply (Gale et al. 2002).

Other potential benefits include preventing saltwater intrusion in coastal aquifer settings and reducing impacts to groundwater dependent ecosystems (Dillon et al. 2009). MAR is particularly applicable in arid and semi-arid regions where underground storage can be a useful method to mitigate against future water scarcity or seasonal fluctuations in supply (Bouwer 2002; Ringleb et al. 2016; Ebrahim et al. 2020).

Aquifer re-injection is the process of re-injecting water into subsurface aquifers via boreholes and has commonly been used as a wastewater and brine disposal option that minimizes environmental risks associated with surface discharge (Knape 1984; Drury 1998; Waterhouse et al. 2017). This practice is used in the energy sector,

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where produced water from coal seam gas (CSG) extraction, geothermal production, as well as onshore oil and gas wells is injected deep below potable aquifers (Ferguson 2015; Kamila et al. 2021; Robertson 2018). Other potential uses for aquifer re-injection include replenishing depleted aquifers, maintaining oil reservoir pressures, as well as reducing subsidence associated with overexploitation of oil reservoirs and groundwater (Laird et al. 2001; Myers 2009).

While global use and technical expertise of MAR and aquifer re-injection is expanding, its application in the mining sector is in its infancy. However, there is considerable potential for its adoption as a mine water management tool. Although the terms MAR and aquifer re- injection are often used synonymously within the mining context, there is a subtle distinction between the two. Aquifer re-injection is a technique used to return fluids to the subsurface regardless of the final objective for its implementation. MAR includes a variety of recharge techniques and prioritizes beneficial use for the replenished aquifer. Despite the nuance between the terms, this paper will focus on applications of MAR for mining in this latter context.

Effective groundwater management strategies are essential for open pit mines operating below the water table. Dewatering of open-pit or underground mine workings is implemented to create dry conditions for mining operations (Rozkowski et al. 2021; Cook et al. 2022). This process creates a cone of depression, where water levels decrease around the mine, resembling the shape of an inverted cone. Depending on hydrogeological properties, this drawdown may extend hundreds of meters to several kilometers from the pit. Groundwater extracted during the dewatering process is often used for ore processing, dust suppression, and potable supply if water quality is sufficient (e.g., Rubio and Fernandez 2010; BHP Billiton 2016; Design Point Consulting 2021). When dewatering volumes exceed water use requirements, surplus water is traditionally discharged to surface water systems such as natural water catchments, dams, or evaporation ponds. Discharge to natural water catchments has environmental implications and may threaten local flora and fauna. Discharge to dams or evaporation ponds has several disadvantages including large evaporation losses, accumulation of sediment, risk of dam or embankment failure, large land area demands, and adverse environmental and sociocultural impacts (Bouwer 2002; Ringleb et al. 2016).

Lowering of the water table itself from dewatering activities may also negatively affect sensitive ecosystems, communities, or other users reliant on that groundwater (Drury 1998; Rubio and Fernandez 2010; Baquero et al. 2016). It is evident that mine site-specific groundwater management strategies are essential to mitigate water table drawdown impacts as well as properly store or dispose of surplus water produced by the dewatering process.

With increasingly strict environmental regulations and controls in place for groundwater, many mining companies have developed an interest in MAR to address these mine water challenges. MAR in mining is generally applied by routing surplus water to injection wells, where water is injected straight into the target aquifer, or to infiltration structures, such as ponds, trenches, dams, or galleries (Figure 1) (Yungwirth et al. 2017). MAR has also been used to maintain groundwater levels for sensitive ecosystems or third-party users that may be impacted by reduced water levels following mine dewatering (e.g., Youngs and Brown 2005; Baquero et al. 2016). More recently, injecting surplus water at a target distance from the pit during mining operations has been considered as a technique for accelerating groundwater recovery following mine closure (Cook et al. 2022). Mine closure may require that pre- mining hydrological conditions are re-established, including the recovery of groundwater levels. However, depending on climate and hydrogeological conditions, a full recovery that relies on the naturally occurring rainfall and recharge conditions may take tens to hundreds of years, if it occurs at all. Through the controlled strategic injection of excess mine water into suitable sections of the subsurface during the operating phase of the mine, post-closure groundwater level recovery can be accelerated (Cook et al. 2022). Water needs to be injected distant enough to prevent excessive re-circulation back to the pit, but close enough that water is stored within the drawdown cone to facilitate groundwater recovery once mining has ceased (Figure 1). More rapid groundwater recovery not only benefits groundwater dependent ecosystems and aquifer users, it also reduces exposure of pit walls within the mine workings and therefore the risks of acid mine drainage (Waterhouse et al. 2017; Bozan et al. 2022).

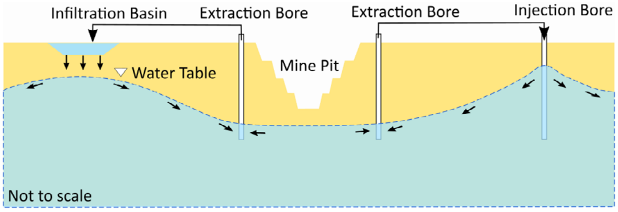

Figure 1. Schematic of MAR types used in mining.

MAR schemes designed and implemented at the onset of below water table mining may result in improved environmental and economic outcomes for the mine.

Despite the growing use of MAR in mining, very little information is made publicly available on site-specific schemes, and there is limited information in the academic literature. The lack of accessible information on successful MAR schemes has resulted in decision makers and water resource managers often viewing it as a costly and risky option (Stefan and Ansems 2018). To improve the communication and shared knowledge on MAR in general, global reviews have been conducted (e.g., Sprenger et al. 2017; Stefan and Ansems 2018; Valverde et al. 2018; Ebrahim et al. 2020; Zheng et al. 2021). However, none of these focus on the use of MAR for mining. This paper critically reviews the use of MAR for mining and establishes an inventory of mine sites using MAR with surplus dewatering volumes. The aim is to provide guidance and recommendations for future planning of its use in mine water management.

MAR and Aquifer Re-Injection Schemes in Mining

The inventory of mine sites using MAR includes 27 cases with data collected from publicly available scientific papers, conference presentations and proceedings, technical government documents, internal reports, company websites, and discussions with industry and government personnel (Table 1, Figure 2). This review is not intended as a complete account of all active MAR schemes in mining, as there is likely additional information contained in internal company documents, technical government reports, or non-English publications. Fifteen of the 27 cases identified in this study are mines with surplus dewatering volumes that have incorporated MAR in their ongoing operations. Eight cases involve active mines that have conducted MAR trials or have proposed MAR schemes for future operations. Also, four prospective mines have been included, where MAR has been proposed or trialed as a sustainable mine water management strategy (Figure 2). Proposed and trial MAR schemes are included to emphasize the progress of MAR in mining but are described in less detail due to limited operational data. Mines from the oil and gas, CSG, and lithium brine sectors are not included in the inventory of this review; however, two CSG cases with surplus water volumes and one lithium brine case are briefly discussed in the text for broader reference. The authors understand that active mine sites are continuously evolving and developing during operations and after closure, so this review is intended as a "snapshot in time" rather than a conclusive account for each case. Detailed information on operational MAR schemes (not including trials and proposed projects) is included in the Supporting Information.

Currently, MAR schemes associated with mining are predominantly located in arid or semi- arid regions. Surface water and groundwater are more likely to be scarce in these areas, making it necessary to preserve local water resources for current and future needs (Figure 2). Australia, Spain, South Africa, and Nevada contain most of the mining MAR schemes, as they are dry regions with a large mining industry. Shallow aquifers in more humid climates may have limited storage capacity to receive additional water. However, MAR may still be feasible in these regions under appropriate hydrogeological conditions, as demonstrated by Garzweiler Lignite Mine in Germany, where MAR is used to reduce impacts to springs and groundwater dependent wetlands (Bucher et al. 2010).

Mines in Nevada primarily use rapid infiltration basins, most of which commenced in the 1990s. In Australia, Spain, and South Africa, mines predominantly use bore injection, which started around the 2000s and 2010s, with more proposed projects to commence in the 2020s. A number of mines started MAR concurrently with dewatering (e.g., [Cloudbreak] Windsor et al. 2012; [Cobre Las Cruces] Baquero et al. 2016; [Elandsfontein] GEOSS South Africa Pty Ltd. 2019; [Pipeline] Nevada Gold Mines LLC 2021; [Ruby Hill] Ruby Hill Mining Company LLC 2020). For these examples, mining may not have been possible without MAR, either due to the projected impacts of dewatering or the quality of water being abstracted and discharged. Other mines have turned to MAR years after dewatering commenced, either due to unforeseen negative impacts from dewatering or due to a significant increase in dewatering volumes to manage (e.g., [Roy Hill] Roy Hill 2021; [Garzweiler] Bucher et al. 2010; [Costerfield] Mining Plus 2022). MAR schemes implemented in parallel with the onset of dewatering may offer improved benefit to operations by mitigating these environmental and surplus disposal challenges before they arise. MAR schemes can be modified as mining progresses to deal with changing water requirements and address MAR challenges that may occur throughout the mine life.

Fully operational MAR schemes at mine sites use bore injection (six sites), infiltration basins (six sites), or a combination of the two (three sites). Scheme designs vary widely dependent on MAR objectives, required injection volumes, aquifer conditions, water quality, access to land for recharge facilities, and proximity to sensitive receptors and groundwater users. Some MAR schemes are relatively simple, for example, Costerfield Gold-Antimony Mine in Victoria, Australia, has just two injection bores within 1 km of dewatering facilities (Mining Plus 2022), and Ruby Hill Gold Mine in Nevada has only two rapid infiltration basins within 2 km of dewatering facilities (Ruby Hill Mining Company LLC 2020). Other schemes, including at Garzweiler Lignite Mine in Germany and Cloudbreak Iron Ore Mine in the Pilbara Region of Western Australia, are comparatively large and complex with over 100 km of dendritic pipeline networks capable of transporting water to more than 100 infiltration structures or injection bores (Bucher et al. 2010; Windsor et al. 2012).

Mining companies generally implement MAR schemes for one or more of the following reasons: (1) surplus water disposal; (2) environmental protection; (3) aquifer preservation for groundwater users; and (4) adherence to zero surface discharge licensing (see Supporting Information). Cloudbreak Iron Ore Mine uses MAR for surplus water disposal, aquifer preservation for their own future use, and environmental protection through limiting the impacts of saline water discharge and reducing the drawdown cone from damaging an adjacent marsh (Windsor et al. 2012). Cobre Las Cruces Copper Mine has been successfully operating a re-injection scheme designed to treat and dispose of surplus water unsuitable for surface discharge and preserve the aquifer water balance for other groundwater users (Baquero et al. 2016). The Pipeline Infiltration Project in Nevada accepts volumes from Pipeline and Cortez Hills Gold Mines for surplus water disposal, environmental protection, aquifer preservation, as well as adherence to a

Table 1
Summary Table of Mines Corresponding with Figure 2

#	Name	Resource	Location	Start Date Dewatering/MAR	MAR Type[1]	Inj. Vol. (GL/year)	Inj. Vol. (%)[2]	Pre-treatment	Ref.[3]
MAR operational schemes									
1	Alquife	Iron ore	Granada, Spain	NA[6]/1984	IP	6.4	91	Nil	a; b
2	Cloudbreak	Iron ore	Pilbara, WA[4]	2008/2008	BI	102	87	Nil	c; d; e
3	Cobre Las Cruces	Copper	Seville, Spain	2006/2006	BI	2.9	91	RO[5]	f
4	Costerfield	Gold and antimony	Victoria, Australia	2006/2017	BI	0.73 (License)	100 (License)	Nil	g
5	Elandsfontein	Phosphate	Saldanha Bay, South Africa	2017/2017	BI	5.6	NA	Nil	h; i
6	Garzweiler	Lignite/coal	Western Germany	NA/Early 1990s	IP and BI	NA	NA	Fe and Mn (filter and oxygenate)	j; k; b
7	Goldstrike	Gold	Nevada, USA	Mid 1990s/NA	RI, RIB and BI	NA	85	As treatment[7]	l; b
8	Kolomela	Iron ore	Postmasburg, South Africa	NA/2014	BI	0.3.	<2	Nil	m; n; o
9	Mining Area C	Iron ore	Pilbara, WA	2010/2012	BI and IP	18.3[8]	NA	Nil	p; q
10	Mt. Whaleback	Iron ore	Pilbara, WA	1970s/1981	Dam, IP and RB	3.4	NA	Nil	b; r; s; t
11	Pipeline and Cortez Hills	Gold	Nevada, USA	1996/1996	RIBs	70 (License)	NA	Nil	u; v
12	Round Mountain	Gold	Nevada, USA	NA	RIBs	5.6	50	Nil	w; x
13	Roy Hill	Iron ore	Pilbara, WA	2014/2018 (2017 trials)	BI	45	35	Nil	y; z
14	Ruby Hill	Gold	Nevada, USA	2003/2003	RIBs	0.6 to 1.2	NA	As treatment	aa
15	Turquoise Ridge	Gold	Nevada, USA	NA	RIBs	NA	NA	As and Mn treatment[9]	bb
MAR trials and proposed schemes									
16	Portia	Gold	South Australia	2015/2014 (trial)	BI	NA	NA	Nil	cc
17	Angas	Zinc	South Australia	2008/2007 (trial)	BI	NA	NA	Nil	dd
18	Fosterville	Gold	Victoria, Australia	2005/2017 (trial)	BI	NA	NA	RO	ee
19	Marandoo	Iron ore	Pilbara, WA	2012/2004 (trial)	BI	NA	NA	Nil	ff; gg
20	Marigold	Gold	Nevada, USA	2019/2023 (prop.)	RIB	NA	NA	Nil	hh
21	Olympic Dam	Uranium, copper, silver, and gold	South Australia	1988/2007 (trial)	BI	NA	NA	NA	ii
22	Relief Canyon	Gold	Nevada, USA	NA (prop.)	RIB	<1.8	~60	NA	jj
23	West Angelas	Iron ore	Pilbara, WA	NA (prop.)	BI	NA	NA	Nil	kk

Table 1
Continued

#	Name	Resource	Location	Start Date Dewatering/MAR	MAR Type[1]	Inj. Vol. (GL/year)	Inj. Vol. (%)[2]	Pre-treatment	Ref.[3]
MAR for proposed mines									
24	Balranald	Mineral sands	NSW, Australia[10]	2014 (trial)	BI	20 to 30 (prop.)	~40 (prop.)	Nil	ll; mm
25	Bird in Hand	Gold	South Australia	2019 (trial)	BI	NA	100 (prop.)	Nil	nn
26	Ghaghoo	Diamond	Botswana	NA (prop.)	BI	3.4	NA	NA	oo
27	Mulga Rock	Uranium	Kalgoorlie, WA	NA (prop.)	BI	<1.5	60	Nil	pp

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[1] MAR type refers to the recharge method used. This includes infiltration ponds (IP), bore injection (BI), reservoir infiltration (RI), rapid infiltration basins (RIB), and river basins (RB).

[2] Injection volume as percentage of dewatering volume.

[3] References include the following: (a) Díaz et al. 2020, (b) Rubio and Fernandez 2010, (c) Windsor et al. 2012, (d) Fortescue Metals Group Ltd. 2013, (e) FMG Chichester Pty Ltd. 2021, (f) Baquero et al. 2016, (g) Mining Plus 2022, (h) GEOSS South Africa Pty Ltd. 2019, (i) Ebrahim et al. 2020, (j) Boehm and Trumpff 1988, (k) Bucher et al. 2010, (l) Nevada Gold Mines LLC 2020a, (m) Gradient Groundwater Consulting 2021, (n) Design Point Consulting 2021, (o) Synergistics Environmental Services 2013, (p) BHP Billiton 2016, (q) BHP Iron Ore Pty Ltd. 2022a, (r) RPS Group 2015, (s) BHP Billiton 2015, (t) BHP Iron Ore Pty Ltd. 2022b, (u) Nevada Gold Mines LLC 2021, (v) Nevada Gold Mines LLC 2022, (w) Dixon 2019, (x) U.S. Department of the Interior Bureau of Land Management 2017, (y) Roy Hill 2021, (z) Roy Hill 2022, (aa) Ruby Hill Mining Company LLC 2020, (bb) Nevada Gold Mines LLC 2020b, (cc) Australian Groundwater Technologies 2013, (dd) Australian Groundwater Technologies 2012, (ee) Fuller and Hann 2018, (ff) Rio Tinto 2015, (gg) Youngs and Brown 2005, (hh) OreWin Pty Ltd. 2022, (ii) BHP Billiton 2009, (jj) Mine Development Associates 2018, (kk) Government of Western Australia Environmental Protection Authority 2019, (ll) EMM Consulting Pty Ltd. 2015, (mm) Hydrogeologic Pty Ltd. 2015, (nn) Terramin Australia Ltd. 2019, (oo) Johnstone et al. 2016, (pp) Vimy Resources Ltd. 2020.

[4] WA refers to Western Australia.

[5] RO refers to reverse-osmosis.

[6] NA refers to information not found publicly available.

[7] As refers to arsenic.

[8] Includes discharge volumes to bore injection, infiltration ponds and surface discharge.

[9] Mn refers to manganese.

[10] NSW refers to New South Wales.

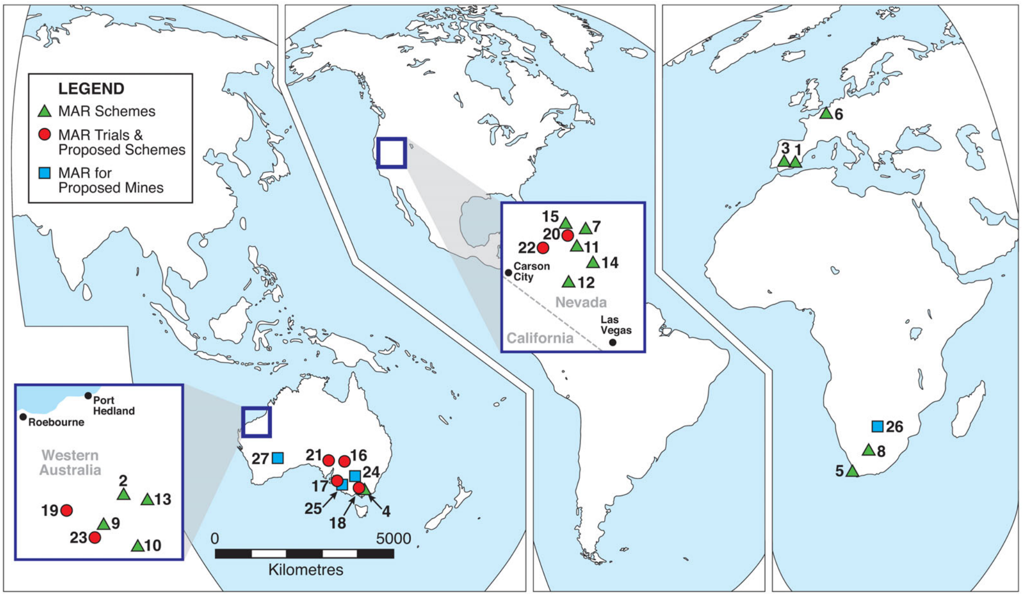

Figure 2. Map of MAR schemes for mining. Case labels correspond to MAR case numbering in Table 1.

zero-discharge permit (Nevada Gold Mines LLC 2021). Overall, surplus water disposal appears to be the most common objective, ecological preservation the second most common objective, followed by aquifer preservation and preventing impacts to third party groundwater users.

MAR schemes have been established in various aquifer settings from unconfined alluvium to confined fractured rock (see Supporting Information). Infiltration structures are used where shallow unconfined aquifers with high permeability and storage are present, such as Garzweiler Lignite Mine, Goldstrike Gold Mine, and Pipeline Gold Mine (Boehm and Trumpff 1988; Nevada Gold Mines LLC 2020a, 2021). For bore injection, aquifer lithology and confining conditions are more variable. This is evident by the wide range of aquifers utilized by mines for bore injection. Cobre Las Cruces Copper Mine in Spain and Elandsfontein Phosphate Mine in South Africa inject into confined sands and gravels (Baquero et al. 2016; GEOSS South Africa Pty Ltd. 2019), while mines in the Pilbara Region of Western Australia inject into fractured rock as well as karstic dolomite and calcrete (e.g., Windsor et al. 2012; BHP Billiton 2016; Roy Hill 2021). Aquifer parameters, such as hydraulic conductivity, transmissivity and storativity are also highly variable within the formations targeted for injection or infiltration (see Supporting Information).

Dewatering requirements of mines who are actively using MAR also varied widely. Annual dewatering volumes for several mines ranged from less than 1 GL/year for Costerfield Gold- Antimony Mine (Mining Plus 2022), 3.2 GL/year for Cobre Las Cruces Copper Mine (Baquero et al. 2016), to 19 GL/year for Kolomela Iron Ore Mine located in South Africa (Gradient Groundwater Consulting 2021). However, for larger mines in high permeability environments, dewatering volumes can be immense. Cloudbreak Iron Ore Mine for instance is licensed to dewater up to 150 GL/year (4750 L/s) (Government of Western Australia Department of Water and Environmental Regulation 2021a), and in 2001 Garzweiler Lignite Mine pumped approximately 110 GL (3500 L/s) from 650 dewatering wells (Rubio and Fernandez 2010). For mines where both dewatering and infiltration volumes are available, injection volumes as a percentage of dewatering volumes are most commonly in the range of 50 to 90%, depending on consumptive use and capacity of alternative disposal options. One exception is Kolomela Iron Ore Mine, where most surplus water is sent to the district municipality (Gradient Groundwater Consulting 2021). However, the mine produces more water than the municipal water supply can accommodate, so excess water is disposed of via the MAR scheme. For a number of mines where dewatering requirements are increasing, their MAR schemes are also expanding in parallel (e.g., [Mining Area C] Government of Western Australia Department of Water and Environmental Regulation 2020; [Cloudbreak] Government of Western Australia Department of Water and Environmental Regulation 2021a; [Cortez Complex] Nevada Gold Mines LLC 2020a; [Kolomela] Gradient Groundwater Consulting 2021; [Round Mountain] Dixon 2019).

Ten of the 15 mines included in this review do not treat the water prior to infiltration or injection, as the water is of equal or better quality than the receiving aquifer. A few mines using rapid infiltration basins in Nevada treat the water for naturally occurring arsenic (e.g., [Goldstrike] Nevada Gold Mines LLC 2020a; [Ruby Hill] Ruby Hill Mining Company LLC 2020) and manganese (e.g., [Turquoise Ridge] Nevada Gold Mines LLC 2020b). Garzweiler Lignite Mine removes iron and manganese through filtration and oxygenation prior to recharge (Bucher et al. 2010), while injection water at Cobre Las Cruces Copper Mine undergoes an extensive reverse-osmosis treatment prior to injection (Baquero et al. 2016).

Although there is no pre-treatment required, Roy Hill and Cloudbreak Iron Ore Mines have injection systems allocated to either brackish or saline water depending on the water quality within the receiving aquifer (Windsor et al. 2012; Roy Hill 2021). Monitoring infrastructure and programs are in place for all mines included in this study to observe water levels and water quality within proximity of recharge facilities and nearby sensitive receptors.

Several active mines that predict increasing dewatering requirements with mine expansion have considered MAR for future water management. MAR in mining is still a new concept, so many of the mines included in this review are in the proposal or trial phase of MAR development. For example, Portia Gold Mine in South Australia conducted injection trials to better characterize paleochannels for potential re-injection of excess dewatering volumes in the future (Australian Groundwater Technologies 2013). Fosterville Gold Mine in Victoria, Australia carried out bore injection trials as an alternative mine water treatment and reuse strategy to their reverse-osmosis plant (Fuller and Hann 2018). In Nevada, Marigold Gold Mine and Relief Canyon Gold Mine have proposed recharging alluvial aquifers via rapid infiltration basins to manage excess mine-water volumes should dewatering requirements exceed the mine's consumptive use (Mine Development Associates 2018; OreWin Pty Ltd. 2022). A few prospective mines have even considered MAR during the pre-feasibility stages for the mine itself. Ghaghoo, a prospective diamond mine in Botswana, expects dewatering volumes to exceed operational demands and is required to dispose of excess water in an environmentally sustainable way (Johnstone et al. 2016). The mine considered several disposal options such as evaporation, constructed wetlands, water treatment for agriculture or domestic supply and game watering, but found re-injection to be the most economical and sustainable. The Mulga Rock Uranium project in Western Australia has proposed re-injection to manage surplus dewatering volumes to adhere to environmental conditions set by the Environmental Protection Authority (EPA) (Vimy Resources Ltd. 2020). The Bird in Hand prospective gold mine in South Australia has proposed and trialed MAR as a measure to manage, limit or remedy groundwater impacts to adjacent farms and wineries that may result from future mining operations (Terramin Australia Ltd. 2019). Prospective mines have been included to highlight the possibility that certain projects may only become feasible where sustainable water management strategies are proposed and utilized to manage surplus water volumes and limit groundwater impacts.

In addition to the mines listed above, there are a few cases of MAR and aquifer re-injection in the CSG and lithium brine sectors that are significant with respect to MAR in mining. Coal mine dewatering and CSG development are the most substantial groundwater users in the Powder River Basin of the USA, and are predicted to impact groundwater discharge to rivers, springs and surface water rights (Myers 2009). Re-injection of produced water into depleted coal seams and rapid infiltration basins near potentially affected rivers are recommended methods to mitigate the impacts to the groundwater flow regime, provided river water quality is not degraded. Reedy Creek in the Surat Basin of Queensland, Australia uses deep re- injection of treated CSG produced water to bank large volumes for later agricultural use and expanded beneficial use of CSG produced water to a broader community (ACIL Allen Consulting 2018). The injection scheme manages produced water from over 2000 CSG wells, and when commissioned in 2015 was the largest re-injection scheme in Australia. Benefits of this project are environmental and economic, as re-injection is less expensive than alternative techniques for managing production water. In addition, prospective lithium brine extraction operations in South America have proposed re-injection of brine, once lithium has been removed using ion exchange beads, as the water chemistry will otherwise remain unchanged (Lake Resources NL 2020). This method is proposed to preserve the local water balance and environment, as well as mitigate against subsidence.

Feasibility of MAR in Mining

Groundwater extraction and recharge by mining is significant. In some areas, particularly in arid to semi-arid regions where multiple large-scale mines operate, mining is the largest consumer of water (Jones 2012). Groundwater extraction and injection licenses for mining operations can range up to 150 GL/year (e.g., [Cloudbreak] Government of Western Australia Department of Water and Environmental Regulation 2021a). For comparison, the largest urban MAR scheme in Australia is the Perth Groundwater Replenishment Scheme, which injects 14 GL/year (Government of Western Australia Department of Health 2020). In recent decades, surplus mine water has started to be re-evaluated as a resource rather than just waste during the mine life (El Idrysy and Connelly 2012). This includes using it for agriculture (e.g., Synergistics Environmental Services 2013; Rio Tinto 2015), environmental management (e.g., Bucher et al. 2010; BHP Billiton 2016), and even mine-closure (e.g., Jones 2012; Rozkowski et al. 2021; Bozan et al. 2022). MAR fits with mine water management, as it allows for disposal of surplus water while at the same time preserving groundwater for sensitive ecosystems and users, including the mine itself.

The main determining factor on whether MAR is feasible for mining is if surplus water is available. Mine development and operations are heavily reliant on the availability of significant volumes of water for activities such as building access roads, processing ore and dust suppression. For mines where water supply from production bores and dewatering activities equals the needs of the mine, there would be no surplus water to manage, therefore MAR would not be considered. Some mines use MAR schemes seasonally in regions with wet/dry seasons where water level and availability fluctuate significantly (e.g., [Mount Whaleback] RPS Group 2015). This allows mines to bank water during the wet season, for improved water availability during the dry season. Alternatively, where dewatering volumes exceed the needs of mining operations, MAR becomes feasible as a tool to manage that surplus.

The presence of a groundwater shortage versus surplus is generally dictated by aquifer transmissivity. Transmissivity influences the volume of water extracted during dewatering, as well as the capacity of an aquifer to accept injected or infiltrated volumes (Drury 1998). It will also affect the shape and extent of the drawdown cone away from the pit. If transmissivity is low, the drawdown cone will be very steep and only impact water levels within closer proximity of the mine workings. This would suggest that MAR may not be a viable groundwater management tool for below water-table mining in tight aquifers, as there may not be any surplus volume to dispose of or drawdown impacts away from the mine.

Where aquifer transmissivities are high, greater volumes of water need to be pumped to lower the water table, and the cone of depression may extend significant distances from the pit, impacting groundwater dependent ecosystems and aquifer users. MAR can address these concerns, provided there is access to a recharge area where transmissivity is sufficient to accept injected volumes.

Water quality must also be considered for MAR feasibility, as regulations often require that injected water be of similar or better quality than the receiving aquifer (Waterhouse et al. 2017). In many cases, clean surplus groundwater sourced from dewatering is routed to injection wellfields or infiltration structures without pre-treatment requirements (Yungwirth et al. 2017). However, contaminated water may be treated prior to recharge, depending on water quality conditions stipulated by government regulators. This can become a limiting factor with MAR feasibility for mining operations, as water treatment is one of the most expensive elements of MAR schemes (Ross and Hasnain 2018). Despite this, appropriate hydrogeological investigations can demonstrate to regulators that treatment may be unnecessary due to natural dilution processes in the subsurface. Davis et al. (2022) used field data, hydrogeological modeling, and geochemical analysis to assess the need for treatment of mine dewatering water with 0.045 mg/L arsenic (As) prior to discharge via rapid infiltration basins. The study demonstrated to the Nevada State Division of Environmental Protection that through dispersion and attenuation the state reference value of 0.010 mg/L As and the natural background level of 0.015 mg/L As would be met at all monitoring wells. Permission to discharge directly to the subsurface was obtained, eliminating the need to construct several water treatment plants. Where mines already have advanced water treatment facilities, pre- treatment may not be a restrictive issue. However, if treatment facilities and infrastructure are required for MAR where they do not already exist, an extensive cost–benefit analysis would be required. Other jurisdictions have demonstrated interest in encouraging mines to undertake MAR activities to manage surplus water. Western Australia, for example, has specifically removed re-injection/infiltration of mine dewatering excess from their MAR definition, as it is the return of water abstracted (usually to the same aquifer) rather than input of additional water (Government of Western Australia Department of Water and Environmental Regulation 2021a, 2021b). This change in mine water guidelines may reduce the strict regulatory approvals process required for other MAR schemes.

In addition to hydrogeological and hydrochemical considerations, economics and government policy must also be well understood (Megdal and Dillon 2015). The relatively slow adoption of MAR is likely a result of uncertainty with its economics (Maliva 2014; Ross and Hasnain 2018; Vanderzalm et al. 2022). Financial, social and environmental benefits of MAR must be demonstrated to equal or exceed upfront and operational costs and show a distinct advantage over other water management strategies (Maliva 2014). Upfront costs include land, feasibility studies, consulting fees, construction supplies and labor, as well any regulatory testing required. Operational costs include labor, utilities, routine testing, maintenance, and water treatment if necessary. Key factors influencing the relative costs of MAR include MAR system type, water treatment, scheme scale, frequency of use, lifespan, and hydrogeological setting (Ross and Hasnain 2018). A few studies have provided estimates for MAR costs in non-mining environments (e.g., Ross and Hasnain 2018; Zheng et al. 2021; Vanderzalm et al. 2022). Cost components in these studies include source water capture, pre-treatment, recharge, aquifer storage, recovery, post-treatment, and end use. (NRMMC-EPHC-NHMRC 2009). Many of these components can be eliminated as added expenses for mines. For example, source water capture is not an added cost where injected volumes are sourced from the dewatering process. Where groundwater is extracted from and injected into the same aquifer within a closed system (i.e., no exposure to air or other fluids), pre-treatment is often unnecessary. Recovery, post-treatment, and end use can generally be eliminated, unless they become part of the MAR program objectives financed by the mine. Additionally, mines can avoid added costs where land is easily accessible and trained maintenance personnel are already employed. When executed properly, MAR schemes have the potential to be considerably less expensive than other groundwater management strategies. Social and environmental values of water should also be included in cost–benefit studies (Maliva 2014).

Challenges and Opportunities for MAR in Mining

MAR schemes for mining are diverse and designed to suit site-specific objectives, geological conditions, limitations, and licensing requirements. Despite the customisation of MAR schemes, common challenges have been reported and new opportunities investigated.

Challenges

Groundwater mounding and expression at the surface is a common challenge associated with MAR, particularly where it can impact sensitive ecosystems. Predictive groundwater flow models are often used not only to estimate drawdown, but also for mounding around recharge facilities (e.g., BHP Billiton 2016; GHD Group Pty Ltd 2019). Water levels around recharge infrastructure must also be regularly monitored during infiltration and injection to ensure the water table remains within an acceptable range. Mining Area C Iron Ore Mine in the Pilbara Region of Western Australia has a vegetation monitoring program to closely observe any degradation to vegetation quality due to recharge activities (Government of Western Australia Department of Environmental Regulation 2014; BHP Billiton 2016). Where mounding is a real concern for mines with active MAR schemes, infrastructure solutions must be in place. Cloudbreak Iron Ore Mine, for example, plans to add an additional 81 injection bores to minimize impacts of groundwater mounding, drawdown, and ponding (Government of Western Australia Department of Water and Environmental Regulation 2021a). The Pipeline Infiltration Project in Nevada rotates infiltration among rapid infiltration basins at each site to aid in the prevention of groundwater mounding and allow for rapid infiltration basin maintenance and improved performance (Nevada Gold Mines LLC 2021).

Clogging is among the most common problems encountered with MAR and can be the result of physical, chemical, or biological processes (Drury 1998; Bouwer 2002; Zhang et al. 2020). Surface filtration, pretreatment, periodic well backwashing, chlorine treatment, and closed systems that block exposure to light and oxygen are well known methods for preventing and managing clogging issues. Potential clogging mechanisms and the associated impacts on well performance were investigated during a MAR trial at BHP Billiton's Mining Area C (Smith 2014). The study recommended several techniques to help mitigate the risks of clogging including: (1) screening only across one hydrostratigraphic unit; (2) analyzing the screen biofilm layer; (3) conducting step-tests pre- and post-pump test using equal rates for improved well efficiency analysis; and (4) conducting short-term specific injectivity tests during injection trials to investigate clogging. This last recommendation involves shutting down the system, allowing a 90% recovery, and measuring the short-term response upon restarting. Cloudbreak Iron Ore Mine has trialed various down-hole valves to manage clogging risks associated with water cascading and air entrainment within injection bores (Windsor et al. 2012). They also only operate a portion of their injection bores at a time, leaving the others for standby or future use. This is helpful with bore maintenance and reducing the risks of well performance degradation due to clogging. At Cobre Las Cruces Copper Mine, the extensive reverse-osmosis treatment provides microbiological purification and eliminates colloids that could result in well clogging (Baquero et al. 2016). After the first 10 years of operations, only three re-injection wells required cleaning at Cobre Las Cruces.

Where advanced filtration and treatment are not necessary for MAR, mining companies should consider developing infrastructure that allows for rotation of injection or infiltration structures and should assess the options for well maintenance by treatment or backflushing versus well decommissioning and replacement.

In regions where several mines exist within proximity of each other, groundwater systems and sensitive receptors may overlap between different operations. This requires both sites to understand the shared impacts of dewatering on downstream receptors, as well as the responsibility to design a MAR scheme that does not negatively impact neighboring operations. Mining Area C Iron Ore Mine and Hope Downs 1 Iron Ore Mine in the Pilbara region of Australia share cumulative effects of drawdown due to dewatering as well as sensitive ecological receptors (BHP Billiton 2016). Mining Area C has considered the influence of Hope Downs dewatering and mine-closure plans in their water management strategy and predictive groundwater models. To reduce the risk of increasing groundwater inflows to the Hope Downs dewatering operations, MAR borefields for Mining Area C are situated to the west of the pit, as Hope Downs is located to the east-southeast. In Nevada, the Carlin Trend has a regional hydrological model to monitor water levels and predict future dewatering requirements for several mines and considers influence from a number of gold mines including Goldstrike, Gold Quarry, Genesis and Emigrant to name a few (Nevada Gold Mines LLC 2020a). It is also possible for multiple dewatering operations to share MAR infrastructure, where access and business operations allow. Pipeline Gold Mine and Cortez Hills Gold Mine are owned by the same company and located within close enough proximity to utilize the same rapid infiltration basin structures for their MAR program (Nevada Gold Mines LLC 2021).

Limited sharing of information from successful or failed MAR schemes provides a challenge for the adoption of MAR in mining. Most reviews on MAR highlight the lack of information sharing and how much value it would add for the future adoption and success of MAR for groundwater resiliency. With more public information, scientists and policy makers would be better equipped to set appropriate guidelines for MAR in mining within local jurisdictions.

This would also make it more appealing for funding agencies, decision makers, and involved stakeholders to consider MAR for current and prospective mine sites.

Opportunities

Several uses for MAR in mining have been addressed in this paper including: (1) surplus water disposal; (2) environmental protection; (3) aquifer preservation for groundwater users; and (4) adherence to zero surface discharge licensing (see Supporting Information).

There are also new opportunities.

There is an opportunity to use MAR infrastructure for water supply, should there be fluctuations between excess water and water shortages during the life of mine. Using the same well for injection and production is a common MAR practice in urban settings (Dillon et al. 2009). A similar approach is also used in geothermal fields where injection wells are converted to production wells (Kamila et al. 2021). This has been proposed for mining environments but is not currently a common practice. For instance, BHP's Mining Area C Iron Ore Mine has proposed that their Camp Hill borefield be used from 2018 to store surplus water, and subsequently be used as water supply after 2035 when modeling projections predict increasing water requirements beyond what the dewatering system can supply (BHP Billiton 2016). This technique can reduce the capital costs and risks associated with drilling new wells.

Where abandoned mine pits occur in proximity to existing mines, there is an opportunity to use these for MAR. This may reduce costs associated with construction of injection bores or infiltration galleries. In southern Poland, groundwater flow modeling found that pumping dewatering volumes into an adjacent closed mine pit would limit the spread of the drawdown cone, resulting in decreased river infiltration and reduced impacts on the aquatic environment (Rozkowski et al. 2021). Leakage of water from the closed mine pit would recharge the aquifer and avoid the need for bore injection.

There is also a potential opportunity to use MAR as a deliberate tool to accelerate post- closure groundwater level recovery. Ceasing of dewatering operations following mine closure triggers groundwater levels at and around mine sites to recover. Depending on climate and hydrogeological conditions, the recovery may take tens to several hundreds of years. Cook et al. (2022) found that groundwater recovery post-mine closure may be enhanced by optimizing re-injection distances from the pit so that injected water flows back to the closed pit soon after mining and dewatering operations have ceased. Water management post- closure is one of the most important aspects of environmental protection, and effective water management strategies during the mining process can significantly reduce the costs associated with rehabilitation (El Idrysy and Connelly 2012). The strategic use of MAR for mine-closure is not described and does not appear to have influenced system design at any existing mine sites.

Conclusion

MAR is an effective strategy to dispose of surplus water, while at the same time preserve aquifers for groundwater users and environmental protection. This review summarizes MAR schemes for 27 mines, including 15 active mines with fully operational MAR schemes, eight active mines with proposed or trialed schemes, and four prospective mines where MAR is proposed for future water management. MAR feasibility is primarily driven by the need to dispose of surplus water, the presence of appropriate hydrogeological conditions, and economics. Groundwater mounding and expression at the surface, well clogging and the risk of groundwater interactions with adjacent mines are potential challenges for MAR in mining. However, it is possible that MAR infrastructure can be used for both injection and extraction where there are fluctuations between a water surplus or shortage. There is also potential for MAR to help facilitate groundwater recovery post-mine closure through the process of recharging aquifers during the life of mine. The environmental and economic benefit of MAR may be greater where it is designed and implemented during the initial stages of dewatering and utilized throughout the entire mine life. There is a need to improve information sharing within the mining community to help improve the uptake of MAR for mining and ensure the success of newly designed schemes.

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Authors' Note

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Table S1. Mine site MAR scheme details including mine name, GPS coordinates (WGS-84), MAR purpose, target aquifer, as well as aquifer properties such as conductivity, transmissivity and storativity.

Table S2. MAR scheme infrastructure, volumes and challenges. This includes dewatering volume (GL/yr), dewatering bores (#), injection/infiltration volume (GL/yr), bores/infiltration structures (#), and distance of recharge structures to mine pit (km).

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