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PAPER

Groundwater-level recovery following closure of open-pit mines

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Abstract
Open-pit mining has increased substantially over the past two decades. Many currently operating open-pit mines are facing the end of mine-life over the next few decades and, increasingly, focus is shifting towards mine-closure planning that provides evidence on available closure options under the given geological, hydro(geo)logical and climatic conditions. This study uses synthetic groundwater modelling to build basic process understanding of closure options and how these will determine the formation of pit lakes. This governs the long-term pit lake water quality and how postmining landscapes may be utilised. Simulations show that the recovery time of postmining groundwater levels increases with decreasing aquifer transmissivity. Final postmining water tables are predominantly controlled by the implemented mine closure options and climatic conditions. The most important decision is, thereby, whether to backfill the pit to above the water table or allow a pit lake to develop. Under moderately transmissive aquifer settings, backfilling of pits leads to rapidly rising groundwater levels within the first decade after mining, with water-table recoveries of above 70%. If mine voids remain unfilled, evaporation from the pit lake surface becomes a governing factor in determining whether the unfilled mine pit becomes a terminal sink for groundwater. Lake levels may remain subdued by several 10s of metres in arid to semiarid climates. If surplus surface water can be diverted into open pits, rapid filling can accelerate groundwater recovery of open pits in regions of low permeability. This is a less successful management option in transmissive aquifers.

Keywords Groundwater management · Mine closure · Pit lakes · Groundwater recovery · Numerical modeling

Introduction

Where open-pit mines extend below the position of the natural water table, they will usually be dewatered to create a dry mining environment (Younger et al. 2002). For pits in very low permeability environments, where rates of groundwater inflow are low and unlikely to cause slope instability, mine dewatering is often accomplished using in-pit pumps. Water is collected in drains and channels within the pit and directed to low points or sumps from where it is pumped to a disposal point (Preene 2015). In higher permeability environments, in-pit pumping will often not be sufficient to remove inflowing groundwater, and vertical dewatering wells are typically installed around the perimeter of the mine pit. While the purpose of the dewatering bores is to create a dry mine, which is achieved by lowering the regional water table, sometimes for distances of several kilometres around the pit (e.g.; Loupasakis et al. 2014; Cook et al. 2017; Roy Hill 2018). Volumes of water pumped to dewater pits vary widely, but for large mines in permeable aquifers, it can be over 2,000 L/s (Cloudbreak 2006; Roy Hill 2019). After mine closure, the groundwater will begin to recover, but complete recovery of the groundwater may take many years or may not occur at all (e.g. de Graaf et al. 2019). The rate and extent of groundwater recovery are important, as it determines the evolution of pit lake water level and influences the evolution of lake water quality, in the case where the pit is not backfilled

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after mine closure. The rate of groundwater recovery may also be important for groundwater-dependent ecosystems surrounding the mine. In some cases, these ecosystems are irrigated during mining operations to prevent adverse impacts, but their fate post-mine closure is sometimes unclear (Cook and Dogramaci 2019).

There are several analytical models that have been specifically developed to estimate the volumes of groundwater required to be pumped to dewater large mines (e.g. Hanna et al. 1995; Vandersluis et al. 1995; Marinelli and Niccoli 2000). However, these dewatering models only allow calculation of groundwater inflows to the mine when groundwater levels stabilise during mining and they cannot predict the rate of expansion of the drawdown cone over time or the subsequent recovery of groundwater levels after mine closure. While most mine developments undertake numerical groundwater modelling of the magnitude of water-table drawdown and the time for water-table recovery following mine closure, these are inevitably site-specific models representing particular scenarios (e.g. Zhao et al. 2017; Shevenell 2000a, b; Ardejani et al. 2007). They are often not sufficient to build a general understanding of processes. To date, there have not been any more generalised studies that have examined how hydrogeological and climatic parameters influence rates of water level recovery or the efficacy of management interventions to influence the rate of recovery. However, given that open-pit mining has increased substantially over the past two decades and will continue to increase into the foreseeable future due to improvements in methods that enable metal extraction from lower-grade ores (e.g. Mudd 2010; Miller et al. 1996), it is crucial to improve basic process understanding of the rebound of regional groundwater levels postmining as well as its impact on the development of pit lakes.

In this study, synthetic groundwater modelling was used to improve understanding of the evolution of the groundwater system in affected open-pit-mining areas following mine closure. The developed models are based loosely on the large open mine pits in the Pilbara region of Western Australia to ensure realistic open mine operations are replicated within the synthetic model set-up while avoiding being site-specific. The climatic conditions and the open pit, bulk mining operations in the Pilbara are comparable to many other open-pit hard rock mining regions around the world, such as mining operations in the arid west of the USA (Miller et al. 1996), mining provinces in the semiarid parts of Southern Africa (de Graaf et al. 2019; van Zyl Dirk and Straskraba 2012) and South America (van Zyl Dirk and Straskraba 2012).

The synthetic modelling examines the rate of groundwater recovery post mine closure under different environmental and management actions. Specifically, it examines how the rate of groundwater recovery is influenced by aquifer hydraulic conductivity, aquifer storage, and how it varies between pits that are backfilled and those that are not backfilled. It also examines the effect of the composition of pit backfill materials (for pits that are backfilled), and the effect of evaporation and recharge for nonbackfilled pits. Finally, the effect of rapid filling of pits was examined using another water source (dewatering from adjacent mines or diversion of river flows) on water level recovery.

Methods

Field site used for model evaluation

A synthetic groundwater flow model was developed based loosely on the Hope Downs North mine as a "classical" large open-pit mine of the Pilbara region of Western Australia. The Pilbara region is characterised by widespread and varied mineralization, including one of the largest iron ore deposits in the world. Consequently, a high number of large open-pit mines operate in the area, all of which require rehabilitation, when mining operations conclude.

Hope Downs North, like most open pits in the region, extends below the water table and dewatering is required to maintain dry pit conditions during mining operations. At the site, a groundwater abstraction license of 100 ml/day has been in place for the mine since 2007. These abstraction rates are representative for open-pit mining operations in moderately transmissive aquifers, and comparable to, e.g. the Victor diamond mine in Northern Ontario, Canada (~870 L/s, de Graaf et al. 2019) or the Betze open-pit gold mine in north-eastern Nevada (2,500 L/s, Miller et al. 1996). Dewatering causes a cone of depression to develop during mining, which maintains the groundwater level below the base of the pit, but also extends regionally beyond the mine itself. At Hope Downs North, the impacted area is approximately 8 km^2, while groundwater drawdown at the mine pit itself is ~75 m (Cook et al. 2017).

The climate of the region is characterised by a semiarid climate with maximum mean temperatures reaching 39.2 °C in December and minimum mean temperatures of 6.5 °C in July (1996–2021, weather station 007151 at Newman). Rainfall exhibits high variability with thunderstorms and tropical cyclones over the summer months contributing most to the mean annual rainfall of 325.1 mm/year (1971–2021). SILO interpolated class A pan evaporation ranges between 3,500 and ~2,860 mm in elevated regions of the Pilbara (Jeffrey et al. 2001), i.e. potential evaporation exceeds rainfall by about one order of magnitude. The climatic conditions restrict groundwater recharge with estimates based on ^{14}C data varying between 1.3 and 13 mm/year (Cook et al. 2017).

Numerical model approach and model setup

Loosely based on the mine dimensions and observed groundwater level changes during the Hope Downs North mining operation, a groundwater flow model was developed which simulated a theoretical single pit mine excavated over a 20-year period at a consistent rate to a final pit depth of 90 m below ground level (Fig. 1). This was followed by groundwater recovery simulations following mine closure over a time span of 100 years (Fig. 2). Initial conditions were obtained through a steady-state model run, which simulated the premining groundwater levels under natural groundwater recharge conditions prior to pumping. The models were implemented numerically using the USGS code MODFLOW applying the Newton formulation of MODFLOW-2005 (MODFLOW-NWT), which provides capabilities to simulate drying and wetting of groundwater model cells during dewatering and water level recovery (Harbaugh 2005; Niswonger et al. 2011).

The 3D model had a lateral extension of 100 km in both x and y directions, selected such that boundaries were sufficiently far from the open-pit area to not impact groundwater levels at the pit during dewatering and recovery simulations. Grid cell sizes increased from 25 m within the pit area at the centre of the model to 5,000 m at the outer model fringes, where a general head boundary was implemented. The subsurface was separated into seven layers and specified as unconfined up to a model depth of 30 m (model layer 1), while unconfined or confined conditions were simulated to a depth of 225 m below ground, depending on the water level elevation in the aquifer (model layers 2–7, Fig. 1). A constant recharge rate of 5 mm/year was applied across the model domain (Table 1).

The mine void was located at the centre of the model and had a lateral extension of 2 km in the x and 1 km in the y direction at surface, based on the extension of the Hope Downs North dry pit area. Pit walls were characterised by a slope of ~30%, with the open void decreasing in areal extend from the surface (model layer 1) to its maximum depth at 90 m (model layer 4) (Fig. 1). The total mine void volume below the premining groundwater level is 155×10^6 m^3. The open mine void was represented numerically through

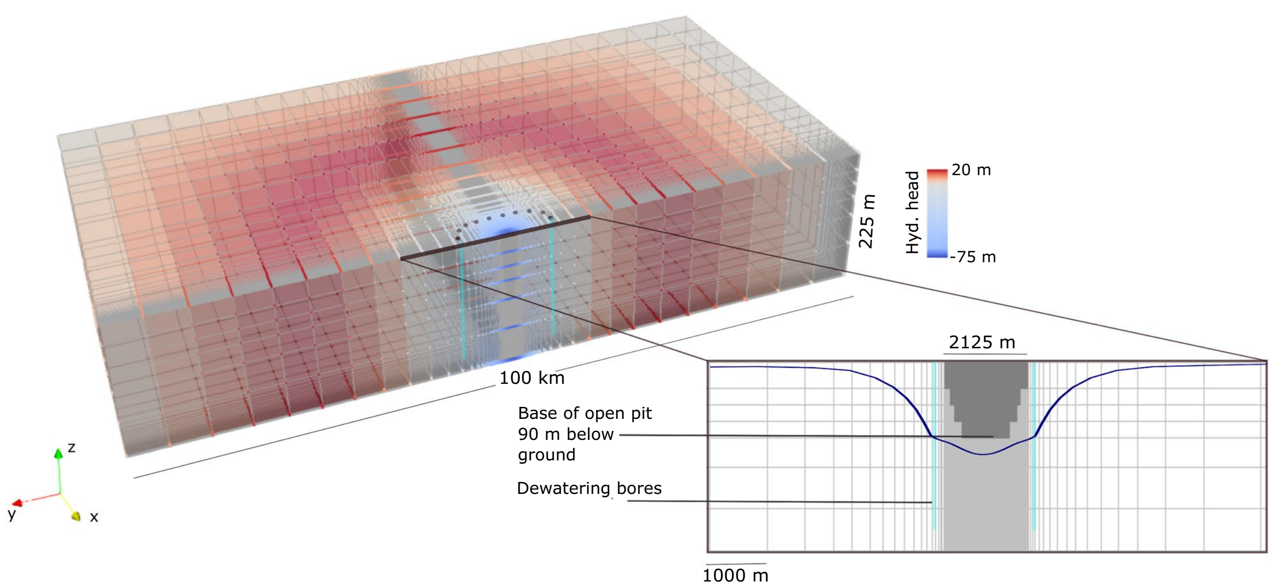

Fig. 1 The 3D model has a lateral extent of 100 km in both x and y directions (one half of model shown here). Grid cell sizes increase from 25 m within the pit area at the centre of the model to 5,000 m at the outer model fringes, where a general head boundary is implemented. The subsurface is separated into seven layers and specified as unconfined up to a model depth of 30 m (model layer 1: 25 to −5 m). Model layers 2–7 (−5 to −200 m) are specified as convertible, i.e. variably saturated conditions (confined/unconfined) are simulated. Hydraulic heads are shown which outline a cone of depression that develops after 20 years of mine dewatering (blue line in 2D cross-section and colour scheme in 3D cross section)

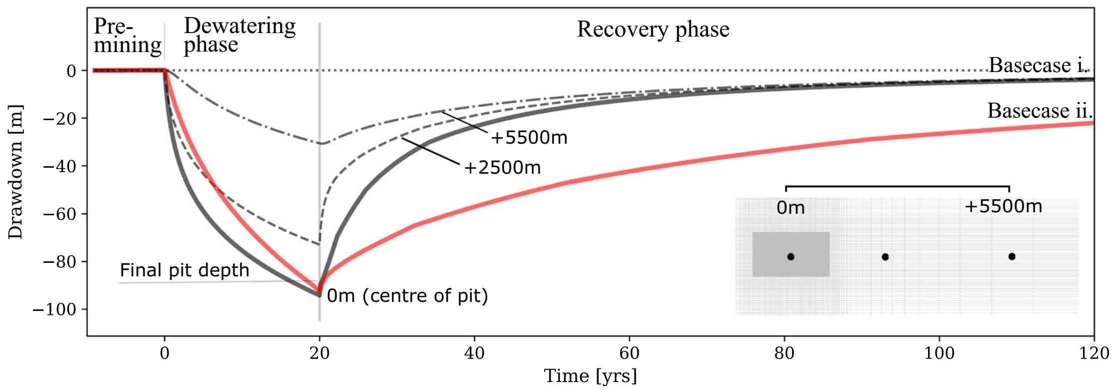

Fig. 2 Premining (steady-state) groundwater levels decline during a 20-year dewatering phase, followed by the recovery of hydraulic heads postmining (100-year recovery phase). The numerical model simulates 20 abstraction bores dewatering a pit that is approximately 2 km × 1 km in size, pumping a combined rate of 80,000 m^3/day (basecase i) and 20,000 m^3/day (basecase ii) over the life of the mine. The simulated water level recovery is shown for the centre of the pit under moderately transmissive (basecase i, black lines) and less transmissive (basecase ii, red lines) geological conditions and under the assumption of an open void and negligible evaporation (scenario pit lake-1, Table 1). A further two observation points illustrate the drawdown at 250 and 5,500 m to the east of the pit as moderately transmissive (basecase i) conditions

the MODFLOW lake package (LAK; Merritt and Konikow 2000). This allowed the mine pit to be represented as a volume of space within the model grid, that fell dry during dewatering and rewetted during groundwater level recovery (Table 1). The transient flow model was run for a simulation period of 120 years, commencing with steady-state premining aquifer conditions under natural groundwater recharge. To represent the dewatering (20 years) and recovery phase (100 years) the simulation time was discretized into two hydraulically differing stress periods each divided into timesteps, which allowed close tracking of water levels over time, while ensuring a water budget error of below 1% throughout the simulation.

Dewatering simulation

Most large open pits will eventually intersect the water table during mining, and consequently dewatering is required over the life of the mine to maintain a dry mining environment. Typically, dewatering is achieved through production bores installed around the perimeter of the mine pit. For the numerical dewatering model, the production bore configuration and abstraction rates were loosely based on the Hope Downs North dewatering operations, with abstraction wells located at a distance of 50–1,300 m around the mine perimeter (Cook et al. 2017).

The dewatering model included 20 production wells, screened over a depth of 150–200 m (model layer 7) and located around the perimeter of the simulated mine void (Fig. 1). A consistent pumping rate was chosen so that the water table was drawn to below the final pit depth of 90 m over the hypothetical 20-year mine schedule. This required an abstraction rate of 80,000 m^3/day for a moderately transmissive aquifers system (basecase i, Table 1), while a rate of 20,000 m^3/day achieved the required water level drawdown in a geologically tighter groundwater system (basecase ii, Table 1). Each bore was allocated the same abstraction rate (4,000 and 1,000 m^3/day respectively) with pumping continuing over a time span of 20 years.

The resulting flow model was able to simulate the expanding drawdown cone created by the dewatering bores and allowed the mine pit to be fully dewatered. The dewatering simulation served as the initial hydraulic condition for the subsequent analysis of groundwater level recovery scenarios following mine closure.

Recovery model

Following mine closure, dewatering operations usually cease, and the groundwater will immediately begin to recover in the vicinity of the mine pit. Local hydrogeology and climate thereby determine how rapidly open-pit mines fill with water after closure; however, full recovery may take decades to centuries or may not occur at all (e.g. Cook et al. 2021; Gammons et al. 2009).

The recovery model was run over a period of 100 years and quantified the rate of groundwater level recovery as well as transient groundwater level depths postmining. The production wells were “turned off” (i.e. 0 m^3/day abstraction rate) and the groundwater level rebound was evaluated based on a number of closure options (Table 1).

Table 1 Simulated mine closure options

Scenario	Comment	*K* and *S* within pit	Recharge within pit	Net evaporation within pit
During dewatering:				
Basecase i	Moderately permeable aquifer	Aquifer material (Kh/Kv = 1.65/0.165 m/day; Sy = 0.01; Ss = 1×10^{-4})	Natural recharge (5 mm/year)	-
Basecase ii	Lower permeability aquifer	Aquifer material (Kh/Kv = 0.165/0.0165 m/day; Sy = 0.01; Ss = 1×10^{-4})		
During recovery, postmining:				
Open-pit scenarios:				
Pit lake-1	Groundwater level recovery under open-pit conditions	Open void[a]	-	-
Pit lake-2		Open void[a]	-	Net evaporation (ET − rain): 1,000 mm/year
Pit lake-3		Open void[a]	-	Net evaporation (ET − rain): 2,000 mm/year
Pit lake-4		Open void[a]	-	Net evaporation (ET − rain): 3000 mm/year
Backfilling scenarios:				
Backfill-B1	Groundwater level recovery for different backfill materials, including changes in permeability (B1–B5) and storage properties (S1–S2). Recharge rates may be elevated due to less compaction of backfill material compared to undisturbed host rocks (R1–R2)	Kh; Kv of basecase i or ii	As basecase	-
Backfill-B2		Kh; Kv of basecase i or ii × 100; Sy = 0.01; Ss = 1×10^{-4}	As basecase	-
Backfill-B3		Kh; Kv of basecase i or ii /100; Sy = 0.01; Ss = 1×10^{-4}	As basecase	-
Backfill-B4		Kh; Kv of basecase i or ii /1,000; Sy = 0.01; Ss = 1×10^{-4}	As basecase	-
Backfill-B5		Kh; Kv of basecase i or ii /10,000; Sy = 0.01; Ss = 1×10^{-4}	As basecase	-
Backfill-S1		Ss; Sy × 10; Kh; Kv of basecase i or ii	As basecase	-
Backfill-S2		Ss; Sy /10; Kh; Kv of basecase i or ii	As basecase	-
Backfill-R1		As basecase i or ii	10 mm/year	-
Backfill-R2		As basecase i or ii	50 mm/year	-
Rapid filling of open-pit scenarios:				
Rapidfill-1	Groundwater level recovery of an open pit if rapid filling occurs over the first 150 days postmining	Open void[a]	Rapid filling: 1 × pit vol	-
Rapidfill-2		Open void[a]	Rapid filling: 1 × pit vol	Net evaporation (ET − rain): 3,000 mm/year
Rapidfill-3		Open void[a]	Rapid filling: 0.5 × pit vol	Net evaporation (ET − rain): 3,000 mm/year
Rapidfill-4		Open void[a]	Rapid filling: 0.25 × pit vol	Net evaporation (ET − rain): 3,000 mm/year

[a]An open void is implemented through the MODFLOW lake package

Simulated mine closure options

The simulated mine closure options included: (1) backfilling the pit with different backfill materials; (2) not backfilling, thereby allowing the formation of a pit lake subject to rainfall and evaporation and (3) rapid filling of the open pit through surplus water from surface water courses.

Backfilling of the open void

Where the amount of ore extracted is less than the volume of material mined, mine void closure strategies may include backfilling of the pit void (Williams 2009). Backfilling may occur with waste rock and/or with tailings, which, overall, will result in different hydrogeological properties of the backfilled mine area compared to the undisturbed geological material premining. Thereby, only a fraction of the original pit volume requires refilling due to the volume occupied by solid particles.

Model scenarios were run to quantify the rate of water level recovery and final groundwater level after 100 years postmining for different backfill materials. The hydraulic conductivities and storage properties of the backfill was varied over several orders of magnitude (backfill B1-5 and backfill S1-2, Table 1), while different recharge rates across the pit were implemented to reflect changes in groundwater recharge due to varying compaction and permeability of backfill material (backfill R1-2, Table 1). The hydraulic properties and hydraulic stresses applied to the model outside the mine pit area remained unchanged.

Pit lake development

For very large voids or for mines, where the mined ore comprises the majority of the mined-out volume, backfilling is often not feasible and mine voids remain open. Examples are open coal mines, with low overburden to coal ratios (e.g. Hancock et al. 2004) or high-grade iron ore (>60% Fe) mining operations which result in low ratios of waste rock removed to ore recovered. One possible management option for open voids is the creation of pit lakes. Pit lakes form by water filling these open pits through hydrological processes such as precipitation or groundwater level recovery (e.g. Castro and Moore 2000).

Model scenarios were set-up to quantify water level recovery in an open pit, where evaporation from and rainfall to the pit lake was taken into account (pit lake-1 to pit lake-4, Table 1). During groundwater level recovery, the temporally variable pit lake stage and water volume in the pit void were recorded. The rise in pit lake levels thereby coincides with a concomitant increase in lake surface area and therefore evaporative loss, due to the sloping mine walls implemented over four model layers.

Rapid filling of mine void

Without any management intervention, pit lakes can take decades to centuries to refill (e.g. de Graaf et al. 2019). This is undesirable in many cases, as it may increase the likelihood for slope erosion and adverse water quality outcomes, e.g. acid mine drainage due to prolonged exposure of pit walls and/or waste material to oxygen (e.g. Mantero et al. 2020). Rapid filling of mine voids is considered an intervention option, which may minimise these risks. However, it can also be considered a management tool which aids the return of the groundwater system to its final post-closure hydrological state (Schultze et al. 2011; Johnson and Wright 2003). Thus, a further scenario explored enhancing water level recoveries in open-pit mines through rapid water addition from the capture of intense rainfall events, diversions of surface-water courses or the use of water from other active pits into the open void (rapidfill-1 to rapidfill-4, Table 1). Rapid filling was implemented numerically by adding a fraction (F = 0.25 – 1) of the original open-pit volume (155×10^6 m^3) to the open void area during the first 150 days following mine closure.

Results and discussion

Dewatering phase

With the onset of pumping, the premining groundwater level commences to decline, and a cone of depression develops. After 20 years of continuous pumping, water levels declined by about 95 m in the centre of the pit, maintaining the water level below the simulated final depth of the 90-m-deep mine (Fig. 2).

The dewatering simulations highlight the effect of geology, i.e. aquifer transmissivity (*T*) and storativity (*S*) and the pumping rate on the rate of the water-table decline. For a given discharge rate, the cone of depression extends deeper in low-yielding aquifers (basecase ii) than in high-yielding ones (basecase i). Consequently, lower values of *T* and *S* enable pit dewatering at lower pumping rates. Thus, dry pit conditions were attained at a discharge rate of 20,000 m^3/day under basecase ii conditions. However, the abstraction rate had to be increased fourfold to achieve the same dewatering depth under basecase i conditions (Table 1; Fig. 2). This abstraction equates to a cumulative groundwater volume of 584×10^6 m^3 (basecase i) and 146×10^6 m^3 (basecase ii) being removed from the aquifer during the dewatering phase.

The area impacted by groundwater drawdown away from the mine increases with time; initially rapidly and then more slowly. Expansion of the cone of depression is thereby faster under more permeable conditions (basecase i), while a less permeable aquifer (basecase ii) results in a reduced lateral spread of the drawdown cone (Bresciani et al. 2020a; Figs. 3 and 4a,b). The areal extent of the water-table depression is, however, in both cases, significant. After 20 years of abstraction, the area within a radial distance of circa 12 km from the mine pit is impacted by water-level declines of more than 10 m (basecase i). This is reduced to a radial distance of about 6.5 km under less permeable conditions due to the steeper cone of depression (basecase ii; Fig. 4a,b). While the actual extent of the cone of depression at individual mine sites will vary according to the geology and structural geology as well as surface features that may recharge dewatered aquifers, groundwater impacts that extend several kilometres from the mine pit are commonplace (e.g. Zawadzki et al. 2017; Guzy and Malinowska 2020).

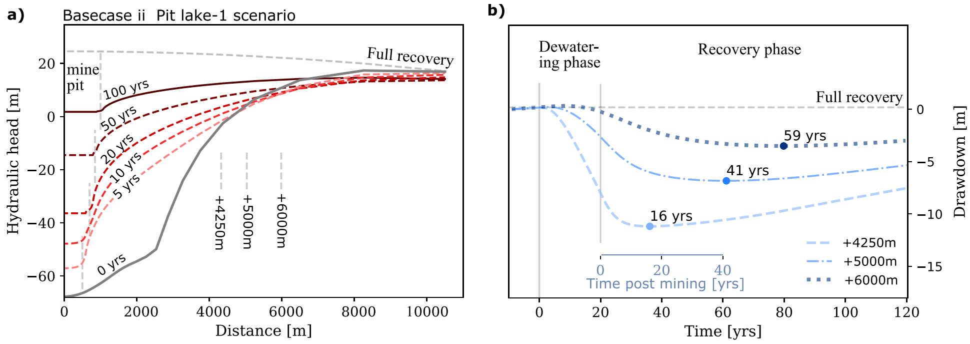

Fig. 3 **a** Cross section of water levels during recovery from the centre of the mine void to 10 km east of the mine pit at 0, 5, 10, 20, 50 and 100 years postmining for basecase ii (pit lake-1 scenario). The grey line illustrates the extent of the cone of depression at the end of mining (0 years postmining). **b** Drawdown over time 4.25; 5.0 and 6.0 km from the centre of the mining void shows the continued expansion of the cone of depression postmining. Time until maximum drawdown is shown in years postmining

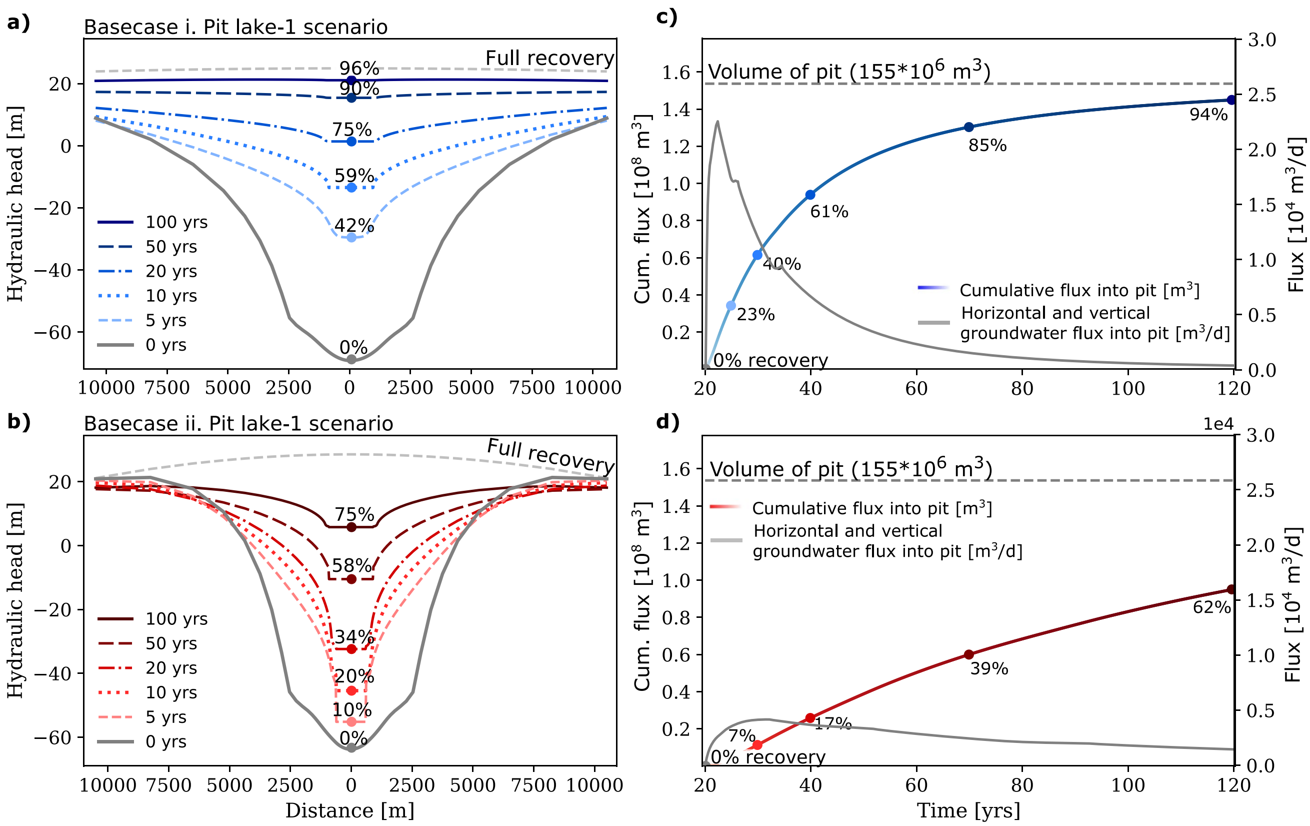

Fig. 4 **a–b** A 20-km E–W cross section through the centre of the mine void shows hydraulic heads and % recoveries of groundwater levels at 0, 5, 10, 20, 50 and 100 years postmining for basecase i (blue lines) and basecase ii (red lines). The grey lines illustrate the extent of the cone of depression at the end of mining. Percentage recoveries [%] are provided based on pit water levels. **c–d** Cumulative groundwater influx [m^3] and rate of influx [m^3/day] into the mine void [155×10^6 m^3] over time for basecases i and ii following mine closure. The model scenarios assume an open mine void and negligible evaporation from the developing pit lake (pit lake-1 scenario, Table 1). Percentage recoveries [%] are provided based on pit lake water volumes and differ from the % recoveries of water levels due to the slope in pit walls

Recovery phase

Following the cessation of pumping, water levels rise promptly in close proximity to the pit, but the drawdown cone continues to expand, and the water table continues to fall in areas further from the pit void (Bresciani et al. 2020b). Thus, the area potentially affected by mining continues to expand postmining and, accordingly, any ecosystems that are dependent on groundwater may be affected many years after mine closure. The continued expansion of the drawdown cone after pumping ceases occurs thereby irrespective of the hydraulic properties of the dewatered aquifer. Under basecase ii conditions, for instance, there is only minor drawdown recorded at 6 km from the centre of the mine pit during the dewatering phase; however, water levels continue to fall postmining and at this distance a maximum drawdown of 4 m occurs approximately 60 years after pumping has ceased (Fig. 3).

If the mine void is left open when mining ceases, a pit lake will form and groundwater levels simulated at the centre of the pit are equivalent to the water level in the developing pit lake (Fig. 4a,b). Under transmissive aquifer settings (basecase i) water level recovery is going to be rapid initially. Within 10 years following mine closure, groundwater levels will have recovered already to more than 50% compared to the premining levels, rising to over 70% after 20 years (Fig. 4a). This is the period in which the pit lake depth increases rapidly, i.e. from a dry pit when pumping ceases to a pit lake depth of approximately 50 m within 10 years postmining. During these early stages, groundwater inflow into the forming pit lake increases with time as the rising groundwater table enlarges the area through which seepage into the pit lake can occur, highlighting the transient dynamics of mine pit hydrology. The maximum groundwater flux into the pit occurs around 3 years postmining at a rate of around 22,000 m^3/day, comprising an upward flow component through the pit floor and a horizontal flow component through the pit walls (Fig. 4c). Groundwater influx then levels off as the hydraulic gradient towards the former mine void decreases with rising lake levels. This leads to prolonged recovery times and the final ~25% of groundwater level recovery requires >80 years of time (Fig. 4). As the pit lake level comes up to its final equilibrium elevation, and under the assumption that evaporation from the pit lake is negligible (pit lake-1 scenario), the groundwater flux approaches zero and recovery is concluded (Fig. 4c).

In less permeable environments, the influx into the mine is less dynamic, allowing for a more even inflow rate over time. The tighter geology, however, gives rise to a slower, albeit steadier increase in lake levels. After 50 years following cessation of mining, groundwater levels have recovered in this case by ~60% compared to premining levels. This translates into a recovery of about 40% of the total pit lake water volume. Percentage recoveries of pit water levels and pit water volumes differ due to the slope of the pit walls that leads to a decreasing void volume towards the base of the mine. Full recovery of water levels will greatly exceed 100 years (Fig. 4).

Recovery of water levels under different mine closure options

While the rate of groundwater recovery is mostly controlled by the aquifer hydraulic properties, the final steady-state postmining groundwater level within the pit is controlled mainly by the implemented mine closure options and the prevailing climatic conditions. Simulation results suggest that the most important decision is thereby on whether to backfill the pit to above the water table or allow a pit lake to develop.

Open void versus backfilling of mine pit

Figure 5 compares the groundwater level recovery of a backfilled mine versus a pit which remained unfilled. In the latter case, the recovering groundwater levels are equivalent to the water levels in the developing pit lake. If a pit remains unfilled, groundwater recovery within the pit is considerably slower, as the entire pit volume requires refilling, rather than the pore volume of the backfilling material. After only 10 years postmining, recoveries of over 70% are simulated for a pit backfilled with material of similar conductivity to that of the original host rock (backfill-B1, Fig. 5b,d). This decreases to 59% in an unfilled pit under negligible evaporation (pit lake-1 scenario, Fig. 4a); however, recovery rates are even less favourable if the evaporative water loss from the pit lake is taken into account (pit lake-2 and pit lake-4, Fig. 5). In these cases, groundwater recovery occurs until the net flux into the pit equals the evaporative loss from the pit lake. This determines the final equilibrium lake elevation level (Fig. 5c).

In arid climates, such as the Pilbara mining region of Australia, net evaporation (evaporation minus rainfall) can be as high as 3,000 mm/year (Jeffrey et al. 2001). This is not unusual and comparable, for instance, to mining areas in the arid West of the US, where net evaporation generally exceeds precipitation by ratios as high as 5:1 (Miller et al. 1996) or to the coal mining region of the Limpopo province in southern Africa, where evaporation exceeds precipitation by a factor of about four (Mpetle and Johnstone 2018). Under such conditions, evaporation exceeds groundwater level influx terms and the final pit lake level will remain permanently subdued below the premining water table. The unfilled mine pit becomes a terminal sink for groundwater. Under basecase i conditions, and an assumed net evaporation rate of 1,000 mm/year (pit lake-2 scenario) and 3,000 mm/year (pit lake-4 scenario), this results for instance in a final equilibrium lake level of ~15 and ~30 m below the premining groundwater head, respectively (Fig. 5a,c).

The situation is exaggerated if mine voids are located in lower permeability aquifers, as groundwater influx to the mine is restricted. Under basecase ii conditions, the developing pit lake will remain shallow after groundwater abstraction ceases, as the net evaporation rate matches the horizontal and vertical influx into the pit. Lake levels remain permanently subdued at about 50 and 65 m below the

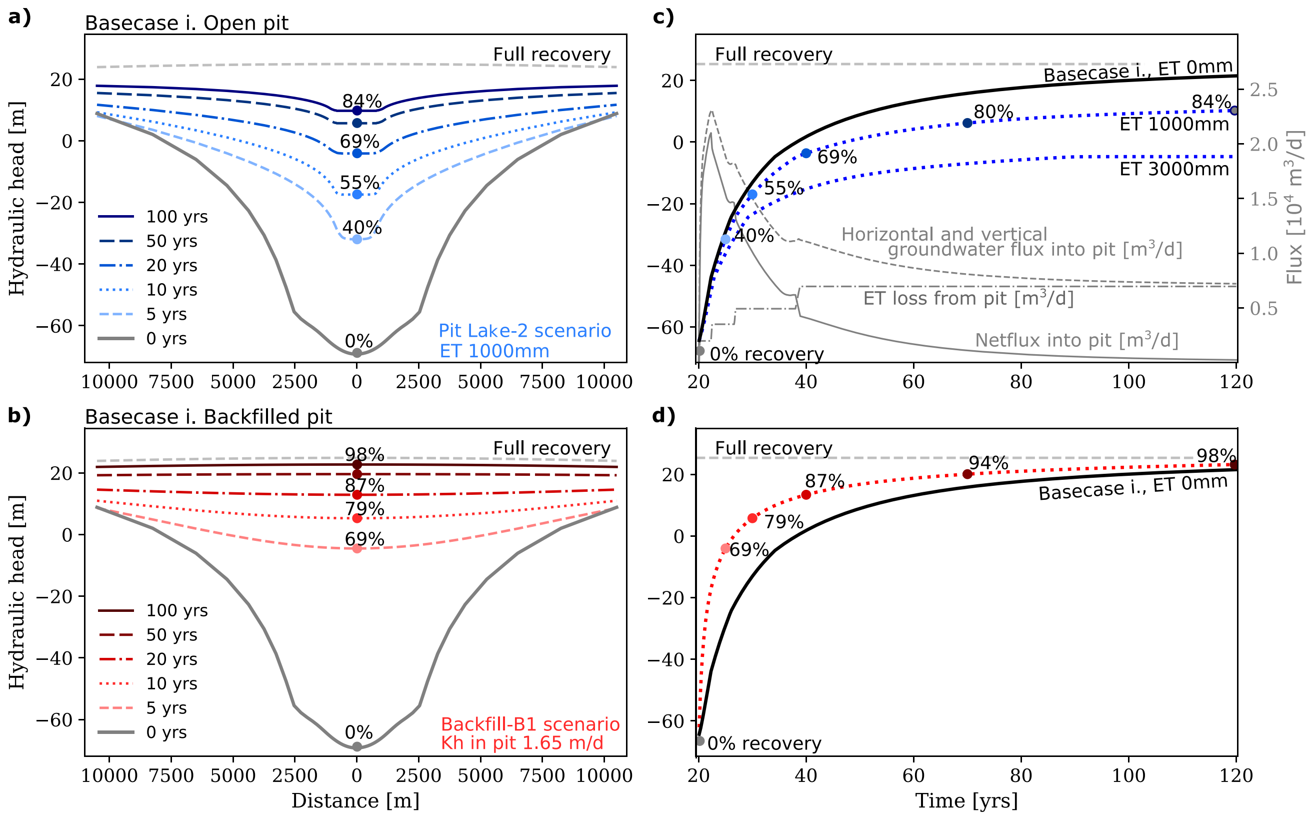

Fig. 5 **a-b** Recovery of water levels postmining along a 20-km E–W cross section through the centre of the mine void under open void conditions (pit lake-2: ET 1,000 mm, blue lines) compared to backfilled conditions (backfill-B1 – Kh 1.65 m/day, red lines) and % recoveries of groundwater levels at 0, 5, 20, 50 and 100 years postmining. **c** Recovery of water levels with time postmining under open void conditions (pit lake-2 – ET: 1,000 mm; pit lake-4, ET: 3000 mm, basecase i). Also shown is the recovery under negligible evaporation for comparison (pit lake-1, black line). Grey lines illustrate the rate of groundwater influx into mine void and loss from evaporation from the pit lake surface over time [m^3/day] (pit-lake 2 ET: 1,000-mm scenario). The loss through evaporation increases with time as the surface area of the pit lake increases with rising water levels. **d** Recovery of water levels with time postmining under backfilled conditions (backfill-B1 – Kh 1.65 mm/year, basecase i). Also shown is the recovery for an unfilled open pit under negligible evaporation for comparison (pit lake-1, black line)

premining groundwater table under 1,000 and 2,000-mm/year net evaporation rate, or pit voids may, indeed, remain dry under very high net evaporation rates—see Fig. S1 in the electronic supplementary material (ESM).

While evaporation will be most pronounced in hot and dry climates, it often still is a significant component of pit lake water budgets in dry, but colder regions. For instance, the Berkeley pit lake in Montana, US, is estimated to lose 25% of water to evaporation based on the stable isotopic compositions (Gammons et al. 2009). It should be noted, that the here presented simulations were aimed at demonstrating the overall importance of evaporation on mine pit recovery. Accordingly, a constant evaporation rate was applied for simplicity. However, evaporation will depend on the bathymetry, meteorological data and topographical features, such as embankments around pit lakes (e.g. McJannet et al. 2017; Sivapalan 2005; Shevenell 2000a, b), and will change over time as the pit lake level recovers.

For mines that are backfilled, the rate of recovery is somewhat dependant on the backfill material. Backfill material of similar or higher hydraulic conductivity to the host rock will thereby accelerate recovery (Fig. 5). However, the rate of recovery is limited by the maximum influx to the mine void which the aquifer surrounding the mine can support. Prolonged recovery times are observed in cases where the backfill material is much less permeable than the surrounding aquifer. However, model simulations demonstrate that this delayed recovery impacts the immediate pit area only. Sharp hydraulic gradients develop at the interface between the relatively impermeable pit area and the more permeable aquifer beyond the backfilled mine void, and water-table recovery in the wider aquifer remains largely unaffected (Fig. S2 in the ESM).

The change in storage properties of the backfill material (scenarios backfill-S1 and backfill-S2, Table 1) leads to only minor changes in the rate of recovery. A reduced

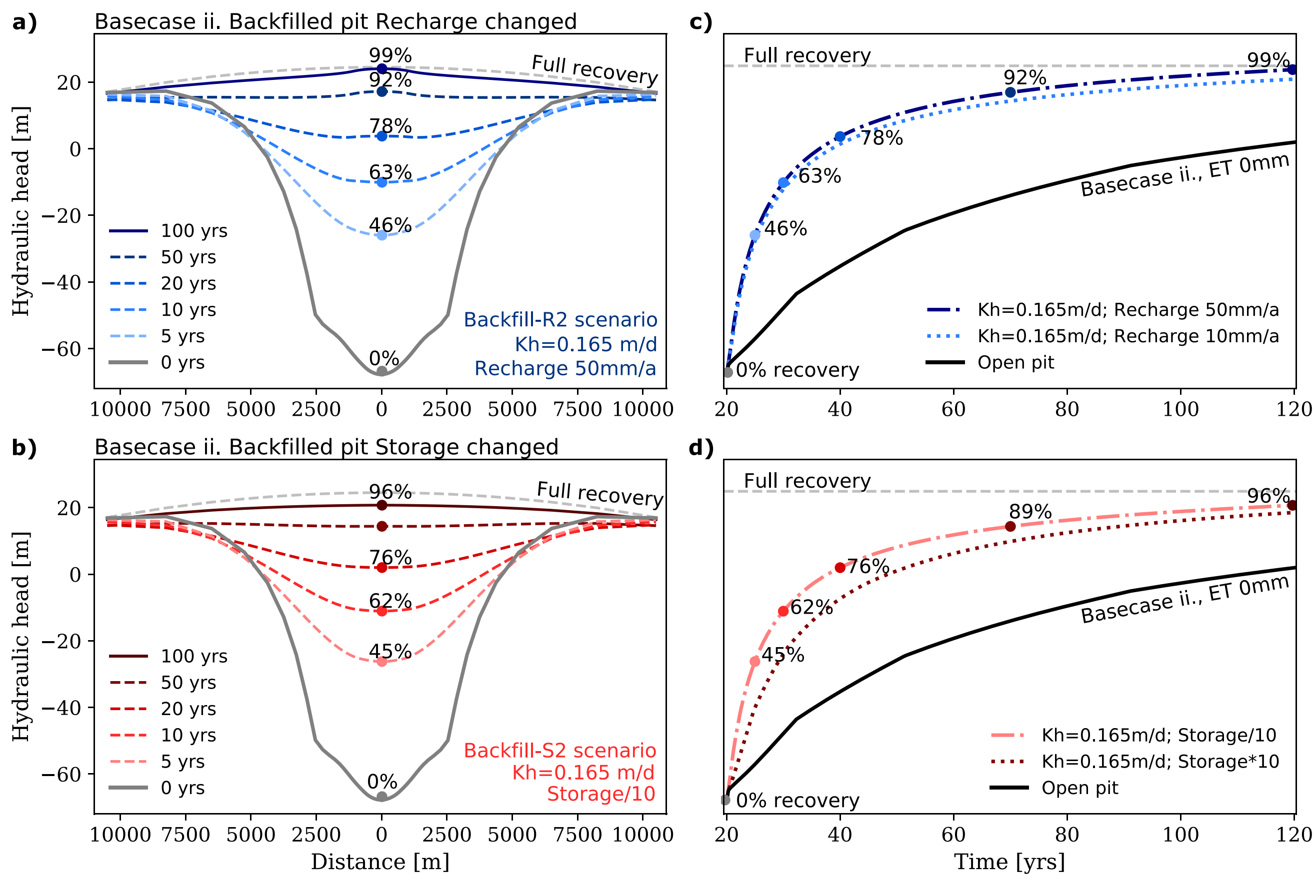

Fig. 6 **a-b** Recovery of water levels in a backfilled pit postmining along a 20-km E–W cross section through the centre of the mine void under basecase ii conditions. **a** Recharge within pit 50 mm/year (backfill-R2, blue lines). % recoveries of groundwater levels at 0, 5, 20, 50 and 100 years postmining are also shown. **b** Storage parameters /10 (backfill-S2, red lines). **c–d** Recovery of water levels in a backfilled pit with time postmining under basecase ii conditions. **c** Impact of enhanced recharge through backfill material (backfill-R1 and backfill-R2, blue lines). **d** Impact of storage properties of backfill material (backfill-S1 and backfill-S2, red lines). Also shown is the recovery for an unfilled open pit and negligible evaporation for comparison (pit lake-1, black lines)

storage volume (backfill-S2) will provide a minor gain in recovery times; however, the overall effect is small (Fig. 6). Similarly, the impact of enhanced groundwater recharge through backfill material is limited, as the net evaporation and groundwater influx terms to the pit overshadow any increase in recharge by orders of magnitude (Fig. 6 and Fig. S3 in the ESM).

Rapid filling of open voids

Rapid filling of the mine void using excess surface water on the order of 25–100% of the mine void volume (155×10^6 m^3) during the first 6 months following mine closure is simulated to have a dramatic effect on groundwater level recoveries in the immediate vicinity of the mine pit. In fact, initial flooding of the pit results in the pit water level being higher than the level of the surrounding groundwater (Fig. 7a,b). With time, this pit water dissipates into the groundwater system; faster in permeable aquifers and over longer times in less permeable media (Fig. 7). The long-term postmining water levels will reach the same steady-state as water levels predicted under comparable open-pit scenarios with the net evaporation rate controlling the final pit lake level (Fig. 7c,d). However, rapid filling is able to accelerate recovery (Fig. 7c,d). This acceleration is more pronounced in areas of low aquifer permeability. Firstly, not only because pit water dissipates less rapidly, but secondly, the mine void volume to be filled is a larger percentage of the total volume which was abstracted during the dewatering phase. Under basecase ii conditions, the augmentation by surface water of 155×10^6 m^3 (1× mine void) amounts to 110% of the water abstracted during dewatering, while it only equates to 25% of the volume of water removed during the dewatering phase under permeable aquifer conditions (basecase i). Nevertheless, even under permeable aquifer conditions, rapid filling achieves a recovery of up to 80% 10 years postmining under negligible net evaporation compared to 59% achieved at the

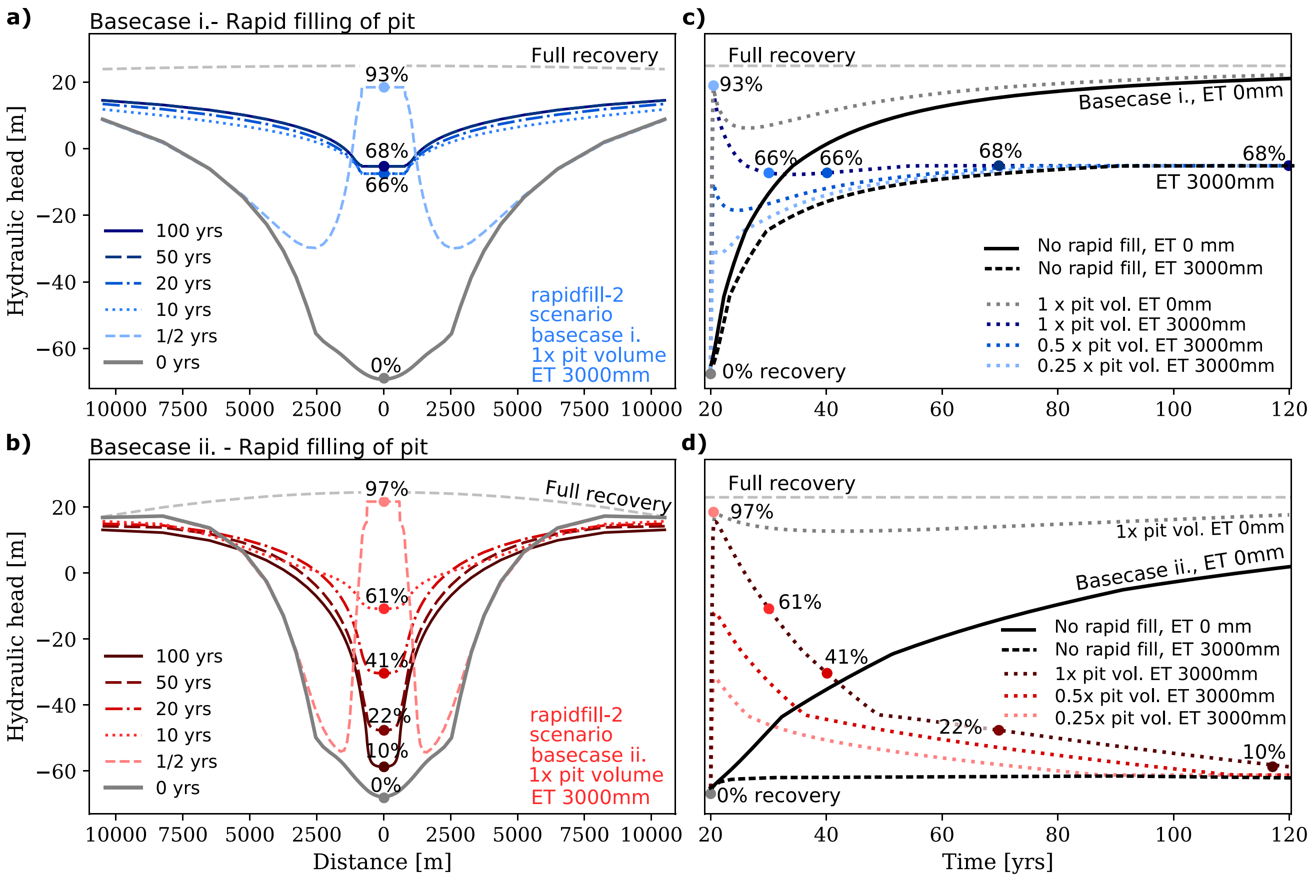

Fig. 7 **a**-**b** Recovery of water levels postmining along a 20-km E–W cross section through the centre of the mine void. Recovery is simulated for an open void, in which groundwater level recovery is augmented by surplus surface water during an initial 150-day postmining period at 1× the pit volume to aid recovery (rapidfill-2, blue lines). Net evaporation is 3,000 mm/year. Recovery is compared between basecase i (**a**) and basecase ii (**b**). % recoveries of groundwater levels at 0, 5, 20, 50 and 100 years postmining are shown. **c**–**d** Recovery of water levels with time postmining under open void conditions, including a 150-day period of aiding recovery through addition of surplus surface water at 1, 0.5, and 0.25 times the pit volume (rapidfill-2, rapidfill-3, rapidfill–4). Evaporation rates are assumed 3,000 mm (red/blue lines) or 0 mm (grey lines, rapidfill-1). Also shown is the recovery for an open pit without rapid filling for comparison (pit lake-1, black solid lines; pit lake-4, black-dashed lines)

same time without water augmentation and is thereby comparable to recoveries achieved in backfilled pits.

Conclusions

Open-pit mining has increased substantially over the past two decades due to improvements in methods that enable metal extraction also from lower-grade ores. Many of these mines are facing the end of mine-life over the next few decades and increasingly focus has shifted towards mine closure planning that provides evidence on available closure options and their viability under the given geological, hydro(geo)logical and climatic conditions. In this context, it is crucial to improve the general process understanding of the rebound of regional groundwater tables once mining ceases, as this, together with climate parameters, will govern the formation of pit lakes and to a large degree the long-term pit lake water quality. In turn, this governs how postmining landscapes may be utilised, i.e. whether a pit lake may be developed and become a beneficial resource (e.g. recreation, aquaculture, irrigation), whether wetlands may form or if water quality issues will prohibit any beneficial use and potentially create community safety issues.

While mine closure plans for these mines need to be developed on a site-specific basis, the findings from synthetic modelling aids basic process understanding and facilitates the analysis of how hydrogeological and climatic parameters influence rates of water level recovery or the efficacy of management interventions to influence the rate of recovery.

The model simulations have shown that the rate of groundwater recovery is mostly controlled by the aquifer hydraulic properties. Simulating moderately transmissive aquifers, recovery was achieved to within 5 m of premining water tables within a century after the end of mining under negligible net evaporation. Simulating tighter geological formations, groundwater rebound was generally slow and premining levels were attained on timescales exceeding 100 years. Any planning for beneficial use of the postmining landscapes needs to take these potentially lengthy timescales into account. Simulations also illustrate how the area surrounding the mine pit that is affected by water-table drawdown will continue to increase after cessation of mine dewatering for some years. It is therefore possible that ecosystems that are not affected during the mine's operational life might become impacted after mine closure.

Simulations also show that the final, steady-state postmining groundwater level is controlled by the implemented mine closure options and the prevailing climatic conditions. Simulation results suggest that the most important decision is thereby whether to backfill the pit to above the water table or allow a pit lake to develop. If a pit is backfilled, groundwater recovery within the pit is considerably faster, as only the pore volume of the backfilling material requires refilling, rather than the entire pit volume. In addition, evaporation is greatly reduced, which, in arid and semiarid areas is the most dominant climatic process impacting on groundwater and surface-water rebound. Our simulations of moderately transmissive aquifer settings, saw backfilling of pits leading to the mine void being filled to more than 70% only 10 years postmining, while recovery of more than 80% was achieved within 20 years. It should be noted, however, that backfilling may not be a viable option where the ore extracted constitutes a large portion of the volume of material mined and, in these circumstances, partial backfilling of mine pits may be considered.

Such accelerated groundwater level recovery may facilitate the planning and implementation of any beneficial use of the postmining landscape, including pit lakes. Any associated economic and social benefits may then be accomplished sooner. However, accelerated recovery may also be of environmental benefit to groundwater-dependant ecosystems, while pit lake water quality may profit from potentially acid forming materials being submerged more rapidly thereby reducing the risk of their oxidation from exposure to the atmosphere.

If, however, mine voids remain unfilled, evaporation from the pit lake surface becomes a governing factor in determining the time for the pit lake water level to stabilise as well as the final pit lake water level. In prominent arid to semiarid mining regions around the world, evaporation can greatly exceed rainfall by ratios as high as 10:1 (e.g. Pilbara region, WA; mining operations in the arid West of the US; arid to semiarid mining regions of southern Africa). Under such conditions, evaporation completely balances groundwater level influx terms and the final pit lake level will remain permanently subdued below the premining water table. Without substantial groundwater gradient and therefore throughflow, the unfilled mine pit becomes a terminal sink for groundwater. Based on our synthetic groundwater models, final equilibrium lake levels simulated for moderately transmissive aquifer conditions varied between 15–30 m below the premining groundwater table for net evaporation rates of 1,000 and 3,000 mm/year, respectively. The situation was, however, exaggerated if mine voids were simulated to be in lower permeability rocks. The simulations in this study suggest that developing pit lakes will always remain shallow in these cases with pit lake levels subdued below the regional groundwater table by several 10s of meters.

In addition, our synthetic simulations suggest that rapid filling of mine pits with surplus water is able to accelerate groundwater recovery of open pits. However, the effectiveness of rapid pit filling is highly dependent on net evaporation from the pit lake surface and aquifer transmissivity. In general, it is an unsuccessful management option under highly transmissive aquifer settings, as any gain in lake level quickly dissipates into the surrounding aquifer. It could be speculated, that managed aquifer recharge may have a role in rapid recovery of groundwater levels in mining regions of higher aquifer transmissivity (Cook et al. 2022). In less permeable geology, added surplus water is retained much longer within the pit and elevated lake and groundwater levels as a result may last for several decades. Any benefits of rapid filling through, e.g. the diversion of surface water, however, has to be balanced against any negative impacts on the local hydrology (Pusch and Hoffmann 2000). Irrespective of the aquifer properties, the final long-term pit lake level is unaffected by filling events and solely governed by the balance between the evaporative loss from the pit lake surface and the long-term groundwater level influx into the pit.

Limitations

While synthetic modelling is able to greatly aid fundamental process understanding, as it is not hampered by local, site-specific complexity, necessarily, such modelling is based on substantial oversimplifications of the groundwater–surface water system. For instance, pit geometries will affect evaporation rates and, together with lake stratifications (e.g. temperature) will influence how evaporation changes as pit lakes fill. Evapo-concentration, resulting in salinisation, in turn, will have an impact on the water exchange between the pit lake and underlying aquifers. Geological structures, which may, e.g. act as flow barriers as well as regional groundwater flow, will influence postmining recovery timescales. Despite these limitations, the present simulations are capable of providing valuable insights into how subsurface permeability, climatic conditions and implemented site rehabilitation measures influence groundwater recovery in postmining open-pit landscapes. This contributes to our understanding of the factors which contribute towards orderly mine-closures focused on enabling beneficial use of relinquished mining assets.

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Declarations

Conflict of interests The authors have no conflict of interest in connection with the submitted material.

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