TECHNIQUES AND DEVELOPMENTS IN QUARRY AND SURFACE MINE DEWATERING

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Abstract

Dewatering is essential for the safe and efficient operation of quarries and open pit mines that extend below groundwater level. Benefits of dewatering include better working conditions and greater efficiency of mining operations, as well as improved geotechnical stability, for example by allowing steeper side slopes.

Dewatering techniques can be divided into two main groups (which may be used in combination). The first group is pumping methods, where water is pumped from arrays of wells or sumps and piped away for disposal. Pumping methods include: in-pit pumping; pumping from wells; sub-horizontal wells and drains; wellpoints and ejector wells; and drainage adits and tunnels. The second group of techniques is exclusion methods, where low permeability walls or barriers are used to reduce groundwater inflows into the pit. Exclusion methods include: bentonite slurry walls; grout curtains; and artificial ground freezing.

Dewatering techniques and equipment have been refined over many decades, and no significant step changes in equipment capabilities are on the horizon. However, there are opportunities for technology transfer from recent developments in other industries. An example is improvements in remote monitoring and control of pumping systems, routinely used in other industries but rarely used on mine and quarry sites. Such systems are ripe for wider application on mine sites, where they offer potential benefits to the mine operator in the form of reduced energy costs, reduced carbon emissions and increased equipment life. This paper reviews the principal dewatering techniques used and the more recent and future developments.

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Introduction

Dewatering of quarries and surface mines is simple in concept. The act of excavating below groundwater level will draw water into the pit wherever it intercepts permeable strata or features (such as fissures or fractures). The inflow of groundwater will interfere with mining, at best reducing the efficiency of operations, and at worst causing flooding and/or geotechnical instability of the pit slopes. Accordingly, groundwater control measures (colloquially known as 'dewatering') are required to allow mining to be carried out safely and in workably dry conditions.

In practice dewatering can often be more complex. As well as the practical issues of removing or excluding groundwater from the pit in a cost-effective manner, consideration needs to be given to the potential environmental impacts of dewatering. This paper will address the background to dewatering of surface mines and quarries, will present the principal methods and techniques used, and will consider future trends and technologies that may allow for improvements in dewatering in the future.

Groundwater Control Requirements For Surface Mining

No mine will carry out significant dewatering operations unnecessarily. Groundwater control is typically done for hard-nosed business reasons, to either improve the efficiency of mining operations, or, for mines that extend deep below groundwater level, to allow mining to continue when it would otherwise be inundated or destabilised by groundwater inflows and pressures. The mention of groundwater pressures is important, because as well as the visible groundwater inflows, the perhaps less obvious groundwater pressures in the pit slopes and floors can have a significant detrimental effect on stability in certain hydrogeological settings.

The detailed objectives of a dewatering programme will vary from mine to mine, and will be influenced by: the type of mine and geological setting (e.g. hard rock, soft rock, sand and gravel), including the presence of potentially unstable overburden; the size and depth of the mine; and, working methods (e.g. type of plant and use of blasting). However, the overall objectives of mine dewatering can be simplified into some simple rules.

Effective mine dewatering should:

- Be cost effective.
- Work in the required timescales.
- Not interfere unnecessarily with working methods used for mining.
- Comply with the relevant environmental regulations, and not create unacceptable environmental impacts.

Typically the aim of dewatering will be to provide benefits to mining operations, which can include:

- Improved geotechnical slope stability and safety: lowering of groundwater levels and reducing pore water pressures (a process known as 'depressurisation') can allow steeper slope angles to be used in pit walls, and reduce the risk of base heave where confined aquifers exist below the working level.
- More efficient working conditions: better trafficking and diggability, reduced downtime due to pit flooding.
- Reduced blasting costs: lowering of groundwater levels in advance of working will provide dry blast holes, reducing the need for more costly emulsion explosives.
- Lower haulage costs: Dry product/ore and waste rock weigh less than wet material, so dewatering of rock provides a haulage cost saving.
- Reduced environmental impacts: Dewatering wells can be targeted to pump from specific geologic horizons (and cut-off walls can be used to exclude groundwater from key layers), potentially making use of aquitards and low permeability layers to reduce external drawdowns that may affect shallow groundwater-dependent features such as wetlands.

Water Management As Part Of The Mining Process

Dewatering is not planned and executed in isolation, but should be an integrated part of mine water management (Figure 1). In addition to the control of groundwater, surface water must also be controlled. This is normally achieved by diverting as much surface water runoff as possible away from the pit, and by pumping away that water which does accumulate in the pit. The surface water pumped from the pit will normally comprise direct precipitation into the pit, any residual groundwater seepages from perched groundwater tables or zones not fully drained by the main dewatering activities, and any surface runoff which is able to find its way into the pit.

The precipitation element will be both episodic and seasonal – in countries with tropical or arid climates the quantity of storm water that must be removed following an individual rainfall event may be very large, but such events may occur only during a relatively short period of the year. In-pit surface water pumping capacities sized to deal with a storm event of a given return period will be significantly oversized relative to long term average pumping rates; this is true even in more temperate European climates. Possible strategies to optimise in-pit pumping include arranging pumps in banks according to duty; 1st assist, 2nd assist, etc. so that one of the pumps, running at an efficient point in its performance curve deals with the long term flows, with the other pumps being called into use at peak times via an automated level controller system. In extreme cases it may not be economic to provide adequate pumping capacity (and the associated power supply and discharge pipe work) and it may be necessary to design the pit with a deep sump section that can be allowed to flood during

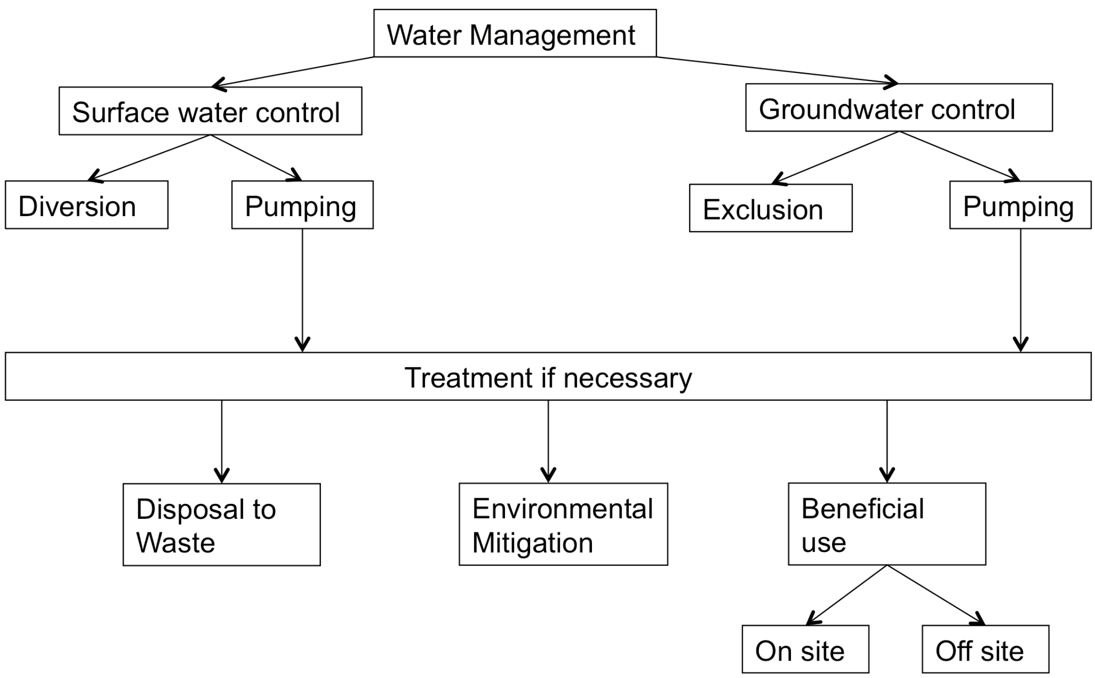

Figure 1. *Groundwater control in the context of mine water management.*

infrequent very severe storm events, to provide water storage, which is then pumped out over a period of days or weeks by pumps rated for less severe events.

A key element of water management is the disposal or use of the pumped water. The most common water disposal routes are:

- Pumped to waste: typically water is pumped to a watercourse or other surface water body that has adequate hydraulic capacity to receive the water without causing downstream flooding.
- Environmental mitigation: water may be diverted to feed specific surface water bodies to maintain flows or water levels, or may be artificially recharged (via recharge trenches or recharge wells) into the ground to maintain groundwater levels.
- Beneficial use: the water can potentially be used as part of the mining operation for uses such as dust suppression, mineral processing etc.

In general, a discharge permission will be required from the environmental regulators, to allow water to be disposed of, or to be used for environmental mitigation. Within the United Kingdom (UK) different requirements apply in different regions, and the relevant regulatory bodies should be consulted. Furthermore, water that is put to beneficial use may require different permissions to water that is pumped to waste or used for environmental mitigation. The UK regulatory bodies are: in England, the Environment Agency (EA); in Wales, Natural Resources Wales (NRW); in Scotland, Scottish Environment Protection Agency (SEPA); and, in Northern Ireland, Northern Ireland Environment Agency (NIEA). Occasionally water from dewatering may be disposed of in the sewerage network. In that case, permission must be obtained from the sewerage utility before this can be done. The relevant sewerage utilities are: in England and Wales, the Regional Water Companies; in Scotland, Scottish Water; and, in Northern Ireland, Northern Ireland Water.

In most cases water pumped from both surface water and groundwater control systems will be treated, prior to discharge, to reduce the levels of suspended solids in the water. This is normally achieved by passing the water through a large settling pond, although more sophisticated settlement methods are available. Occasionally, more complex treatment methods are used, including chemical dosing or filtration to meet specific water quality requirements of discharge permissions, or the specific water requirements for environmental mitigation or beneficial use.

Groundwater Control Techniques

If mining is to be carried out to below groundwater level, there are a range of groundwater control techniques that can be used. The choice of technique at a given mine will be controlled by several factors, principally including the hydrogeological conditions and the objectives of the dewatering at that site.

Groundwater control techniques can be grouped into two main types – pumping and exclusion methods. Groundwater control by pumping involves pumping from wells or sumps to lower groundwater levels, below the pit working area. In contrast, groundwater control by exclusion involves installing low permeability barriers around the pit to reduce groundwater inflows to the working area. Principal features of key techniques are summarised in Table 1. Further details on the various methods can be found in Cashman and Preene (2012) and Beale and Read (2013).

Groundwater control by pumping

The most common form of groundwater control by pumping used in surface mines is in-pit pumping (Figure 2). Essentially, this uses the pit as a 'groundwater sink' allowing water to flow into the pit, via any permeable strata or fissured zones that are encountered. Within the pit the water is collected in open drains or channels and directed to low points or sumps and then pumped away to the surface. In addition to pumping groundwater, the in-pit pumping system will also be required to pump any surface water generated in the pit. The water reaching the sumps and pumps will typically have run over the pit floor and along drainage channels and will have picked up some degree of suspended solids. Accordingly, in-pit pumps must be capable of pumping 'dirty' water with some suspended solids, and the pumped water will typically require treatment to remove solids prior to discharge from site.

In-pit pumping is most appropriate for use in pits in relatively stable rock, where the inflow of groundwater is unlikely to cause instability in the pit slopes and base. Where in-pit pumping is applied in relatively unstable rock or in granular deposits such as sand or sand and gravel, the seepage of groundwater through those materials may lead to instability. Furthermore, in-pit pumping can only depressurise the pit slopes indirectly, and high pore water pressures may remain in the slopes long after the main pit is dewatered, with the slopes draining only slowly into the pit. This can lead to the risk of geotechnical instability of the slopes.

Depending on the size and geometry of the pit, it may be possible to keep the pit almost entirely dry (with standing water confined only to small sump areas). In other cases the bottom of the pit may be allowed to flood and form a pond or lagoon whose level fluctuates in response to differing groundwater and surface water inflow rates. In such cases the in-pit pumps may be mounted on floating pontoons, to allow them to rise and fall with the lagoon water level.

For cases where in-pit pumping alone is not sufficient to ensure stability, the use of perimeter dewatering wells (Figure 3) may be appropriate. This involves a series of bored vertical dewatering wells, most commonly outside the crest of the pit. The wells typically extend to a significant depth below the base of the pit, and are pumped by specialised slimline borehole electrical submersible pumps. This approach has two principal advantages over in-pit pumping. First, if pumping from the dewatering wells is started long enough in advance of sinking of the pit, the wells will intercept lateral groundwater flow into the pit and groundwater levels can be lowered in advance of mining, thereby improving operational conditions in the mine. Second, because the dewatering wells are located behind the pit slopes, in

Technique*	Notes
Groundwater control by pumping	
In-pit pumping	Widely used in surface mines and quarries both for groundwater and surface water. Water is allowed to enter the pit, is collected in channels and sumps and is then pumped away. Pumped water likely to be 'dirty' with a significant suspended solids load; pumps need to be capable of handling some solids and water may need treatment to reduce suspended solids content before discharge. Typically appropriate for pits in relatively stable rock, and where pit slope depressurisation is not a critical requirement. Less effective in unstable rock or in sands or gravels, where the groundwater inflow to the pit may result in geotechnical instability of the pit slopes.
Perimeter dewatering wells	Vertical dewatering wells located outside of the pit crest, and pumped by specialised slim line borehole electric submersible pumps. If pumping is started sufficiently far in advance of mining, the wells can intercept lateral groundwater inflows to the pit and can lower groundwater levels in advance of mining, thereby improving operational conditions in the mine. In favourable geological conditions, pumping from perimeter dewatering wells can have a significant groundwater depressurisation effect on pit slopes.
In-pit dewatering wells	Dewatering wells located on benches or in the base of the pit. The presence of such wells (and the associated cable and discharge pipework) in the pit may impact on mining methods and sequencing. Normally used in combination with perimeter dewatering wells.
Sub-horizontal slope drains	Small diameter passive (i.e. unpumped) drains drilled out horizontally or with a slight upward or downward inclination from benches in the pit slopes, to provide preferential drainage pathways for groundwater as part of pit slope depressurisation programmes. Water flowing from drains must be dealt with by in-pit pumping.
Wellpoints and ejector wells	Small diameter shallow wells installed at close spacing (typically 2 to 6 m between wells) in lines along slopes to intercept seepage and reduce pore water pressures. Wells are connected to common header pipes so one surface pump can pump on many wells simultaneously. Particularly suited to superficial and drift deposits of moderate to low permeability.
Relief wells	Passive (i.e. unpumped) wells typically drilled vertically through the base of a pit to provide a preferential pathway for upward groundwater flow to allow depressurisation of confined aquifers below working level. Water flowing from relief wells must be dealt with by in-pit pumping.
Vertical or angled drains	Passive (i.e. unpumped) wells typically drilled vertically through pit slopes to provide a preferential pathway for downward groundwater flow (into a zone which is already depressurised) to allow more rapid drainage of groundwater perched above low permeability layers.
Drainage adits and tunnels	Drainage tunnels (and associated drain holes radiating out from the tunnels) are constructed behind or beneath a mining area. If topography allows the tunnel to have a low level outlet it can function as a passive (i.e. unpumped) drain capable of depressurising a very large zone.
Horizontal directional drilled (HDD) wells	Relatively new and innovative technique. Directionally drilled boreholes are drilled from outside the mining area and steered into the geological zones targeted for dewatering and depressurisation.
Groundwater control by exclusion	
Steel sheet-piling	Interlocking steel sections (typically of a 'Z' or 'U' profile) that are driven, vibrated or pushed into the ground to form a continuous barrier. Can be removed at the end of a project to avoid leaving a permanent barrier in place.
Slurry trench wall using cement-bentonite or soil-bentonite	Formed by the excavation of a trench that is supported during excavation by being kept topped up with bentonite fluid. Excavation is by long reach backhoe, clamshell grab or specialist trench cutters. Following completion of the trench, backfill is placed of a soil-bentonite mixture or a self-hardening cement-bentonite mixture, to form a low permeability barrier.
Concrete diaphragm walls and bored pile walls	Formed by the excavation of a trench that is supported during excavation by being kept topped up with bentonite fluid. Excavation is by clamshell grab or specialist trench cutters. Following completion of the trench, backfill is placed of concrete, to form a low permeability barrier that can have significant structural strength. Rarely used in surface mines and quarries.
Grouting – permeation and rock grouting	A form of ground treatment where fluid grout is injected via closely spaced grout holes at relatively low pressure into the ground to fill the fissures in rock and pores in soils. The injected grout sets, creating a zone of modified in-situ material of lower permeability. The most common grout types are suspensions of cement in water. However, such grouts are only applicable in sealing coarse soils and wide fissure openings in rock. More expensive chemical grouts may be necessary to treat lower permeability soils and rocks.
Jet grouting and mix-in-place methods	A jetting head mounted on a drilling rigs is used to create a disturbed zone of ground in soils and soft rocks, into which grout is injected. A column of mixed grout and the disturbed in-situ material is created at each jet grouting drill hole. Overlapping columns of jet grouted material can create a low permeability barrier. Rarely used in surface mines and quarries.
Artificial ground freezing	Circulation of a low temperature refrigerant (either calcium chloride brine or liquid nitrogen) through a line of closely spaced freezeholes. The refrigerant chills the groundwater causing 'ice cylinders' to develop around each freezehole. With continued circulation of the refrigerant the ice cylinders from adjacent freezeholes will increase in diameter and will intersect to form a continuous low permeability 'freezewall' of frozen ground. The refrigerant must continue to be circulated to maintain the freezewall. The freezewall is temporary, and will slowly thaw at the end of the project when refrigeration is stopped. Rarely used in surface mines and quarries, although it is a fairly common technique used for the sinking of deep mine shafts.

Notes: *Techniques may be used in combination

Table 1. *Principal techniques for groundwater control in surface mines and quarries.*

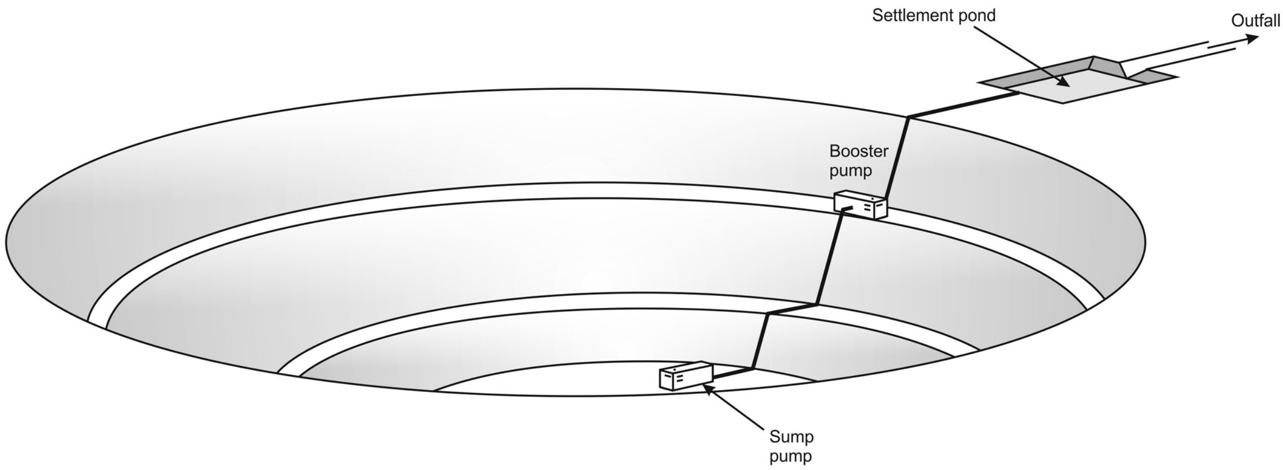

Figure 2. *Schematic arrangement of in-pit pumping for a surface mine.*

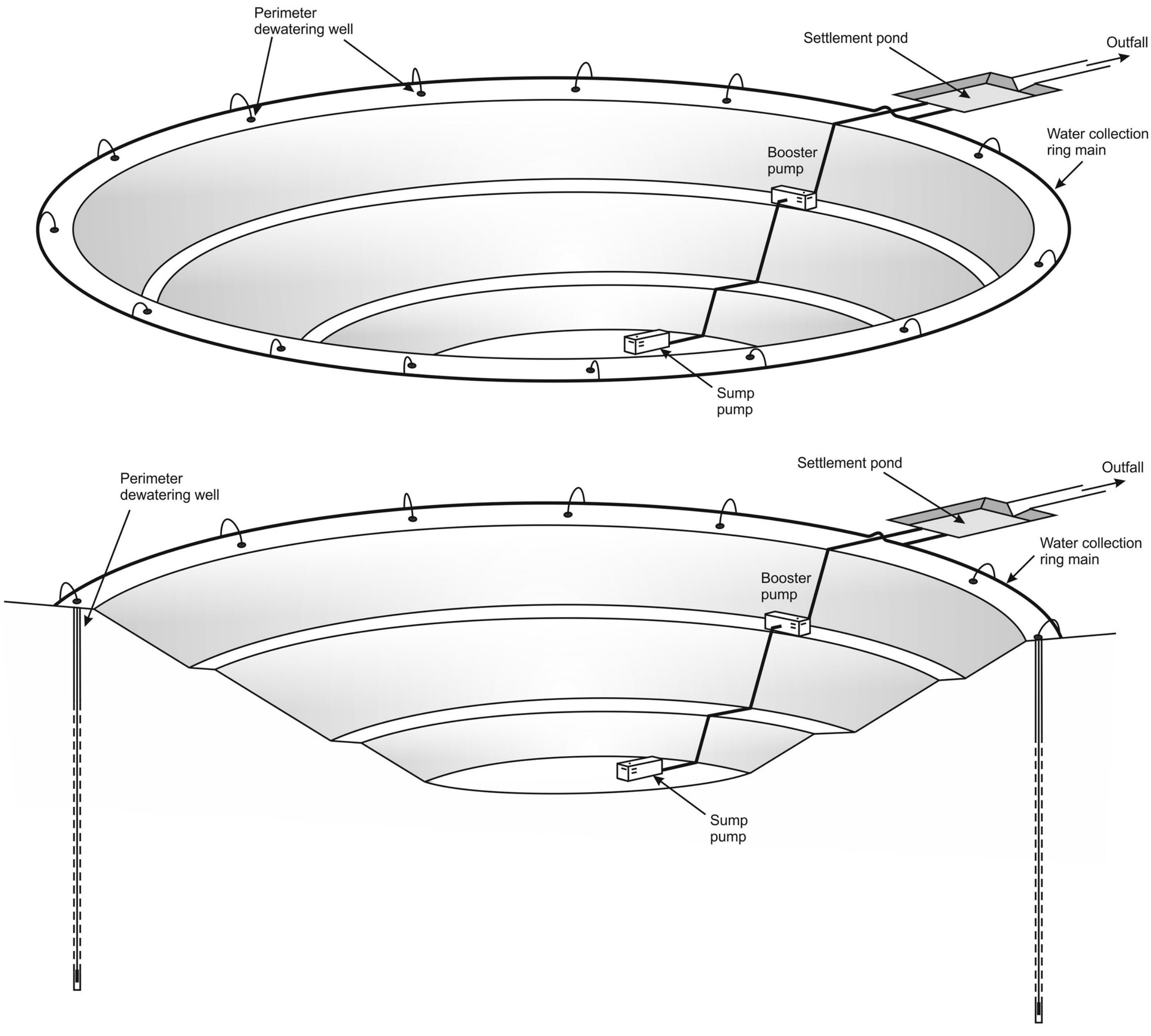

Figure 3. *Schematic arrangement of in-pit pumping and perimeter dewatering wells for a surface mine (top) and the cut-away view (bottom).*

favourable geological settings they can provide a significant groundwater depressurisation effect in the pit slopes. In some cases perimeter dewatering wells may be augmented by in-pit wells, but the presence of such wells (and the associated cable and discharge pipework) in the pit may impact on mining methods and sequencing.

Because perimeter dewatering wells are typically located behind the pit slopes, in favourable hydrogeological conditions (for example an extensive permeable strata with significant hydraulic continuity in the vertical and horizontal direction) pumping from perimeter dewatering wells can have a significant depressurising effect on the pit slopes. But if the strata penetrated by the dewatering wells contain low permeability faults, layers or other geological complexities it is possible that perimeter dewatering wells alone will not depressurise the slopes sufficiently to allow the slopes to be adequately stable. One possible option is to install sub-horizontal drains out from the pit slopes, to create additional permeable pathways for water to enter the pit (Figure 4).

Typically these drains are installed in lines at regular spacings, drilled out horizontally, or with a slight upward or downward inclination, from benches in the pit slopes, with a drilled diameter of 50 to 100mm. In competent rock the drain holes can be left unlined if the geological data indicates they are unlikely to collapse; in less competent material a slotted well screen is installed in the drain on completion of drilling. The drains are 'passive' and are not pumped directly. The presence of the drains provide a preferential pathway for groundwater flow from the slopes into the pit. The water pressures in the slope drives water along the drain, so that water bleeds from the open end of the drain, and is typically collected in drainage trenches and pumped away. Because the drains can only be installed from within the pit, their installation sequence must be integrated with the mining sequence. Such drains often flow copiously when first installed, but the flow will reduce as the pit slopes are depressurised, and drains in the upper pit slopes may completely dry up in time. Further details on slope drainage systems are given in Leech and McGann (2008) and Beale and Read (2013).

Where pit slopes contain zones of materials of relatively low permeability, widely spaced perimeter wells may be of limited effectiveness, because each well has a limited 'zone of influence'. In such cases specialist methods of pumping from closely spaced lines of small diameter wells can be used (Figure 5). Two methods widely used in the construction industry for sands, gravels and superficial deposits are wellpoint dewatering (where the wells are pumped by suction pumps) and ejector dewatering (where wells are pumped by an ejector system using the nozzle and venture principle). Such methods are occasionally deployed in the side slopes of surface mines and quarries. The lowering of the groundwater level that can be achieved by such systems is limited by the method of pumping, and multiple lines of wells may be required at different levels in the pit slopes.

A dewatering technique that is used less frequently is drainage galleries or adits. Typically this involves the construction of a tunnel behind a pit slope or beneath a pit bottom, to drain and depressurise that zone of the mine (Figure 6). The method is most efficient if topography allows the tunnel to be constructed with a portal at a lower elevation than the final pit bottom or target slope depressurization level. This allows the gallery to act as a passive (i.e. unpumped) drain with water flowing from the tunnel portal by gravity. The size of the zone drained directly by the tunnel is usually increased by drilling angled drain holes out from the tunnel. Tunnels and galleries may be constructed specifically for drainage purposes. However, in some mines, tunnels originally constructed for access or exploration purposes have been identified as having a significant drainage effect and have subsequently been incorporated into mine depressurisation programmes.

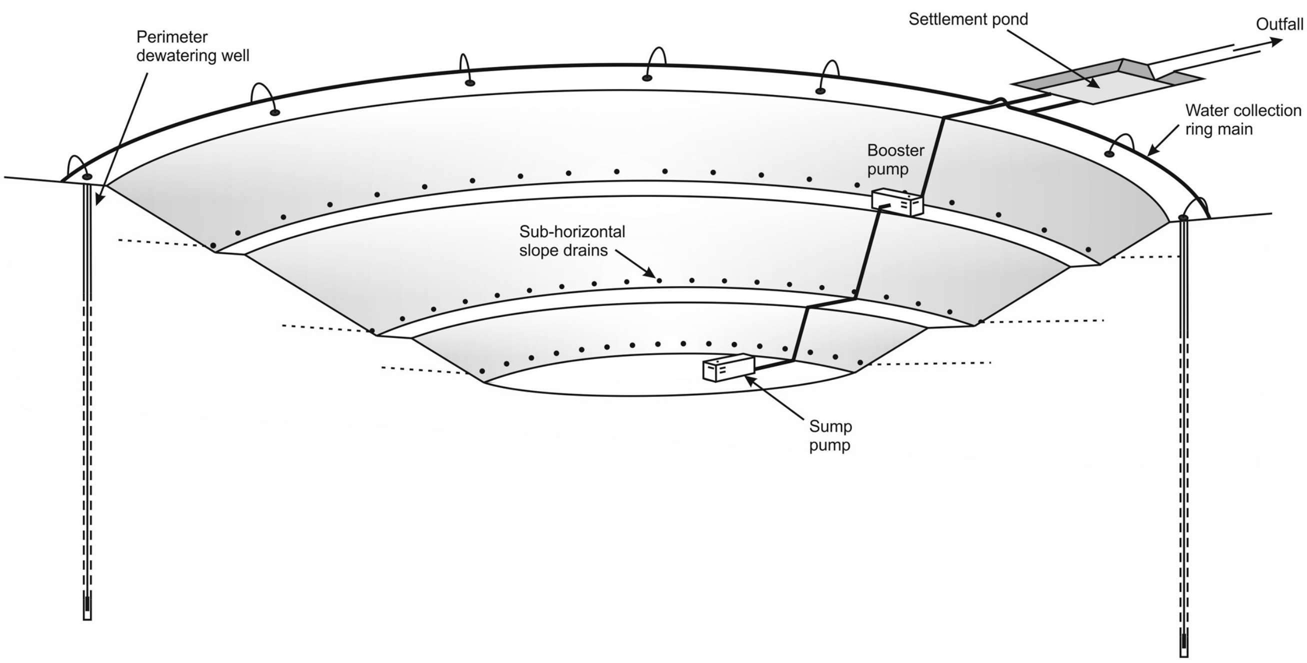

Figure 4. *Schematic arrangement of in-pit pumping, perimeter dewatering wells and sub-horizontal slope drains for surface mine (cut-away view).*

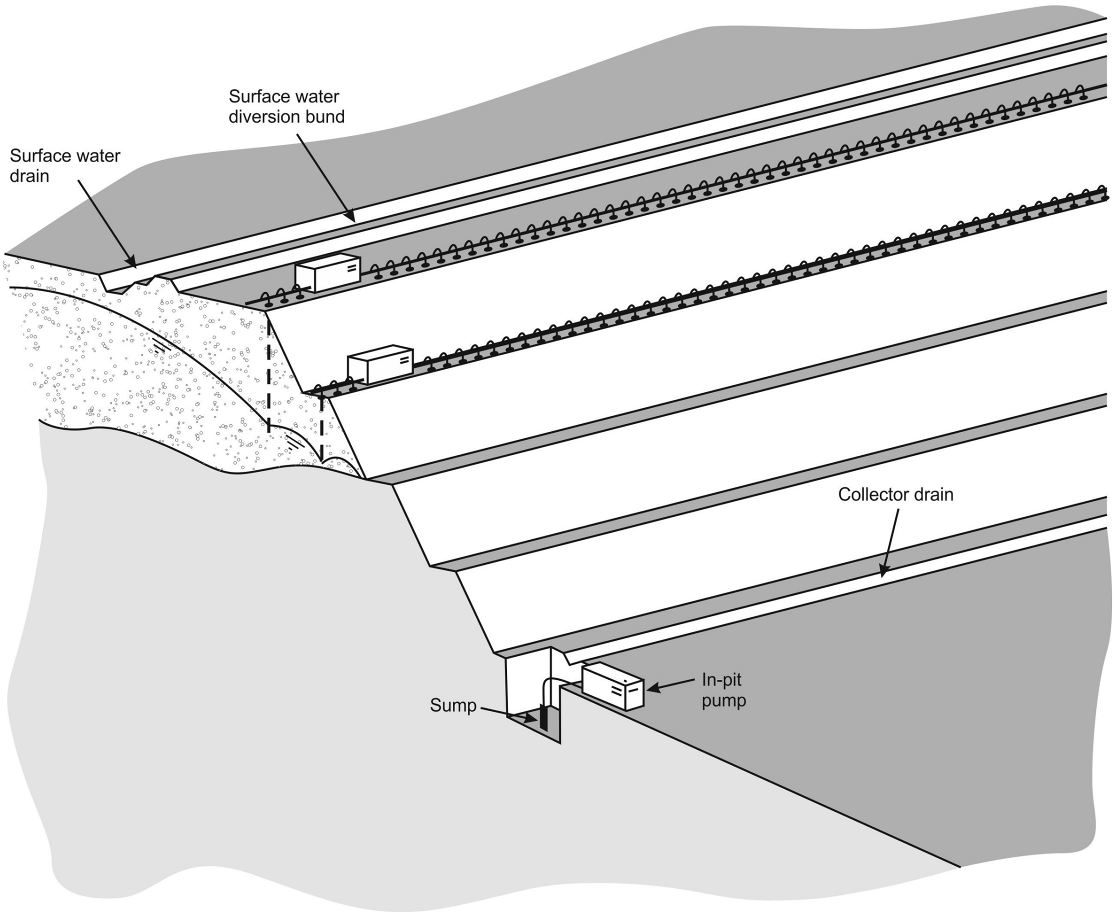

Figure 5. *Schematic arrangement of a wellpoint pumping system used for localised slope dewatering in surface mine.*

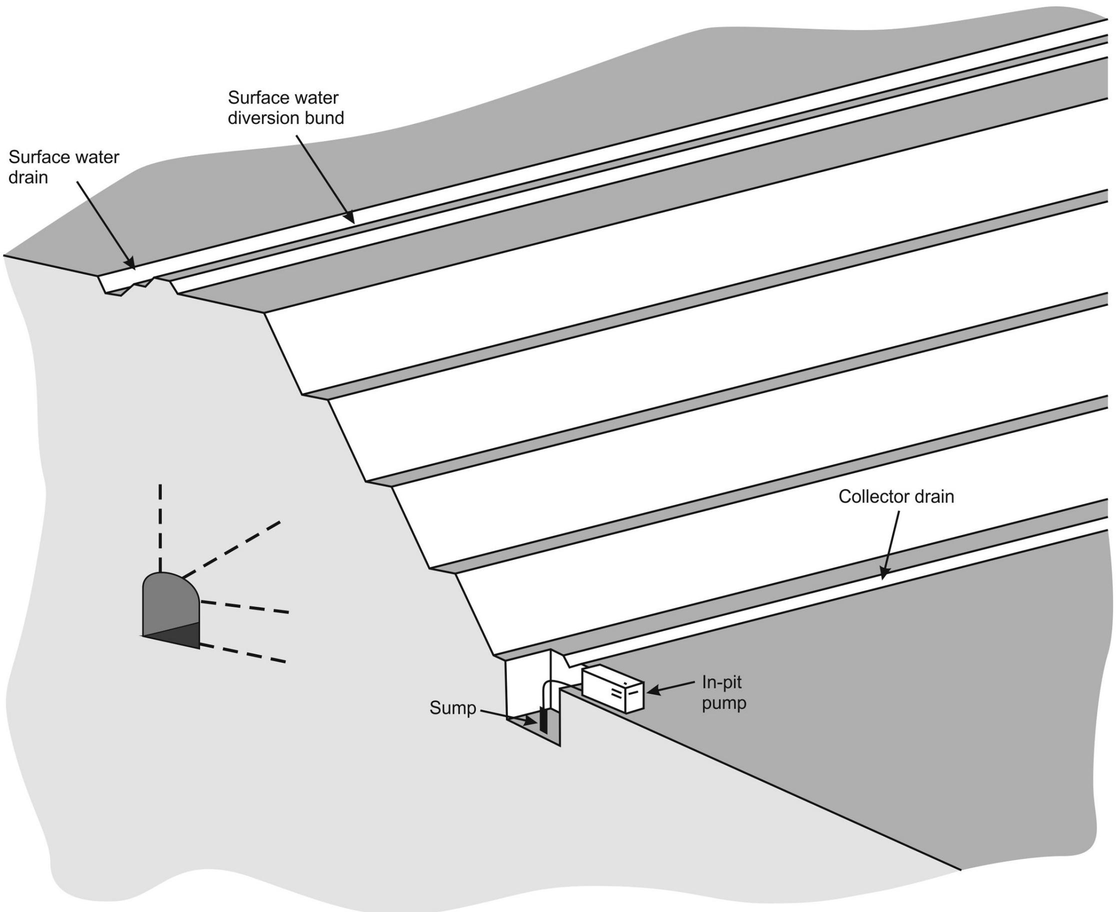

Figure 6. *Schematic arrangement of a drainage gallery used for dewatering of surface mine.*

Groundwater control by exclusion

Groundwater control by exclusion involves engineering measures to exclude groundwater from the workings of the surface mine or quarry. This is typically achieved by either installing a physical in-ground barrier of low permeability or by some form of ground treatment to reduce the in-situ permeability of the strata. Such low permeability in-ground barriers are generically known as 'cut-off walls'. In some cases the objective may be to reduce groundwater inflows to minimum levels. In other cases the objective may be to target the exclusion measures on key permeable strata or zones where groundwater inflows into the pit are predicted to be difficult to manage or where geotechnical instability is a concern.

For most quarries or open pit mines, the perimeter length around the crest is so long that it would be prohibitively expensive to install a cut-off wall around the complete perimeter. Cut-off walls are most frequently applied to specific sectors of an open pit, where groundwater ingress or instability is a particular concern. A common application for exclusion methods is where one side of the pit is formed close to a surface water feature. If the pit is adjacent to an open body of water (a river, sea or lake) that is in direct hydraulic connection with the groundwater regime, there is a risk that significant groundwater flows may be concentrated on that side of the pit, and that high pore water pressures may affect slope stability. This risk is particularly severe if shallow alluvial or superficial deposits are present and in direct hydraulic continuity with the surface water body. One solution is to install a low permeability cut-off wall along the pit edge closest to the surface water body, penetrating through the superficial deposits and sealing into underlying lower permeability strata (Figure 7). When correctly designed and executed this can significantly reduce inflows to the pit and, in combination with pumping on the pit side of the cut-off wall, can result in much lower pore water pressures in the pit slopes. Where the pit is located close to an environmentally sensitive surface feature (such as a wetland that is partly fed by groundwater) a cut-off wall can be used to reduce drawdown impacts on the feature.

The methods used to form cut-off walls are summarised in Table 1. They can be characterised either as methods that:

- Form a continuous physical 'wall' in the ground, either by driving in of a low permeability structure (e.g. steel sheet-piling) or by excavating a trench and placing low permeability materials (e.g. bentonite slurry trenches), or
- Modify the *in-situ* properties of the ground to produce a continuous zone of treated soil or rock of lower permeability than the native material. This can be achieved by the injection of fluid grouts that set or solidify in the soil pores and rock fissures or by circulating low temperature fluids that cause the groundwater in the soil or rock to freeze, creating a very low permeability material (artificial ground freezing).

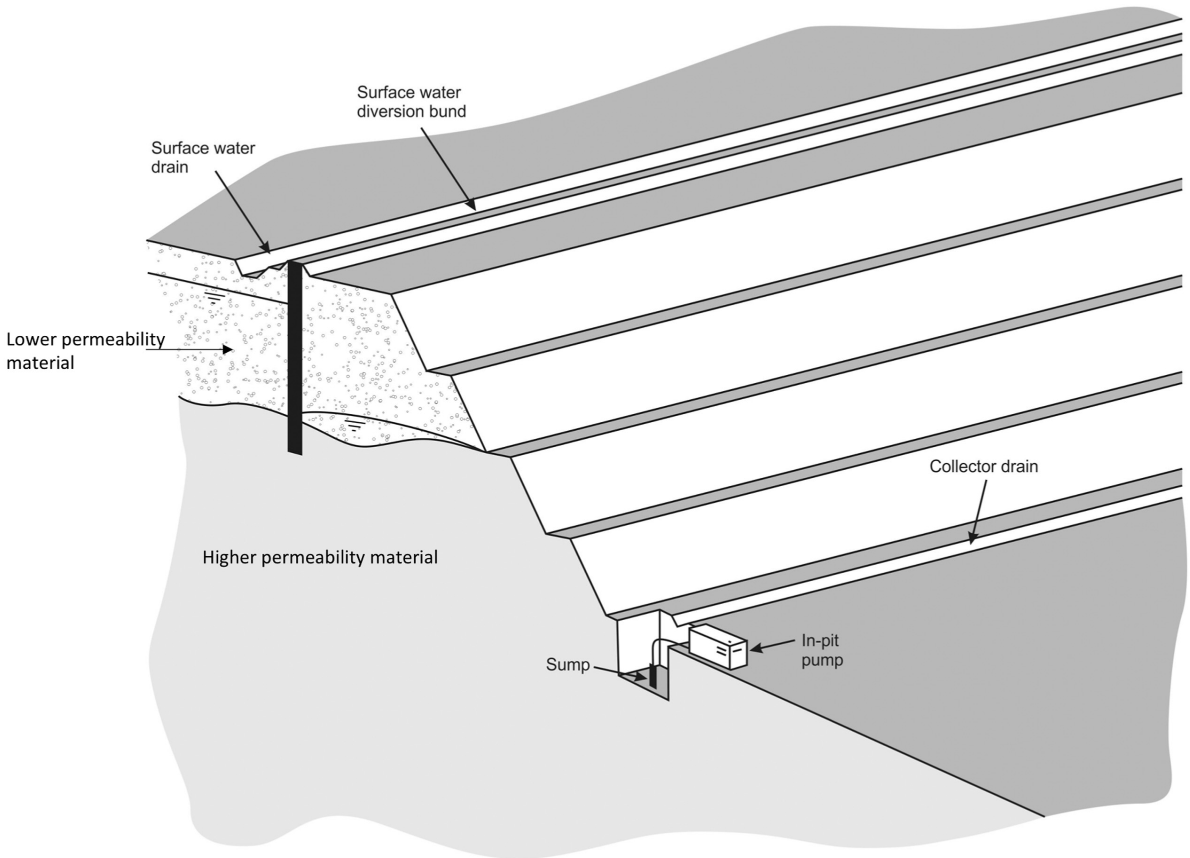

Figure 7. *Schematic arrangement of a wellpoint pumping system used for localised slope dewatering in surface mine. Schematic arrangement of a low permeability cut-off wall used as part of a groundwater exclusion strategy for a surface mine.*

The different methods used to form cut-off walls vary widely in cost and capability in relation to depth and applicable soil and rock types. Further information on the characteristics and pros and cons of the various techniques can be found in Privett et al (1996) and Cashman and Preene (2012).

It is important to recognise that even where extensive groundwater exclusion measures are deployed, groundwater pumping will still be needed to handle precipitation water and any leakage through or beneath the cut-off walls.

Groundwater disposal by artificial recharge

As discussed earlier in this paper, the most common route for pumped water from a dewatering system to be disposed of, is 'to waste' to a surface watercourse. This effectively means that there is a net abstraction of groundwater, and it is natural to expect that, with prolonged pumping, groundwater levels may be lowered over a wide area around the dewatered pit. For deep pits dewatered for many years, this zone of drawdown may extend for several kilometres from the pit.

In some hydrogeological settings such widespread drawdown may be unacceptable from an environmental or regulatory perspective. Examples include, where nearby groundwater-supported wetlands may be at risk of drying up, or where abstraction wells used to supply drinking water or irrigation water may suffer from reduced yields or degraded water quality. In such circumstances, the option of artificial recharge may be considered.

Artificial recharge involves taking a portion of the discharge flow rate (sometimes 100%, sometimes less) and directing it back into the ground in a controlled manner, normally via recharge wells or recharge trenches. Figure 8 shows a schematic artificial recharge arrangement using recharge wells. The pumped water from the dewatering system is passed along a pipeline to an array of recharge wells, which are connected together by a manifold pipework arrangement (Fernández-Rubio and Lorca Fernández, 2010). Figure 8 shows the recharge wells being relatively close to the dewatering system, but this is purely to make the figure useful at this scale – in practice recharge wells have to be installed a considerable distance (sometimes several kilometres) from the dewatering system. This is necessary to reduce the risk of significant re-circulation of recharged water back to the dewatering system, which can increase pumped flow rates.

A practical problem that often affects recharge well systems is that they can become clogged by physical, chemical and bacterial processes in the wells – most commonly the precipitation of insoluble iron-related compounds (often visible in the form of red-brown 'ochre' deposits) or carbonate deposits (hard pale-coloured scale deposits). This may require mitigation by the provision of water treatment to improve water quality prior to recharge, and/or periodic rehabilitation of the recharge wells by physical and chemical treatment to remove the residues of the clogging process.

Where the intention is to recharge the water into shallow strata, such as superficial or drift deposits, it may be more appropriate to use shallow recharge trenches (Cliff and Smart, 1998; Huxley et al, 2004), rather than recharge wells. Such trenches can be excavated with conventional excavating plant and can offer a low-technology solution to artificial recharge into shallow strata. Recharge trenches may be affected by clogging due to suspended solids settling in the base of the trenches; this can be mitigated by periodic cleaning out or scarifying of the base of the trenches using excavating plant.

OPERATING COSTS AND POWER CONSUMPTION

One of the challenges facing dewatering practitioners is that mine and quarry operators often view dewatering as a 'distress purchase' – they will only implement it when there appears to be little option to avoid it. There is therefore a focus on cost minimisation as the primary mechanism to select and manage a dewatering programme. This can be shortsighted, since there are trade offs between direct dewatering costs and potential reductions to wider mining costs as a result of the benefits of dewatering. The dewatering programme with the lowest direct cost is not necessarily the scheme that will deliver the lowest overall cost (dewatering cost minus savings in mining costs resulting from dewatering benefits). It should also be recognised that monitoring

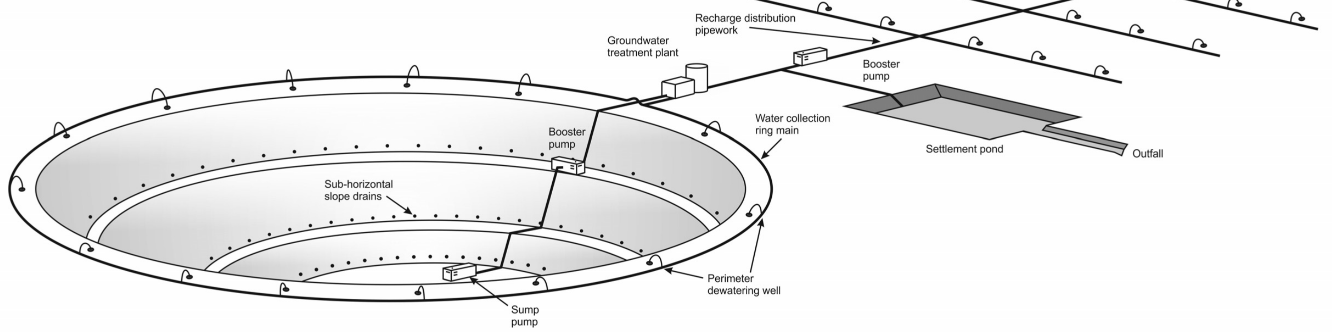

Figure 8. *Schematic arrangement of an artificial recharge system fed by perimeter dewatering wells at surface mine (note that recharge wells are normally located at considerable distance from the dewatering system, the recharge wells are shown close to the pit to make the figure legible at this scale).*

(e.g. of pumped flow rates and groundwater levels) is vital for the effective management of dewatering programmes, and without it there is little hope of any form of optimising the dewatering, either in terms of cost or other factors such as environmental impacts.

Dewatering costs can logically be divided into capital expenditure (CAPEX), and operating expenditure (OPEX). CAPEX comprises the capital cost of pumps and other equipment, installation and commissioning costs (including costs of drilling dewatering wells and the installation of any cut-off walls). OPEX comprises costs of power (mains electrical power or diesel fuel for pumps and generators), monitoring and maintenance, and replacement equipment/spares/consumables.

For a surface mine or quarry with a long development and production life, it is not unusual for OPEX to be large in comparison to CAPEX. Power costs to drive pumps are often a large part of OPEX, and when looking to lower operating costs, reducing power consumption is an obvious aspect to investigate. Reducing power usage will also have the further benefit of lower carbon emissions, which will be aligned with the environmental and corporate social responsibility (CSR) policies pursued by many mining companies and mineral producers.

A pump is, in essence, a mechanical device used to lift fluid (in this case water) against gravity, and the power required to do so is determined by relatively few parameters. The power requirement P (kW) to pump a water flow rate Q (m^3/s) against a total head H (i.e. the actual vertical lift plus the additional head caused by friction losses in the pipework and fittings) is expressed as:

$$P = \frac{Q \times H \times \rho \times g}{\eta} \qquad (1)$$

where ρ is the density of water (1,000 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2) and η is the pump efficiency. The energy consumption E (kWh) of a pump (assuming the parameters do not vary with time) is the power P multiplied by the pump run time t (hours):

$$E = \frac{Q \times H \times \rho \times g \times t}{\eta} \qquad (2)$$

It can be seen from equation (2) that the energy required for dewatering pumping can be reduced by: reducing the flow rate Q; reducing total head H; reducing the hours run t; by increasing pump efficiency η; and by a combination of these measures. Good design and implementation of a dewatering programme has the potential to reduce energy usage and significantly lower OPEX over the life of the mine. Some examples are given below:

- Use of low permeability cut-off walls to seal off significant permeable zones (reducing flow rate Q);
- Effective monitoring of groundwater levels to allow pumping to be controlled to avoid excessive lowering of groundwater levels below the current production level (reducing flow rate Q);
- Good design of pumping pipework, using larger diameters, lower friction materials and avoiding unnecessary bends and restrictions in fittings (reducing the friction losses and thereby reducing H);
- Effective control systems to allow pumps to switch on/off in response to groundwater levels (reducing hours run t); and
- Selection of appropriate pumps for the duty, so that they run at an efficient point in their performance curve, and suitable control systems (e.g. inverter drives) to allow pumps to operate at high efficiency in a range of duty conditions (increasing pump efficiency η).

The Future

When considering possible future trends in dewatering and groundwater control, there is no realistic expectation that there will be a step change in technologies or costs in the foreseeable future. The basic laws of physics govern the hydromechanical performance of pumps and it is difficult to see how there could be any more than incremental improvement in these systems. Similarly, most groundwater exclusion technologies have existed in their current form for more than 50 years, and have been highly refined in relation to costs and effectiveness.

However, developments in materials, equipment design, and information technology will undoubtedly lead to improvements in plant efficiency, reliability, and safety over time. It is also possible, indeed likely, that some unheralded technological advances, apparently far removed from mining and quarrying may have a significant impact on mine dewatering. History shows that any consideration of the future needs to be tempered by Amara's law, which states 'We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run.'

Three areas where mine dewatering may change in the future, and that are discussed below, are:

- Improved efficiency,
- Technology transfer for new technologies, and
- Alternative business models to procure dewatering.

Improved efficiency

The efficiency of a dewatering system is not straightforward to define fully. However, it is probably uncontroversial to state that a 'more efficient' system will have reduced energy costs, reduced carbon emissions and increased equipment life relative to a 'less efficient' system. The efficiency of a dewatering system is affected by the efficiency of the individual elements as well as the way the system operates as a whole.

Efficient dewatering systems can be characterised in terms of good hydrogeological design, appropriate selection of equipment and materials, and effective control, maintenance and operation.

- *Good hydrogeological design*

The focus of dewatering design is usually to ensure that dewatering will be effective in lowering groundwater levels within the required time period. Although it is rarely explicitly stated as such, because of the natural hydrogeological uncertainties, this means the dewatering design is often relatively conservative, with excess pumping capacity and oversized pipes and pumps running at a fraction of their capacity (which is inherently inefficient). To get more efficient operation of dewatering systems and reduce energy costs and OPEX, better use could be made of: 3-dimensional numerical groundwater modeling to get better estimates of dewatering inflows; groundwater exclusion cut-off walls and barriers to reduce dewatering inflows; and phased dewatering plans to use data from initial dewatering activities to refine later stages of pumping.

- *Appropriate selection of equipment and materials*

Dewatering systems should take advantage of incremental improvements in dewatering equipment, such as more efficient pumps, better pipework (to reduce friction losses) and improved control systems. For a mine dewatering system with a long life (greater than, say, 15 years) uprating of key equipment for the latest equipment partway through the mine life may offer cost and energy savings that offset the additional cost. In the shorter term, pumped flow rates may reduce significantly between the initial drawdown period and the later steady state pumping when the pit is fully dewatered. Rea and Monaghan (2009) describe an example where borehole pumps were swapped for smaller units at the end of the drawdown period, with the aim to reducing energy usage.

- *Effective control, maintenance and operation*

Perhaps the biggest change in pumping and monitoring equipment in the last 20 years is the improvement in electronic control and communication systems. Real time remote monitoring (of groundwater levels, flow rates and water quality) and control of pumping systems can be an economic reality on almost any site. Where there are 4G and 3G cellular communication networks, hard-wired data connections are obsolete. Inverter (variable speed) controllers for pumps can allow significant 'automation' of systems to give more efficient operations, where pumps operate in feedback to actual conditions, so they can remain at optimum operating efficiency as much as practicable.

In practice, the maximum improvements in efficiency are most likely to result from a combination of the above options. Additional initial investment will be required, but payback should be obtained in the form of reduced energy costs, reduced carbon emissions and increased equipment life.

Technology transfer for new techniques

Mine dewatering can also learn from other industries, and there are opportunities for technology transfer from other industries. This may be as simple as looking at alternative pump types or pipework materials, or may involve looking at alternative control systems or drilling methods.

One example is the use of Horizontal Directionally Drilled (HDD) wells for dewatering purposes (Figure 9). HDD methods are not new technology and are routinely used to install pipelines for river crossings or beneath inaccessible areas, where drilled distances of 500 to 1,000m can be achieved in a range of geological conditions. However, installation of HDD wells to for dewatering purposes presents some particular challenges. First, HDD installations typically use thick bentonite or oil-based drilling muds, which can impair the permeability of the soil or rock around the well. Second, the perforated well screen must be pushed or pulled into the well; because the well is deviated, the longitudinal loading on the well screen can be very large, risking damage to the screen. However, there are an increasing number of wells, outside the mining industry, installed by HDD methods. For example Cox and Powrie (2001) describe a HDD application to extract leachate from beneath closed landfills.

To date the number of HDD wells drilled for mine dewatering purposes is very small. In future HDD wells may become a more established mine dewatering technique, allowing wells to be located outside of the mining area and steered into the geological zones targeted for dewatering or depressurisation.

Alternative business models to procure dewatering

The traditional business model for procuring pumped dewatering systems has changed little in the last 50 years. Commonly, the mine operator obtains the pumps and ancillary equipment by sale/lease/rental. During operation, maintenance is carried out either by the mine operator site team or under a maintenance contract by the pump supplier, while the mine operator provides and pays for the power and fuel. While maintenance programmes do involve an element of preventative maintenance, typically major equipment upgrades or changes normally occur in response to equipment failures or operational problems – the cliché 'if it isn't broken don't fix it' describes this approach quite well.

It is hard to consider this procurement model as providing a 'dewatering service'. Essentially this model is focused on providing the pumps to site and keeping them operating to a reasonable level of availability. There is little incentive for the pump supplier or maintenance company to ensure the pumping systems operates efficiently or to minimise energy costs.

It is useful to look at how procurement models have changed in other industries in recent decades. The airline industry relies on jet engines to power its aircraft, and spends billions of dollars on engines and fuel. However, in the 21st century, jet engine suppliers such as Rolls Royce, Pratt & Whitney and General Electric no longer sell engines. Instead they offer a service based on 'thrust hours', focused on, and paid according to, the service availability and efficiency of the engines on their client's aircraft (Wharton University of Pennsylvania, 2007). Rolls Royce has trademarked the term 'Power by the Hour' to describe their business model.

This type of procurement is generically known as 'performance-based logistics', and is intended to focus on what the client cares about – for airlines this is reliability and availability of aircraft, and fuel economy – and not the details of the equipment – in this case the jet engines. These arrangements are made possible by: long term agreements; remote monitoring and control (for example

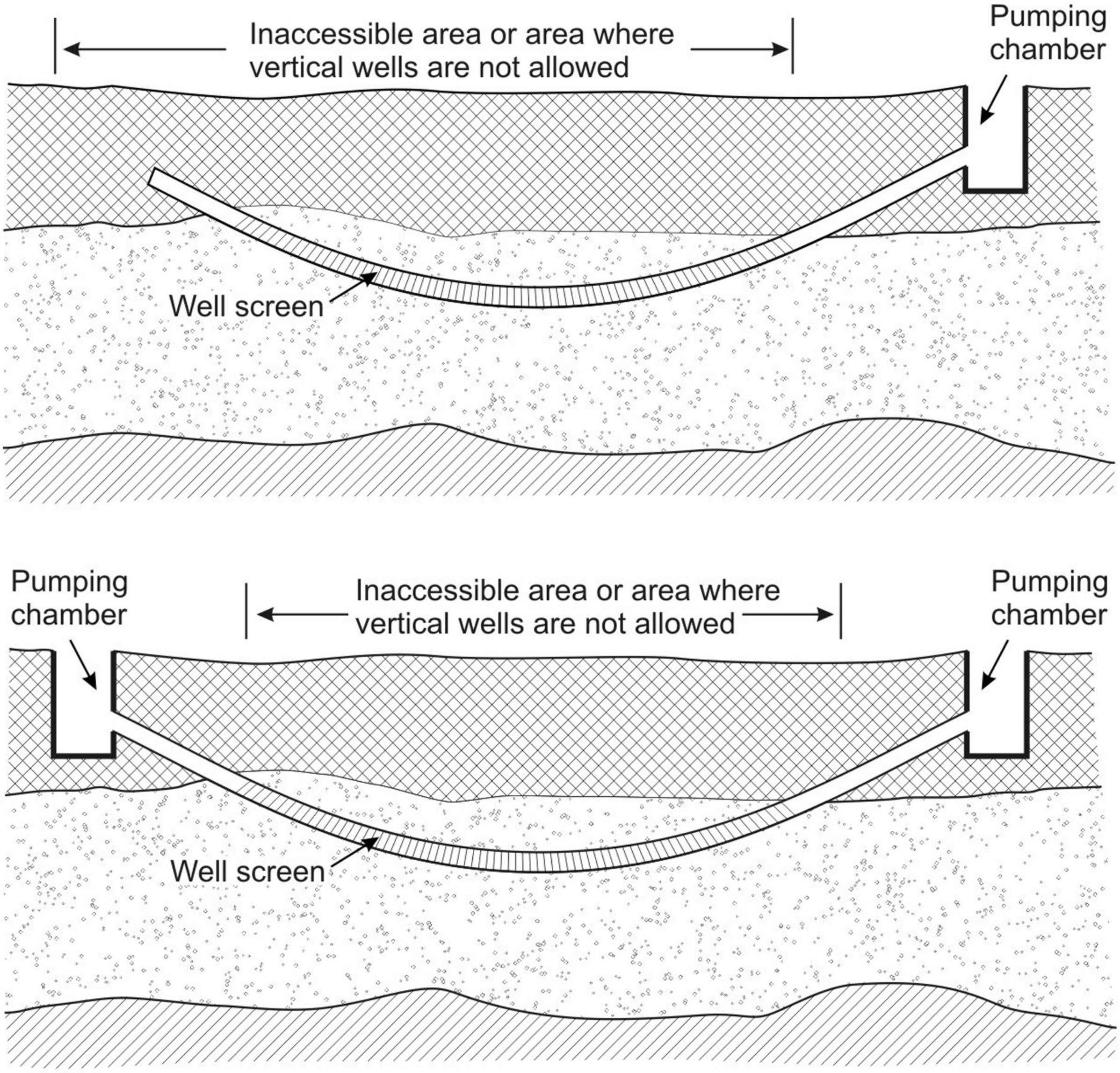

Figure 9. *Schematic arrangement of horizontal directionally drilled (HDD) dewatering wells (reproduced with permission from Cashman and Preene, 2012).*

where the jet engines remotely communicate with the manufacturers via satellite link); and, contractual arrangements where the service provider has vested interest in reducing energy usage, and improving efficiency.

The business focus of a mining or quarry operator is to maximise output of product (which needs reliable and effective dewatering), while minimising unit cost (which needs efficient systems to reduce energy costs). The details of the pumps *per se* are of little interest to the operator. Mine dewatering systems, applied on mines with long planned lives, and using pumping systems equipped for remote monitoring and control are well placed to be procured on a performance basis, where the dewatering provider is paid not based on how many pumps are on site but based on the availability of an effective dewatering system, and where there is an incentive to reduce energy costs year-on-year, with savings shared between the mine operator and dewatering provider. The mine operator would get the benefit of shifting the main investment from CAPEX to OPEX and would gain certainty of cost over the mine life, and confidence that pumping availability will not affect mining.

Conclusion

Dewatering remains a fundamental part of the mining and quarrying process when working below groundwater level. Effective dewatering can enable mining in relatively dry conditions, thereby providing better working conditions and greater efficiency, and can improve geotechnical stability, for example by allowing steeper side slopes. While the focus of dewatering is typically on pumps and pumping systems, exclusion methods such as cut-off walls and grout curtains can have a role to play in reducing groundwater inflows, thereby reducing operating costs.

While dewatering techniques and equipment have been refined over many decades, and no significant step changes in equipment capabilities are on the horizon, there may be opportunities for technology transfer to allow mine dewatering to benefit from recent developments in other industries; improvements in remote monitoring and the control of pumping systems are routinely used in other industries but are rarely used on mine and quarry sites. The robustness and reliability of such equipment has improved, and at the same time capital costs have reduced. Such systems are ripe for wider application on mine sites, where they offer potential benefits to the mine operator in the form of reduced energy costs, reduced carbon emissions and increased equipment life.

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