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Groundwater control and mud rush prevention for caving mines

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Abstract

Caving methods create drainage of all water from within a predictable radius. The diameter and shape of the radius are functions of the sources of water, the country rock hydraulic conductivity and geological structures which drain towards the caving areas (active and closed). Although some water is advantageous to production rates, too much water creates hazardous conditions and contributes to mud rushes.

Understanding the sources of water and monitoring head distribution are essential for the calculation and management of water ingress. Over 45 years, the author has developed a phased approach to mine dewatering design and water management. This has been adapted to support caving operations and used to reduce mud rushes.

Flood control requires a top-down approach including surface water management, flow path mapping, stormwater prediction and diversion, and modelling of flood events. This can then be incorporated in the mine's water risk management strategy and reported in the risk register. Prevention of mud rushes requires a thorough understanding of the causes and hydrogeological environment. Mud rushes have 4 components: presence of mud-forming materials (low-friction material or fines), driving head of water (phreatic surface above a specific maximum level), discharge points present for mud to enter the workings and one or two triggers. Triggers include water pressure head exceeding a target head, seismic events, (natural or man-made), blasting pattern and overdraw. Water is the most important factor. The head of water around a caving area can be monitored, diverted and managed. Numerical modelling, based on a detailed understanding of the groundwater regime, can be used to help predict the pattern of pressure distribution and the range of maximum head for specific configurations of extraction advance.

Methods are discussed for achieving improved mine dewatering design and the prevention of the ingress of both water and mud.

Keywords: *mud rush, caving, monitoring, in rush, flooding, dewatering, water management, drainage, water balance*

1 Introduction

Caving methods use gravity to drive ore to collection points. Gravity also drives all the water above the caved area, within a predictable radius, towards the lowest points in the mine. The diameter and shape of the radius are a function of the sources of water, country rock hydraulic conductivity and the geological structures which drain towards the caving areas (active and closed). Although some water is advantageous to production rates, too much water creates hazardous conditions and also contributes to mud rushes. Since 1815, there have been over 86 flooding and mud rush disasters worldwide, resulting in the deaths of over 1,800 miners underground (Vutukuri & Singh 1995; Butcher et al. 2000, 2005; Morton et al. 2026a, 2026b; WMC 2003). The most recent are the 17 February 2026 mud rushes at Ekapa diamond mine Kimberley that killed 5 (SANews 2026) and at Freeport McMoran's copper and gold Grasberg Mine in Indonesia on 8 September 2025 which killed 7 (Freeport-McMoRan 2025)

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It is clear that the mining industry requires a better understanding of the causes of mud rushes and inflows to save lives. Understanding the sources of water and monitoring head distribution are essential for the calculation and management of water ingress. Over 45 years, the author has developed a phased approach to mine dewatering design and water management (Morton & Van Niekerk 1993; Morton 2024). This approach has been adapted to support caving operations, install monitoring networks, reduce heads of water, and reduce mud rushes.

Work undertaken by De Beers (1993, 1996) and Du Toit (2005) investigated specific mud rush events and their causes, while publications by Butcher et al. (2005), Holder et al. (2013), Hilton et al. (2012), and Morton (2022a, 2022b) reviewed and recommended methods for the control and prevention of mud rushes.

The booklet published by Butcher et al. (2000) lists 4 elements for a mud rush to occur:

1. potential mud-forming materials must be present
2. water must be present
3. a disturbance of the mud, in the form of drawing or other mining activity
4. discharge points must be present through which the mud can enter the mine workings.

Of these elements, water is the dominant factor and easiest to control provided that the provenance, water balance and movement of the water is well understood. Therefore, the elements for a mud rush to occur can be re-worded to:

1. presence of mud-forming materials (with low frictional resistance or fines)
2. head of water (phreatic surface above a specific maximum level)
3. discharge points present for mud to enter the workings
4. triggers including:
    a. overdraw
    b. seismic event (natural or man-made)
    c. increase in head of water (natural or man-made).

This paper concentrates on and discusses the role of water in a mud rush and the work required to understand and control the water regime of an underground mine. The phased approach is based on the logical and physical understanding of all sources of water, paths followed by the water, and where the water is stored, then assigning ranges of hydraulic conductivity and a detailed water balance .

When these are known, the overall hydrogeology of the mine can be understood, volumes and inflow rates can be calculated, and practical methods developed to divert water from the operational areas. This then addresses the main cause of mud rush, water, and enables prevention of mud rushes by controlling the cause not the effect.

2 Hydrological cycle and movement of water into and through an underground mine

As soon as ground is excavated below the water table (phreatic surface), the natural groundwater regime changes affecting the well-known hydrological cycle. Figure 1 is a schematic, not to scale, that shows the location of a pit and underground mine within the hydrological cycle. It is important to note the ground water flow path is ‘u’ shaped reflecting the movement is orthogonal to equipotentials.

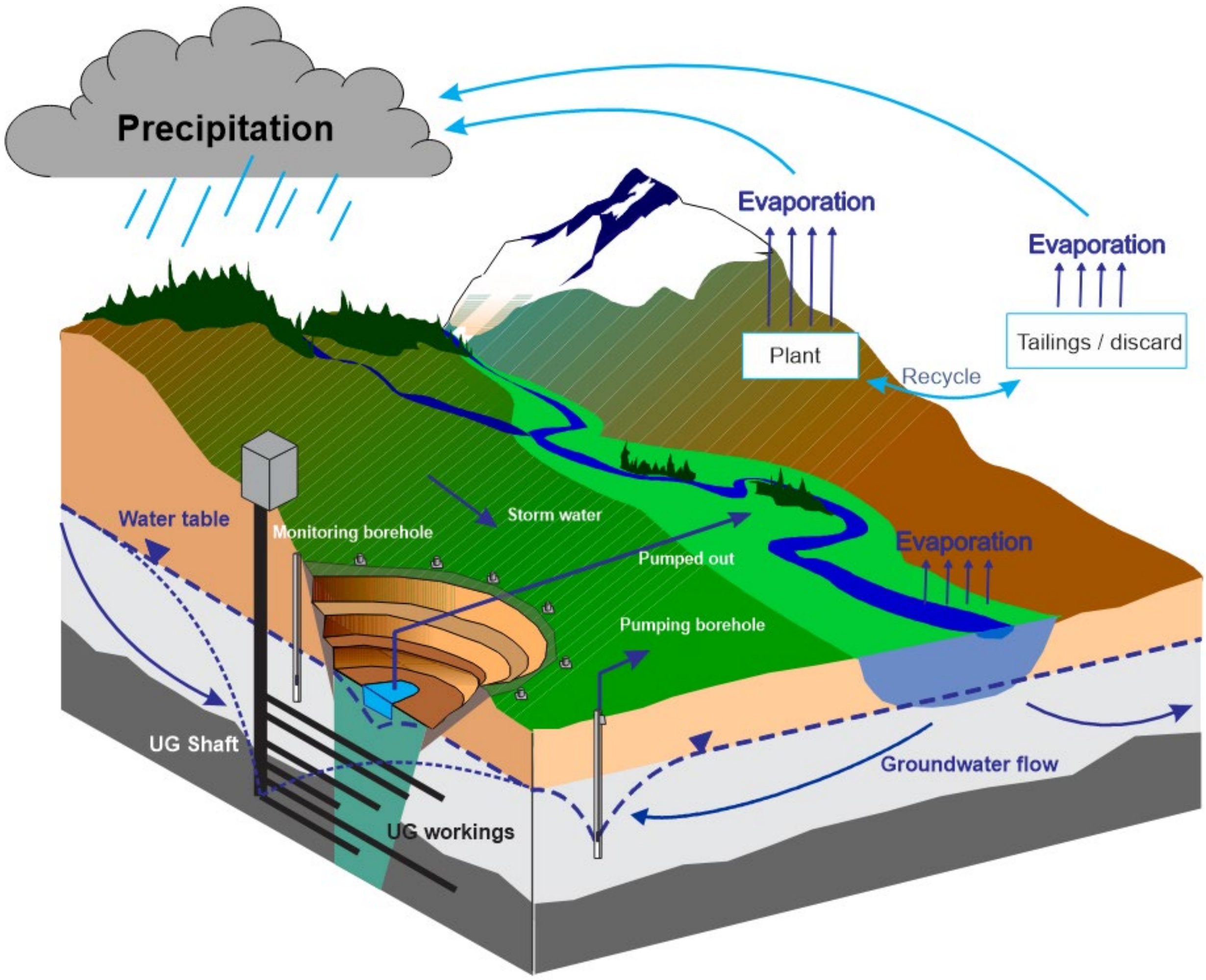

Figure 1 Location of an open pit and underground mine within the hydrological cycle

Water entering the mine is originally from precipitation and groundwater (which is recharged by precipitation, nearby lakes, rivers or natural and man-made impoundments). Water always flows from high pressure to low pressure. At its simplest, water flows into the pit and underground, then is pumped to surface where it is either discharged away from the mining area or recirculates back into the mine workings. Mining creates cracks in the ground, which makes it easier for water to flow into the mine (Morton 2022). Figure 2 is a diagram showing the zone of relaxation (ZOR), which is created around an open pit as the rock 'relaxes' towards the pit centre and along lines of vertical and sub-vertical structural weakness (faults, contact zones, shear zones, bedding planes, etc). The ZOR can obscure the seepage face in the high walls behind relaxed or broken rock. The ground below the pit also relaxes as tonnes are removed and the rock can relax upwards. Figure 2 illustrates the concept of the ZOR in plan and section.

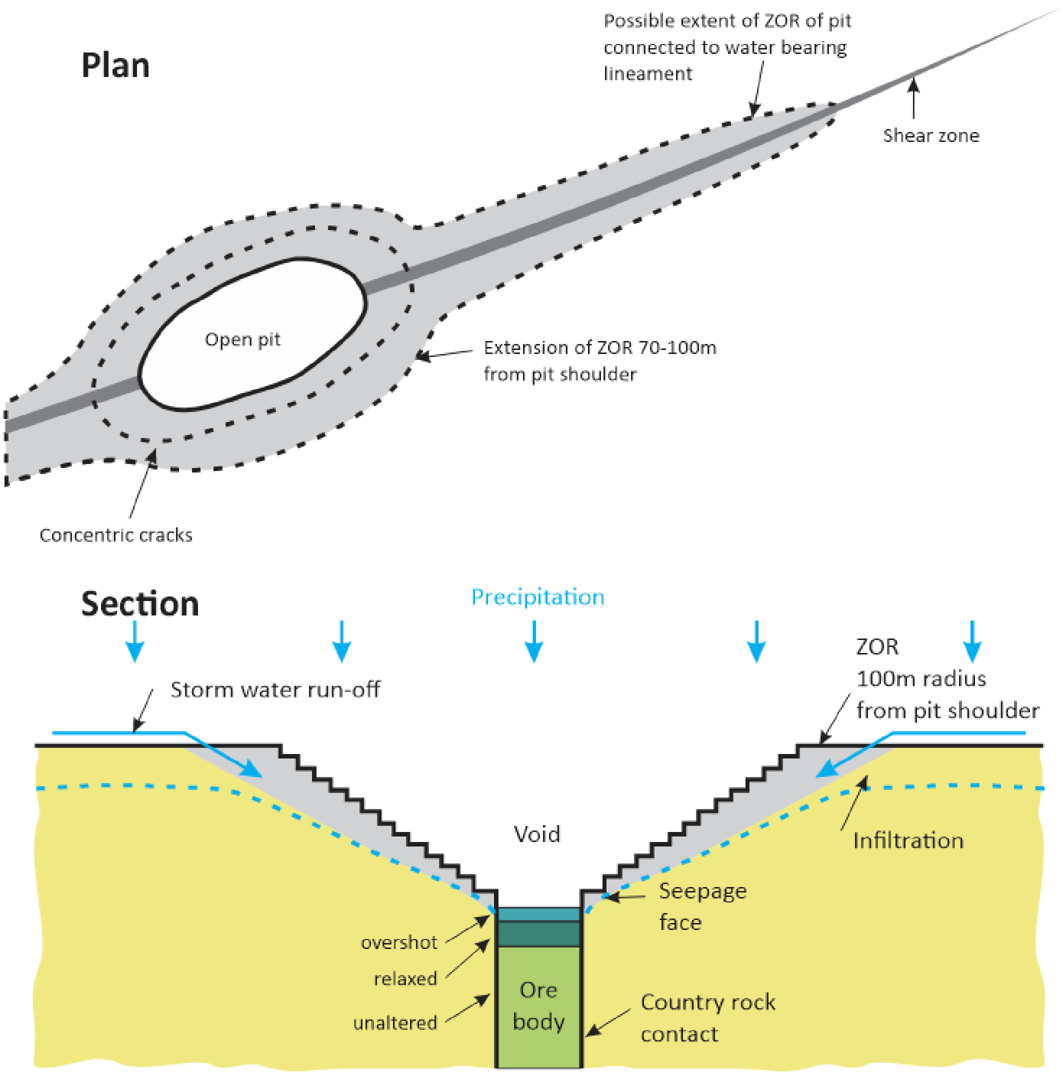

Figure 2 **Schematic of zone of relaxation (ZOR) around a pit which enables seepage water to enter the pit slopes and is obscured by broken rock**

The relaxed rock has higher permeability and can transmit water faster into the pit and underground; often the country rock/orebody contact zone is open and creates a preferential path for water flow.

Understanding the ZOR is important for caving mines established under an open pit, as the ZOR creates an easy path for water to enter the mine and muck pile. The caving method can create high permeability zones which connect underground workings directly to the surface and increase inflows.

Once water enters a mine, it moves along mine workings, permeable and broken rock and through conduits such as faults, shear zones, dyke contacts, bedding planes and sometimes the orebody itself. A good 3D hydro-structural model of the country rock is essential for understanding how the water moves into a mine (Morton & Millsteed 2023). This type of model is based on the country rock model for the mine. Understanding the regional stress regime is also important, as tensional structures, such as north–south faults in Southern Africa, tend to carry more water than compressional east–west faults, particularly if they intercept aquifers or water sources north or south of a mine. The model also needs to include the mine workings and planned workings as they become very good carriers of water along the footwall and sidewall drains. Figure 3 illustrates an example of a 3D hydro-structural model (Yuan et al. 2025).

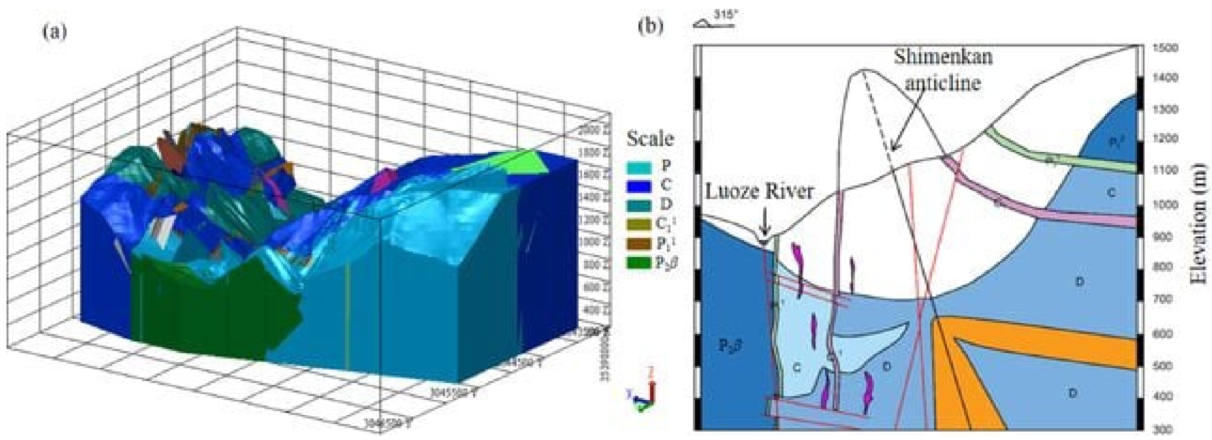

Figure 3 Example of a 3D hydro-structural model (Yuan et al. 2025)

Once the hydro-structural model has been created the paths that the water takes to reach underground can be plotted. Groundwater enters the mine from all directions following Darcy's Law (Equation 1):

$$Q = KIA \tag{1}$$

where:

Q = inflow (m^3/day)

K = hydraulic conductivity, also known as permeability for water (m/day)

I = hydraulic gradient (h/l of water elevation) (m/m)

A = cross-sectional area (m^2).

This law is the basis of all numerical hydrogeological modelling. Inflow and outflow can be measured with flow gages, hydraulic conductivities can be assigned and cross-sectional area can be estimated from the hydro-structural model. Hydraulic gradient is usually the least well-known. It can be measured using a network of piezometers installed in core holes that have been drilled for other uses too. Figure 4 shows the measurement of hydraulic gradient from underground and the construction of a sealed piezometer (Vibrating Wire Piezometer type). More detail is given in Morton (2022). A very good explanation of the movement of water relevant to engineering geology is given in De Freitas et al. (2025).

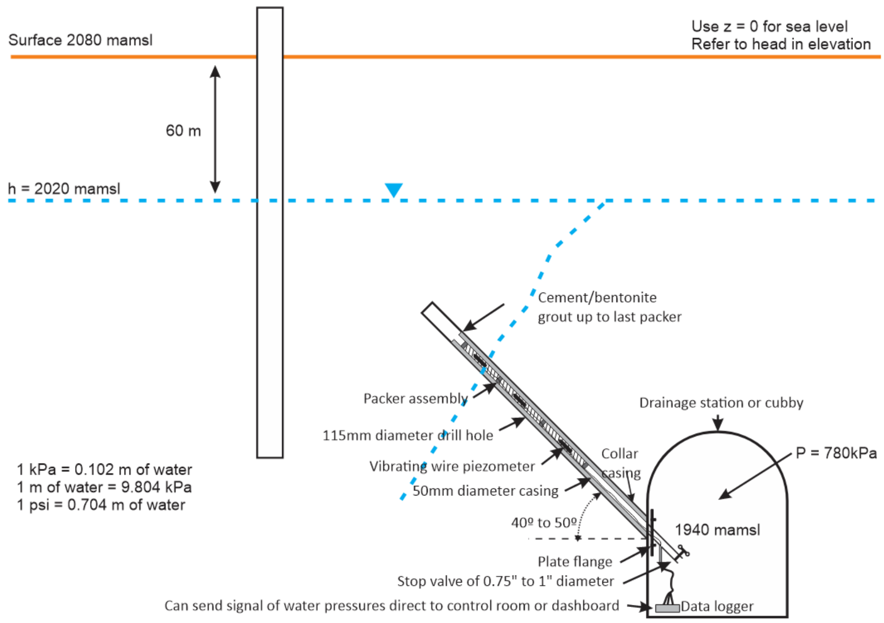

Figure 4 Measurement of hydraulic head underground

In older mines, there are often closed (abandoned) areas that do not have drainage systems installed to stop them from flooding. This creates a huge risk as the flooded area can cause inrushes to the active mine. It is very important, prior to closing mining levels, to install passive drainage systems that stop water accumulating. If this is not possible, it is important to survey old workings, and map and monitor outflows for flood risk regularly.

Once all the above is understood, a conceptual model of the flow into the cave area can be created to include:

- sources of water (precipitation, groundwater, and structurally connected surface water)
- hydrological catchment areas affecting the mine (surface and groundwater)
- conduits for groundwater flow (ZOR, workings, shafts, ore passes, geological structures, high permeability zones, bedding planes)
- barriers to flow (compartments), e.g. dykes and closed fault/ shear zones, impermeable rock
- highlighted risk and critical zones.

In some carbonatite mines, such as kimberlites, there is an unbonded contact between the orebody and the country rock. When the orebody is cylindrical or semi–cylindrical in shape the contact zone can be a preferential zone that carries water from near surface to the mined or caved area. At Finsch mine near Kimberley, South Africa, a research project used packer testing to measure the hydraulic conductivity of the contact zone and showed that it had at least 10 times that of the country rock (Morton 2008). As the contact zone also intercepted the regional faults and bedding planes, it became a very useful target for drainage of the whole mine and the muck pile, using underground pumping boreholes (wells).

Figure 5 illustrates some of the geological structures that carry water into a block cave that is mining a carrot-shaped carbonatite which intercepts water-bearing regional faults and bedding planes and is connected to the muck pile.

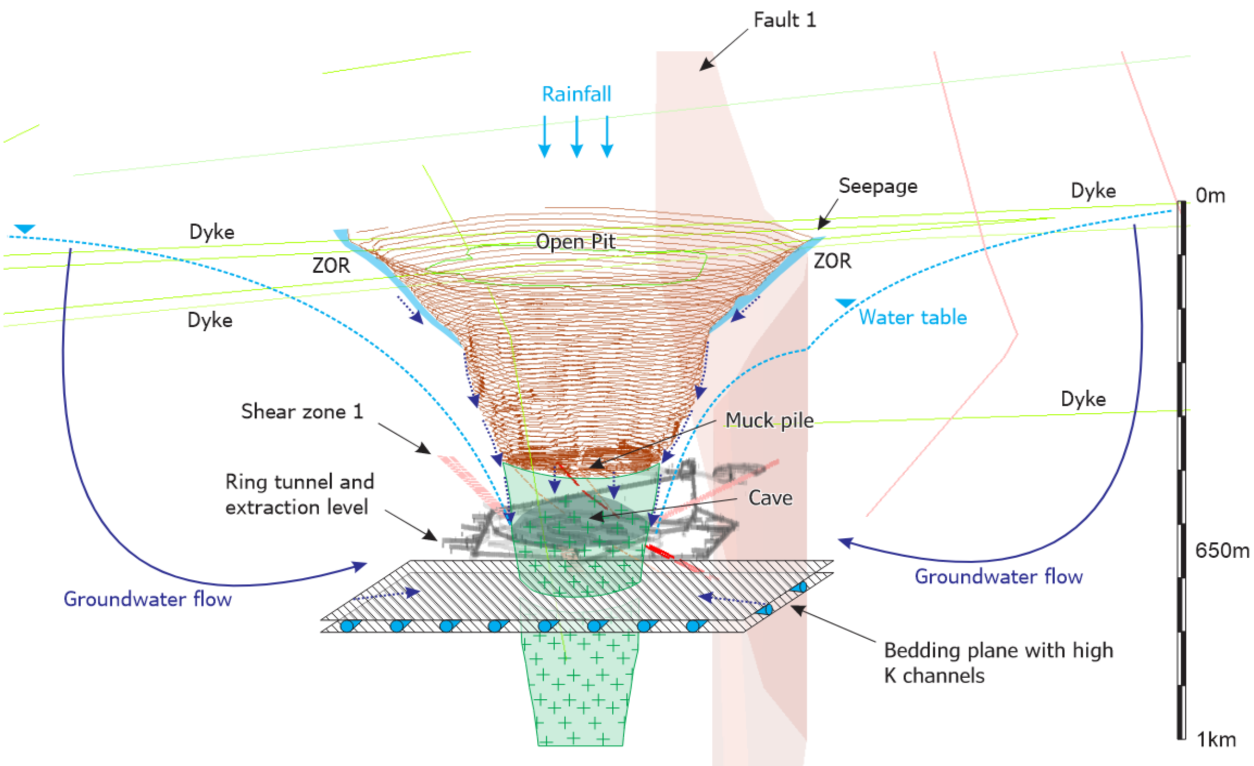

Figure 5 Conceptualisation of a block cave showing flow paths for groundwater moving into the muck pile and extraction level

Once the structural geology skeleton of the hydrogeological conceptual model is understood, the water balance can be added. The water balance for the overall mine is very important for understanding mud rush risk. The mine needs to ensure that the water table (phreatic surface) is always maintained below the extraction level and that the amount of water pumped out of the mine is equal to or exceeds the amount of water entering the mine. If the phreatic surface is maintained below the extraction level, the head needed to create a mud rush cannot develop.

If more water is pumped out than enters a mine, it will be impossible for excess water to become stored in the muck pile or country rock. The water balance does not need to be exact but can be estimated as a range. The conceptual model delineates the catchment areas for ground and surface water, which can then be used to estimate the volume of water which will enter the catchments monthly, quarterly, or annually. This then determines the volume of water that needs to be drained or pumped out of the mine over the same or shorter periods. The water level monitoring network is used to measure the height of the phreatic surface around the mining area, and the dewatering design is used to keep the phreatic surface below the extraction level.

3 Management of underground water to prevent mud rushes

The first step is to control the surface water, which also includes prevention of water inrush. Flood control requires a top-down approach including surface water management, flow path mapping, stormwater prediction and diversion, and modelling of flood events. This can then be incorporated in the mine's water risk management strategy and reported in the risk register which should be updated at least every 6 months, preferably quarterly, or before the start of each new precipitation season. Best practice is that the board approves guidelines and the general manager approves standards (Anthony Guthrie, pers. comm 2026). Stormwater design often includes the construction of berms planned for 1:100 precipitation events, climate resilience planning now includes 1:1,000 year events and 50 days above average precipitation days. The berms can be damaged during mine activities and need regular checks using site inspection, drone inspection and/or InSAR mapping.

Of the contributing elements of mud rushes, in the author's experience, water is the most dominant and easiest to control. The head of water around a caving area can be monitored and managed. Numerical modelling can be used to predict the pattern of pressure distribution and the maximum head for specific configurations of extraction advance. Table 1 lists the 4 contributing elements causing mud rushes and the techniques to control them.

Table 1 Elements of a mud rush

	Element	Techniques for control
1	Presence of mud-forming materials ('low-friction resistance' rock or fines)	Reduce muck pile, reduce pit slope failure, adapt blasting, reduce contact time with water
2	Head of water (phreatic surface above a specific maximum level)	Keep phreatic surface below extraction level by accurate pumping, diversion and drainage
		Maintain a detailed water balance which ensures more water is drained out of the mine than water entering the mine catchment
		Monitor head distribution in 3D using vibrating wire piezometers (VWP) and use dashboards to show risk in real time (traffic light system)
		Measure water ingress at drawpoints and seepages into open pits
		Improve mine design to divert water in advance of mining
		Ensure good drainage of closed areas of the mine
3	Discharge points (drawpoints)	Best practice geotechnical design taking into account the sources of water and flow paths
		Mapping of water ingress
		Early warning system of water pressure build-up above and around the drawpoints
4	Triggers include:	
	Over draw	Manage draw
	Seismic event (natural or man-made)	Use quake prediction tools to warn of natural events, adapt caving design to reduce seismic events
	Increase in head of water (natural or man-made)	Accurate stormwater diversion, drain upper levels of mine, control pit drainage, ensure water out is greater than water in

Each of these can be monitored and controlled. The dominant factor (which can be controlled) is the weight of water (head) that drives a mud rush. This can be reduced by accurate management of the water drainage for the whole mine and the country rock using a monitoring network of vibrating wire piezometers, plotted in real time, similar to the networks used to monitor water pressure for slope stability analysis (Morton et al. 2008).

The open pit above an underground mine needs to be accurately drained using stormwater diversions and in-pit catchment dams (that are constructed before pit closure). Drainage needs to be continuous. When well-managed, it also improves slope stability and reduces build-up of muck at the bottom of the pit, which can also retain water.

Drainage is best achieved using large diameter drill holes or tunnels. Small drill holes cannot move large volumes of water and encrust very quickly. Figure 6 shows the head distribution in a hypothetical mine being drained by small diameter drillholes and an improved, best practice phreatic surface (water table) which can be achieved with a circular drainage gallery, that lowers the head below the extraction level. When water levels are maintained below the extraction level, there is little risk of mud rush.

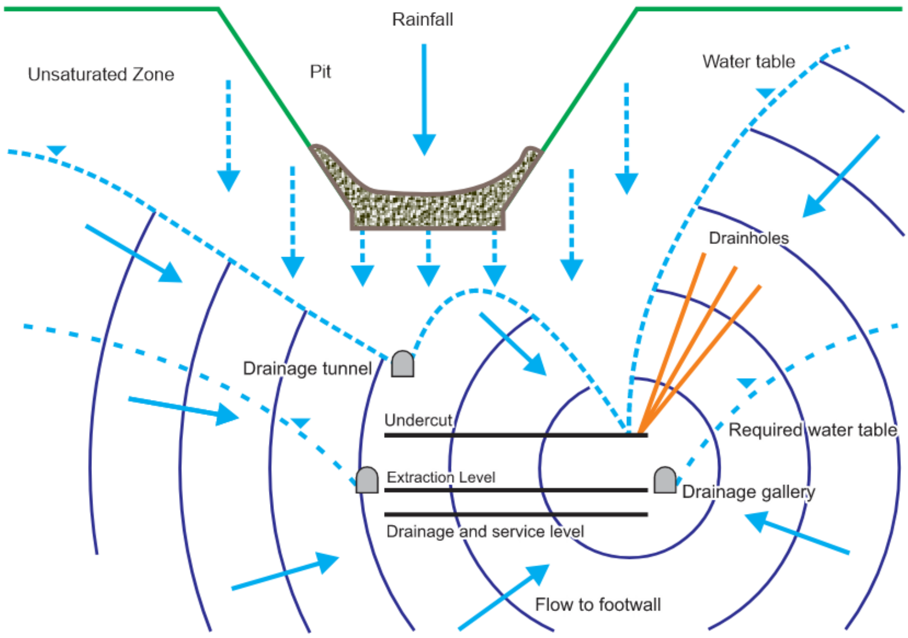

Figure 6 Schematic head distribution of a hypothetical underground mine

Structural geological mapping and modelling can be used to plot the routes that water can take to reach underground (Morton & Millsteed 2023). Monitoring of the head distribution of water around block caves can be used to understand and then reduce the water pressure which drives mud rushes. The distribution of water can be managed by accurate diversion of stormwater and drainage of country rock surrounding the mining area. Flood control can be improved using satellite precipitation prediction techniques, satellite mapping and catchment monitoring to design systems that prevent the inrush of water to underground mines.

Active and passive methods for underground mine drainage include:

- water passes
- sump pumping
- drainage galleries including ring tunnels
- underground boreholes/wells
- drainage drives and drainholes.

Dewatering galleries are very effective and have been used for over 100 years. Figure 7 shows the layout of the dewatering galleries used in Wesselton mine, Kimberley (Morton 2008, 2022a).

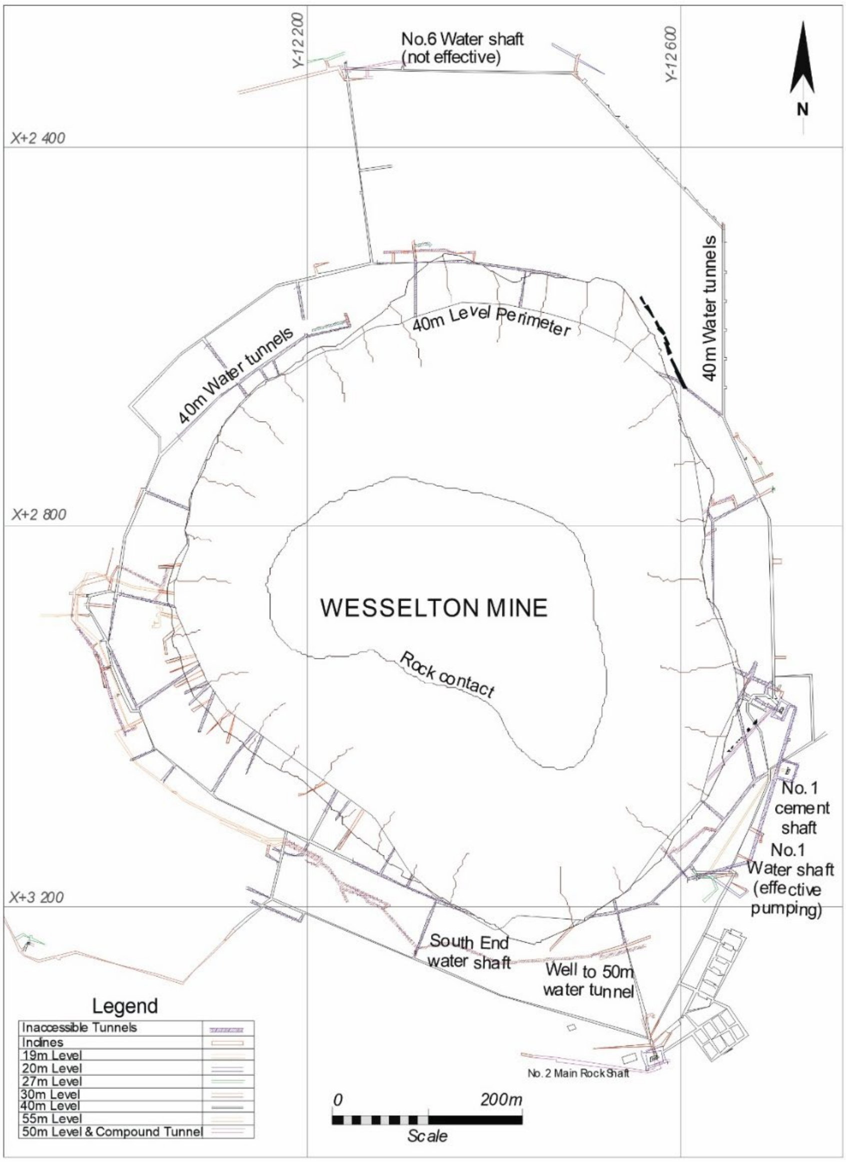

Figure 7 Drainage galleries used at Wesselton mine, Kimberley (Morton 2008, 2022a)

They are a combination of passive and active methods; the tunnel and its upward-angled drain holes collect the water, which drains along a graded footwall to a shaft, where pumps lift the water to surface. They are very effective provided they are maintained, drain holes are cleaned out regularly, and pumps are operated continuously.

Finsch mine, near Kimberley, successfully drained a block cave to +1.2 km depth using a combination of a decline from surface, ring tunnel dewatering (65 Level, 650 mbgl) and vertical large diameter dewatering wells drilled from the 65 L ring tunnel. The ring tunnel and decline aided the dewatering of the muck pile by diverting water towards the kimberlite contact zone. The large diameter dewatering wells were drilled into the geological structures in the country rock that intercepted the contact zone, which then drained water away from the block cave. Figure 8 shows the layout in cross-section of the decline, dewatering tunnels and underground dewatering wells.

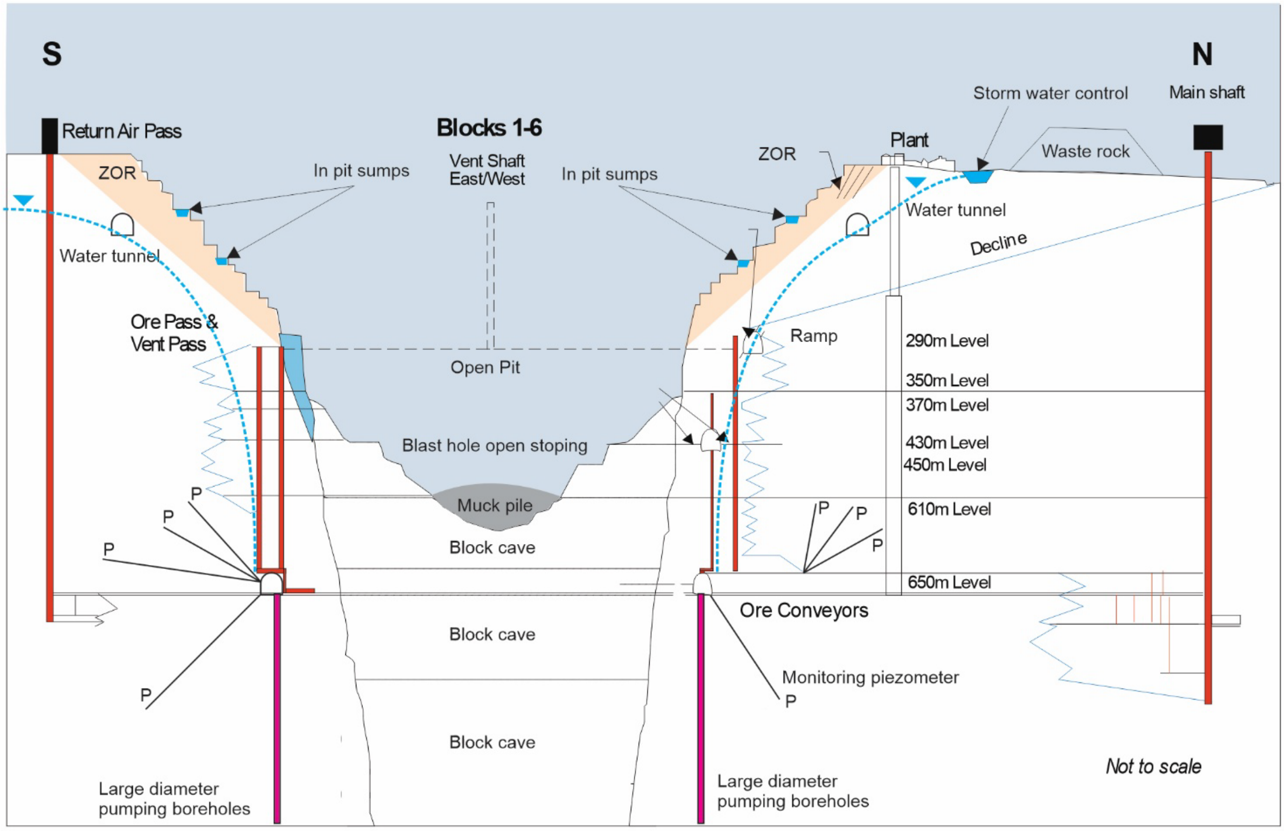

Figure 8 Finsch mine dewatering layout (Morton 2008)

Recirculation of water back underground is prevented by implementing accurate drainage systems within the mine that use lined storage dams that are sited away from broken ground. Mines that are established at altitude, well above sea level, can benefit by using gravity drainage to drain all water away from the mine. This technique has been used since Roman times (Younger 2004) and relies on large diameter (>1m) drainage tunnels diverting water away from the mine workings. The tunnels must be maintained, and the water balance checked regularly to ensure the tunnels are draining out more than is entering the mine.

Historically, mines have tried to use plugs to stop water entering the muck pile and underground workings. Plugs do not work as they cause water to build up behind or above them. It is always better practice to divert water than try to hold it back. Mir underground block cave mine in Siberia tried to plug the water in the overlying pit above the block cave, but the plug failed, killing 8 people (Al Jazeera 2019).

4 Conclusion and summary

The causes of mud rushes are well-known and comprise 4 contributing elements:

1. mud-forming materials (low-friction geomaterials or fines) above and around the cave
2. an elevated phreatic surface above a specific maximum target and trigger level
3. discharge points where mud can enter the workings
4. triggers for a mud rush including:
   a. overdraw at drawpoints
   b. seismic events (natural or man-made)
   c. increases in head of water (natural or man-made) above a trigger level.

Each of these can now be monitored and controlled more precisely using modern instrumentation and dashboards. The dominant factor (which can be controlled) is the weight of water (head) that drives a mud rush. This can be significantly reduced by accurate management of the water drainage for the whole mine using:

1. a regularly (quarterly) updated water balance that ensures water out > water in
2. annually reviewed, detailed hydrogeological conceptual model based on a detailed hydro-structural model
3. seasonally updated and accurate surface water control to prevent water entering the pit and underground mine through open holes and the ZOR
4. detailed dewatering designs for each sector of the mine using dewatering galleries and large diameter drains or pumping wells which keep the phreatic surface below the extraction level
5. annually updated monitoring network (heads and volumes) that reports on the location of the phreatic surface in 3D.

The most important aspect is monitoring the causes of mud rushes and not only the flow of water from drawpoints. By understanding the causes and drivers, mud rushes can be prevented.

Acknowledgement

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