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Managing the Unintended Consequences of Mining: Acid Mine Drainage in Johannesburg

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Preface

The South African economy is based on mining, with the Witwatersrand Goldfields having provided 40% of all gold ever mined by humans in all of recorded history. Central to this is the city of Johannesburg, which owes its existence entirely to the gold mining industry. Unlike Kalgoorlie in Western Australia that is also a gold mining city, Johannesburg is a major urban center currently experiencing exponential population growth due to in-migration. The city is unique in many ways, most notably because of the intimate coexistence of a large human population, mostly in informal settlements, with mining waste. The South African gold mining sector is in rapid decline and is not expected to last as a viable industry for more than a decade. This raises the issue of managing the unintended consequences of mining in a city that is water-constrained and straddles a continental watershed divide.

This chapter deals with the issue of acid mine drainage (AMD) that became prominent in 2002 when the first of three major mining basins beneath the greater conurbation of Johannesburg flooded and began decanting into a small stream that had not flowed for more than a century because of active dewatering. The problem is complicated by the existence of uranium in vast quantities in the many mine tailings dams that litter the landscape. It is argued that it is in nobody's best interest for the mining industry to become insolvent, as this will leave the hundreds of tailings dams to collapse under the natural forces of wind and water erosion. The case is made for the transformation of conventional mining into what is called closure mining in which the treatment and reuse of AMD is a central element. The combined decant potential of the three mining basins is equivalent to 14% of the daily needs of the city, so the various options for the use of this water are analyzed.

46.1 Introduction

Johannesburg is a unique city from a water resource and water services perspective because it is not located on a river, lake, or waterfront. Instead, it straddles a continental watershed divide between two great river basins—the Orange that discharges into the Atlantic Ocean and the Limpopo that discharges into the Indian Ocean. This makes it an engineering masterpiece because water has had to be pumped uphill, from ever-distant basins, simply to sustain a growing city. As with all heroic battles against the persistence of gravity, however, the water simply flows away once used, this time as sewage or water contaminated by industry. Johannesburg is also the epicenter of the Witwatersrand Gold Mining Complex, which has produced a staggering 40% of all gold that has ever been mined in all of recorded history. The name for the city in the vernacular is "eGoli" (isiZulu) and "Gauteng" (Northern Sotho), both of which mean "place of gold." This chapter tells the story about the linkage between the engineering challenges to sustain a modern African city, in the face of the social challenge arising from the unintended consequences of externalities from more than a century of mining where state regulation was minimal.

46.2 The Problem and Its Setting

The Witwatersrand Gold Mining Complex is the result of the deposition of metals into a lagoon in what used to be an inland ocean. This drained a hinterland rich in metals, including gold and uranium, which flowed through high velocity braided rivers discharging into this lagoon, rich in filamentous algae that trapped these heavy particles [32]. This is the richest single gold deposit on Earth, yielding 40% of all gold mined in recorded history; this area is also rich in uranium [13]. In fact, depending on the reef band being mined, for every tonne of gold produced, between 10 and 100 tonnes of uranium was brought to the surface, mostly discarded as waste because it had limited commercial value at that time [33]. The legacy of gold mining is the existence of 600,000 tonnes of uranium in various species that currently lie discarded in these old dumps [9,30]. There is a swathe of land running just south of the center of the Johannesburg, approximately 98 km long and 2 km wide, that has been undermined and is thus geotechnically unstable [24,26]. With a complex surface striking reef band consisting of more than 12 clearly defined packages, there are openings to surface approximately every 100 m along the entire length of the strike, creating multiple ingress points for water and access points for illegal artisanal miners (see Figure 46.1).

The Witwatersrand mining basin beneath the city of Johannesburg and its immediate conurbation of satellite towns is divided into three distinct geohydrological units, each separated by clearly defined aquitards or impervious barriers associated with tectonic activities over geological timescales. These consist of the Eastern Basin (under the satellite conurbation towns of Brakpan, Springs, and Benoni), the Central Basin (under the city itself but stretching to Roodepoort), and the Western Basin (under the satellite towns of Krugersdorp and Randfontein).

The main gold reserves are largely depleted, with the life of the total resource based on existing economics and technologies expected to be at an end in the next decade [13], at least if current business models are used. The legislation that governs mine waste is complex [11], in essence removing it from the normal waste management regime by defining it as a resource that can be reused in the future. The unintended consequence of this is

FIGURE 46.1 Shallow undermining into gold-bearing reef. Thousands of these shallow workings exist in the Johannesburg area.

that all mine dumps in the Johannesburg region are not in their final resting place, so they cannot be rehabilitated without the significant investment of taxpayers' money into this process. The reason for this is that mineral resources have been closely linked to the national security of the country [12]. This meant that during the international isolation of the South African state arising from the imposition of comprehensive economic sanctions against the policy of Apartheid, the industry was protected as a matter of perceived national survival [29]. In effect, the state ceased to be a regulator from 1961 to 1994, becoming a partner in an elaborate collaboration that maximized profits to the mining houses by externalizing liabilities, but always assuring healthy revenue streams needed to keep the embattled pariah state afloat [27]. In all probability, had the gold sector not been as powerful as it was for such a long time, the transition to democracy would have occurred sooner than it actually did in 1994.

The strategic-level challenge that is now confronting the government is how to deliver potable water services and create jobs in a stagnating and water-constrained economy where the legacy of mining externalities have become constraints to future development.

46.3 Unintended Consequences

The economics of mining are driven on the supply side by three major costs—energy, labor, and ore grades. The price of energy is rising rapidly as a result of the failure by the state to recapitalize the national electricity utility called ESKOM, with year-on-year escalations of 16% over the last three years and 8% increases planned for the next three years. The price of labor is also rising rapidly, most notably as a result of demands by militant trade unions that are unrelated to increases in productivity, with year-on-year escalations in the order of 10% [1]. Ore grades are falling, with the majority of the resources considered to be economically viable having been depleted [13].

One of the biggest challenges facing the gold producing industry is the cost of dewatering deep mines. The gold bearing reef dips from the surface in a southerly direction, where it is overlain by one of the largest karstic aquifer systems in the world [3,16]. A number of mines coexist in a given mining basin, each linked in a geohydrological sense by virtue of their geographic location in a confined aquifer system. Because of the need to create multiple exit points from deep mines in the event of an emergency, all of these underground workings have been interconnected, further enhancing their hydrological connectivity. This means that under normal operational conditions, the volumes needed to be abstracted are large and variable, dependent on the ingress into the void during the rainy season. The volumes per basin needed to retain steady state operations once the void level has been drawn down to environmental critical level (ECL) are as follows: Eastern Basin—
Q1 70–100 mega-liters per day (M*l*d); Central Basin—30–90 M*l*d; Western Basin—19–27 M*l*d [7]. When compared to the 1500 M*l*d supplied by the public utility Johannesburg Water, AMD decant from these three basins equals approximately 14% of the total daily needs of the city.

In order to ensure the economic viability of the industry, a number of independent mining companies share the cost of pumping. The unintended consequence of this approach is that when a given company ceases to be financially viable due to increasing costs of labor and energy in the face of falling ore grades, then it shuts off the pumps, placing an additional burden on the remaining companies in the given mining basin. This implies that the probability of insolvency for the remaining companies is inversely related to the number of mines still operating. This principle is known as "The Last Man Standing."

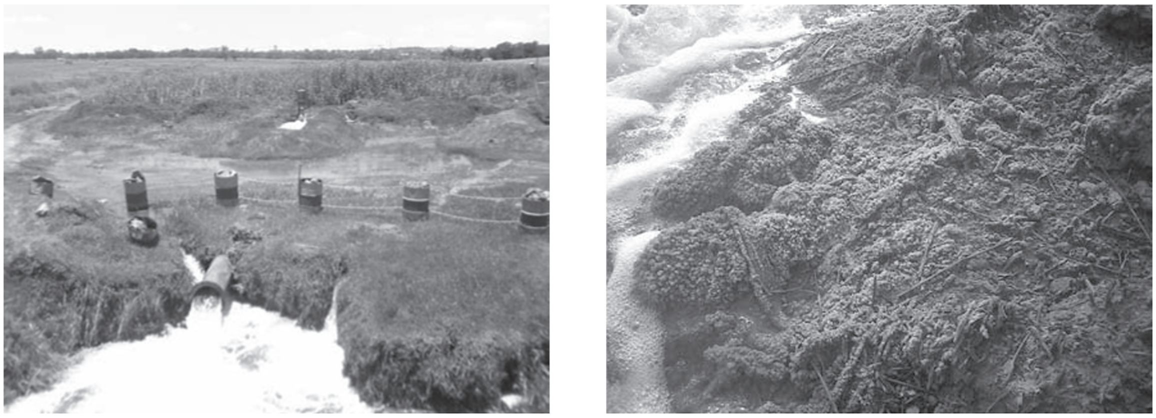
In the Western Basin, all underground mining ceased in the 1990s and the void started to fill with water. This became increasingly acidic as a result of exposure to pyrite, the majority of which is found in the surface tailings dams, which enters the void via multiple ingress points [28] (see Figure 46.3). This is exacerbated by the existence of many surface holings and cracks in the rock caused by shallow underground mining (see Figure 46.1). In 2002, the water level in the void reached the Black Reef Incline (BRI) Shaft, which is the lowest entry point into the Western Basin mine void, where decanting occurred into the Tweelopies Spruit, a small stream emerging from a karst structure that had been dry in living memory because of the dewatering. The decanting water (see Figures 46.2a and b) was highly acidic with a pH value of around 3, into which a large number of heavy metals (including uranium) had been dissolved along with sulfate loads of up to 4000 ppm [4,14,22,34].

Public interest was massive as the media picked up the story. The interest grew when scientists reporting on the subject were harassed and attempts were made to suppress their work [5,6,31]. Public interest was magnified when the cost to the taxpayer of derelict and ownerless mines was estimated to be ZAR 100 bn
(US$ 10 bn)> in 2007 [2], but this is, in all probability, a gross Q2
underestimation of the true value, given the known complexity of the problem [4]. This interest turned to anger as the media began presenting the story as an example of a greedy mining industry and an uncaring government [21,23,25].

46.4 Turning the Tide

In response to the growing tide of public anger, the government created the Inter-Ministerial Task Team on Acid Mine Drainage, which tabled a public report in December 2010 [4,19]. This report concluded with the following:

> Currently two plants are treating AMD to potable quality in South Africa at full scale. These are, however, not financially self-sustaining. This is similar to the experience internationally that has shown that AMD treatment is unlikely to be financially self-sustaining. The costs of this treatment are estimated at around R11 per cubic metre (approximately US$ 1.10/m^3), with a capacity of treating 20 Ml/d (20,000 m^3/d) at each plant, including amortisation of the capital costs of the plant (several hundred million



Q5 **FIGURE 46.2** (a) shows the decanting mine water under conditions of winter low flow. (b) shows the precipitation of salts in the Tweelopies Spruit approximately a kilometer downstream of the decant point.

> Rand) over the projected 20 year design life of the plant. This is not economically self-sustaining and relies on a subsidy from the mining companies. Therefore, it is foreseen that there will be a shortfall between the cost of clean water produced in a plant and the revenue recoverable from the sale of water [4].

What this report does not acknowledge is the growing tide of public anger, most notably as a consequence of perceptions that government is increasingly authoritarian and corrupt [8,15]. In Johannesburg, this anger has already resulted in the demise of an initiative by the mining sector known as Western Utilities Corporation (WUC), which sought to obtain mine closure certificates by treating AMD to potable standards using the lowest cost technology, without adequate public consultation [27]. It is against this background that the potential for urban water reuse as it pertains to the gold mining areas of Johannesburg needs to be understood.

46.5 Understating AMD as Discreet Hydrological Flow Pathways

There has been a lack of conceptual clarity needed to accurately understand what AMD is actually about, or more importantly, where interventions need to be made in the overall cycle. In the absence of this clarity, but in the face of growing public anger fuelled by environmental activists, all of the perceived evils of the mining industry have been placed at the door of AMD [23]. This has caused a shift in focus to one item only—the neutralization of acidic water at the decant point. We therefore need to better understand AMD as a complex hydrological flow in which a number of nested subsystems exist [28]. This is presented in Figure 46.3.

There are four discreet, but nested, flow pathways for AMD, each capable of being accurately modeled. The genesis of AMD is in Flow Pathway "A," which is driven by rain with a low pH (<4) falling on flat-topped tailings dams, where it attacks the hydroxide coating around quartzite particles that also contain pyrite. This oxidizes the pyrite, triggering the generation of additional acid, which in turns starts to leach the uranium in situ. The uranium concentrates in a crust that is eroded by wind when it desiccates. This flow pathway is thus limited in geographic scale to the mine dump itself, becoming the source of both acid and uraniferous dust that enters subsequent flow pathways.

Flow Pathway "B" is a gatekeeper, as it determines whether the water will either subsequently flow across the surface into aquatic ecosystems or into the underground void. The scale is limited to the footprint of the mine dump and the land immediately adjacent to it.

Flow Pathway "C" is driven by aquatic ecosystems with three main inputs, each of which can be numerically modeled. These are rainfall as an episodic series of events; fallout of uraniferous dust over large swathes of land that is mobilized hydraulically with each rainfall event; and direct runoff from tailings dams as a result of the surface flowing output from Flow Pathway "B." The scale of this sub-system ranges from quaternary catchment up to river basin level, with an increasingly large footprint as uraniferous dust deposition escalates from poorly maintained and collapsing tailings dams.

Flow Pathway "D" is entirely underground, with three unique but specific inputs: seepage of acidic water from beneath the footprint of the surface tailings dam (Flow Pathway "B"); infiltration of rainfall via multiple ingress points such as naturally weathered rock and shallow underground workings (Figure 46.1); and direct ingress of surface flows from wetlands and rivers that intersect preferential pathways such as faults, fissures, and dykes. Once underground, this acidic water attacks the pyrite in the remaining pillars and stopes, aided by the bacterium *Thiobacillus feroxidans*, where it eventually decants from the void via the lowest shaft opening to the surface.

Armed with this enhanced conceptual clarity, it becomes evident that AMD is highly complex, so there is no single silver bullet solution. More importantly, it becomes increasingly evident that the predicted imminent demise of the gold mining industry, at least in the current format in which it is operating, will have catastrophic implications for water resource management in an area that will be defined by the fallout of uraniferous dust mobilized by rainfall events and deposited into aquatic ecosystems (wetlands and rivers). More importantly, the case for managing AMD as a desired outcome of closure mining (see Figure 4.5) is made more robust because it is only by means of such an integrated approach that management interventions can occur at appropriate points in the overall cycle. Ideally, these interventions should be aimed at removing surface tailings for placement back into the void while sequestering uranium as far as possible (Flow Pathway "A"); prevention of wind mobilization of uraniferous dust by means of adequate rehabilitation of remaining surface dumps; prevention of surface retention of rainfall and subsequent runoff from the dumps through re-engineering the profile (Flow Pathway "B"); active management of wetlands as natural sinks for uranium and other elements (Flow Pathway "C"); active management of ingress through a directed approach designed to identify all intersections and develop appropriate solutions (Flow Pathway "D"); and finally the active pumping and treatment of the void water to prevent breach of the ECL.

46.6 Urban Water Reuse

The Inter-Ministerial Report noted that the following volumes would initially have to be dealt with in order to achieve the steady-state operation noted above: Eastern Basin—108 Mld; Central Basin—60 Mld; Western Basin—40 Mld [4]. As these volumes are quite significant and would require substantial infrastructure to treat and reticulate the water, focus is now
Q3 shifting onto two distinct aspects:

- What is the most appropriate business model to sustain AMD treatment over time?
- What is the most appropriate process model that is socially acceptable?

With respect to the business models, there are two distinct versions—the Legacy Business Model and the Public Private Partnership (PPP) Business Model.

The Legacy Business Model is based on the assumption that AMD is the result of irresponsible mining. The few remaining mining companies are inevitably destined to become insolvent within the next decade, as a direct result of rising costs of labor, energy, and water treatment in the face of falling ore grades. Because of this, the mining industry is to be bypassed in solution seeking, with contracted third parties acting as service providers. The preferred technology is the high-density sludge (HDS) process, followed by desalination. The source of revenue for this solution would be taxation that will need to be provided in perpetuity. The disposal of HDS, rich in heavy metals and sulfate, and subsequently brine, is a major cost in this model. At a technical level, the core assumption is that AMD is generated in the mine void, so it is blind to the existence of the various flow pathways shown in Figure 46.3, focusing only on Flow Pathway "D," but without reference to that model. This means that surface tailings dams are not part of any remediation plan and would remain there in perpetuity. As a direct result of this, the 600,000 tonnes of uranium lying in those combined dumps will become a growing hazard as the dumps start to collapse through erosion by both rain and wind. The latter is inevitable as soon as revenues cease to flow because conventional mining operations include the constant maintenance of dumps needed to retain the structural integrity of these flat-topped stepped-sided structures. Of even greater significance, the mining void would remain open as this is not part of the overall management objective, which means that the long-term issue of illegal artisanal mining will,

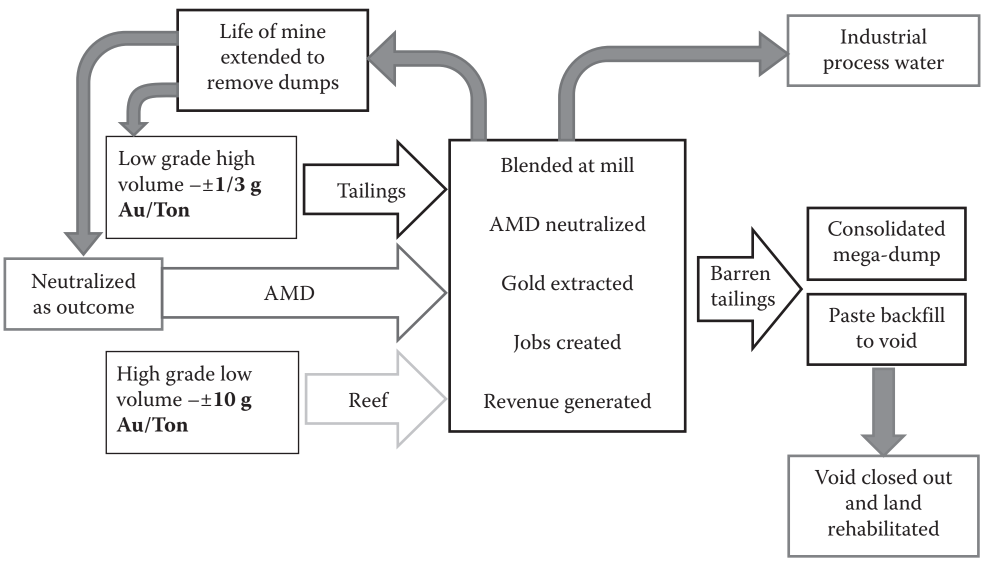


FIGURE 46.3 AMD flow pathways showing the existence of discreet subsystems. Q5

in all probability, grow in magnitude. Rehabilitation of mine impacted landscapes and ecosystems is not part of the management objective, which is focused only on the prevention of the breach of ECL and the neutralization of AMD before it causes environmental damage. The absence of a revenue stream means that not only does the taxpayer have to pay for the treatment cost, but also the water has to become potable in order to recover some of that cost. The current thinking has not factored in the possibility of public hostility, currently manifesting with some vigor in the form of opposition to the recent introduction of electronic tolling to certain highways around Johannesburg without adequate consultation [17]. The known cost for the pretreatment phase only (neutralization of the acid by means of the HDS process and subsequent disposal of sludge) is ZAR 12.00/m^3 (US$ 1.20/m^3).

The PPP Business Model has an inherently different logic underpinning it. As a point of departure, it acknowledges that the scale of complexity is so great that no single entity can resolve it unassisted. More importantly, it recognizes that in effect, it is the future of Johannesburg, the financial capital of the entire African continent, which is at stake if the transition to a post-mining economy is inappropriately managed. Because of this logic, the ethos of partnership lies at the very heart of the solution. The mining sector is not regarded as the sole source of the problem, so remaining mining companies are encouraged to become rehabilitation-oriented as part of their adaptive response to the imminent closure of the resource. By adopting the concept of flow pathways (Figure 46.3), this model acknowledges that the majority of AMD is created on the surface, when acid rain attacks the hydroxide-coated tailings particles on the flat-topped tailings dams, exposing the pyrite to further oxidization (Flow Pathway "A"). Because of this bigger picture approach, it is accepted that AMD is a temporary manifestation only, with the closure of the void central to all management planning. This is to be achieved by embracing state-of-the-art mining practices that include the backfilling of high-density paste, sometimes with a binding agent like cement, back into the void as a deliberate part of rehabilitation mining [10]. Surface tailings are re-processed to yield the remaining gold they contain. More importantly, this allows for the removal of uranium from the dumps, either as a sequestered Uranyl ion complex or as a chemically pure mineral recovered through an ion exchange process to be further beneficiated. By virtue of the fact that mining is still part of this solution, restructured mining companies become service providers to the state, locked into a PPP contract with all the necessary performance clauses needed to protect the public interest. With closure mining as the core element of the solution, the cost of rehabilitation and water treatment is subsidized by revenue generated from gold recovery. Given the known economics of uranium recovery, there is a case to be made for the possible subsidization by the fiscus, given that a public benefit would accrue from the safe removal of 600,000 tonnes of uranium from the environment. The interesting aspect of this model is that because rehabilitation drives the actual process, the end result is land that has been rendered safe for future economic and social use in a post-mining economy. Calculations show that 5445 ha of land can be brought back into safe use this way, in a city that has seen exponential population growth since the collapse of Apartheid in 1994, where the population will be 20 million by 2020 with 4.7 million households that can only be built on mine residue areas [9,24].

One of the technologies in this model is called the tailings water treatment (TWT) process [18] (see Figure 46.6). This uses alkaline gold tailings (pH 10.5) to neutralize AMD (pH 3), with a range of benefits, which include the following:

- Uranium is sequestered in a chemically stable complex.
- There is no need for HDS disposal as the sludge naturally generated is co-disposed with the barren tailing stream, so a major cost is removed from the model.
- The reprocessing of old tailings dams removes a source of long-term hazard, enabling the barren tailings to be placed into the void in order to close out future AMD generation underground, while also depositing to the surface as required in dumps that are engineered to twenty-first century design standards.
- All shallow surface striking reef is removed as part of the closure mining model (see Figure 46.5), which permanently closes out ingress points for water and access points for illegal artisanal miners (see Figure 46.1).
- Marginal mines can be rejuvenated as rehabilitation companies, creating a 20-year extension to the life of the mine, buying time to complete the necessary work while creating livelihoods in a sector currently shedding jobs.

The known cost of AMD neutralization using the TWT technology is ZAR 4.00/m^3 (US$ .40 c/m^3). This cost includes both CAPEX and OPEX items with water treated to the same standard as the HDS process used as an industry benchmark [18]. This water need not enter the potable water stream as it is ideally suited for industrial process water, most notably in the platinum mining industry, but it can also become feedstock for desalination processing if that is the final decision made by the regulatory authority in consultation with society. The TWT approach is thus suited to either the Centralized Process Model or Dual Stream Process Model, but it naturally favors the latter.

With respect to the operational models, there are also two distinct versions—the Centralized Process Model and the Dual Stream Process Model.

The Centralized Process Model is based on the core assumption that the state owns all of the water resources in the country, consistent with the National Water Act [20]. This means that the state has the sole right to treat and distribute water as it alone sees fit. The best analogy is the equivalent in the South African energy sector where the state-owned enterprise called ESKOM is the sole energy provider in the country. Within this model, all water is treated to one national standard and is sold at a national average cost, irrespective of the actual cost of reticulating it to the specific end user. This means that treated AMD is regarded as an integral component of the national water resource, so it will logically become potable water, irrespective of the wishes of the consumer.

Public support for this model has been assumed, but not yet tested, so this manifests an as yet unquantified risk. Significantly, within this model, the reconciliation of localized demand and supply is managed at the national level through a centralized decision-making entity. Given that this is essentially a monopoly, the overall process is somewhat price insensitive, with no real incentive to favor any least-cost maximum-benefit solution. Having said this, the Centralized Process Model is the product of current laws and policies, so there is no need for any reform, which makes the roll-out relatively easy, assuming no public hostility.

The Dual Stream Process Model is based on a core assumption that when a national water resource approaches closure (where demand starts to exceed supply at a high level of assurance), then it becomes logical to treat water as a flux rather than a stock. Water moves in time and space so it is in effect a flux, which means that different quality water can be used for different purposes at different price structures. In essence then, a dual stream reticulation system is one that differentiates different water qualities at different prices for different users. In South Africa, this was pioneered in the late 1990s when the Southern Sewage Works in Durban entered into an agreement with Veolia as service provider, to treat sewage effluent to industrial standards for onward sale to bulk users in the paper-making and oil refining industries. In this model, the state retains the sole right to treat and distribute water, consistent with the National Water Act [20], but this is no longer done to one standard and one national average price. The analogy in the energy sector is the emergence of Independent Power Producers (IPPs) to augment supply by ESKOM. Because of the flexibility of this model, prices are based on local treatment costs and the needs of the end user. Of greater importance, the treated AMD need not necessarily become potable water, thereby negating one major risk silently embedded in the Centralized Process Model. However, if there is public acceptance of this practice, then it is technically feasible with the TWT process [18] (see Figure 46.6). Reconciliation of demand and supply is done at the localized level, freeing up potable quality water for use elsewhere in the national economy. An example of this is current practice in the platinum mining industry, based in the Crocodile West & Marico Water Management Area. Potable quality water is supplied into the platinum industry from the Orange River Basin by means of a high-pressure pipeline that literally flows within a few meters of the Western Basin decant point. This potable water is not suitable for the flotation process central to the metallurgy of platinum, so it is modified to the point where it meets the technical requirements. These requirements are identical to those inherent to the treated AMD emerging from the TWT and HDS process, so by using this industrial water instead, potable water is spared for use elsewhere in the water-constrained national economy. With the emergence of independent water producers acting as agents on behalf of the state, this is non-monopolistic, so it is inherently more price sensitive. It will require some policy and legal reform, so it is not that easy to roll out, but the precedent has already been created in the form of the Durban sewage works noted previously.

These two business models and process models can now be evaluated in the context of a matrix shown in Figure 46.4.

From Figure 46.4 it is obvious that the Legacy Business Model favors the Centralized Process Model, but this means that the mining sector is naturally excluded as a potential partner in solution-seeking. In effect then, this limits the range of solutions by naturally excluding the rehabilitation of mine-impacted landscapes and ecosystems. Given that it is centered on the HDS technology, not only are the surface dumps left unrehabilitated, but additional space is needed for sludge storage facilities. The economics of this combination means that the treated AMD has to become potable water, irrespective of what the end consumer feels about this inevitability. The strategic challenge in this combination is for the regulatory authority to make the case to an increasingly angry taxpaying public, that they will be expected to foot the bill in perpetuity, without the added benefits of a rehabilitated landscape, but with the added bitterness of being forced to drink the water. The Legacy Business Model when combined with the Dual Stream Process Model does not work well as the economics simply do not stack up.

From Figure 46.4 it is clear that the PPP Business Model tends to favor the Dual Stream Process Model. The advantage of this combination is that the last remaining mining companies are given the chance to adapt by becoming rehabilitation companies instead of becoming insolvent, which is the inevitable outcome of retaining the business-as-usual approach. This means that closure mining becomes the solution (see Figure 46.5), which brings in mining companies as service providers capable of moving the vast quantities of tailings that lie in the surface dumps. The obvious advantage of this approach is that the surface dumps can be rehabilitated, either by being placed into consolidated mega-dumps engineered to twenty-first century standards, or by being backfilled into the void as high-density paste strengthened with a binding agent like cement [10]. This closes out the void as a potential future source of AMD, while increasing the geotechnical stability of the mine-impacted landscape and removing access points for illegal artisanal miners.

46.7 Lessons Learned

The major lesson learned from this whole AMD problem is the unintended consequence of unplanned mine closure. Given the significance of mining to the South African economy, the collapse of the gold sector has national implications, which seem not to have been grasped by the authorities in charge of the city of Johannesburg. The general rhetoric in the media, as a reflection of the discourse underpinning the issue, is that the mining industry is irresponsible, so what needs to be done is to neutralize the acidic water to prevent future decant. The simple fact of the matter is that Johannesburg is arguably the most uranium-contaminated city in the world, with the implications of this becoming apparent only after the mining industry ceases to function as a viable entity. Seen in this light, the AMD issue is in fact nothing more than the manifestation of a transition from an extractive to a post-mining national economy, with the

	Centralized process model	Dual stream process model
Legacy Business Model	• Mining is the *problem* • State to *contract third party service provider* (E-tolls) model) • Taxpayer to pay in *perpetuity* • *Landscape* not rehabilitated • **AMD** becomes *drinking water* • *HDS Storage* facilities needed • Cost = ≥ **R12.00 m3** (neutralized)	• *Economics* do not stack up for this combination • *Process* can support this combination • **HDS storage fiacilities not necessarily needed** *depending* on process selected
PPP Business Model	• *Economics* supports this combination • *Process* supports this combination • **HDS Storage facilities not needed** *depending* on process selected	• **Closure Mining** is the *solution* • *Mines* are service provider • *Mining revenues* cover majority of cost (partnership) • *Landscape* is rehabilitated • AMD *does not become drinking water* • HDS Storage facilities *not needed* • Cost= ±**R4.00 m3** (neutralized)

Q5 **FIGURE 46.4** Matrix showing the various combinations of the two business models and two process models.

core challenge of needing to deal with environmental externalities now manifesting as constraints for future development and job creation. Unfortunately, very few people see it this way, with aggressive anti-mining activists shaping public opinion [23] and thus driving the response by government in a direction that is ultimately going to be unsustainable because it fails to recognize the need for an integrated response.

Another as yet dangerous lesson to be learned is the issue of human population migration into the city of Johannesburg. From 1900 to 1994, the population of Johannesburg grew to

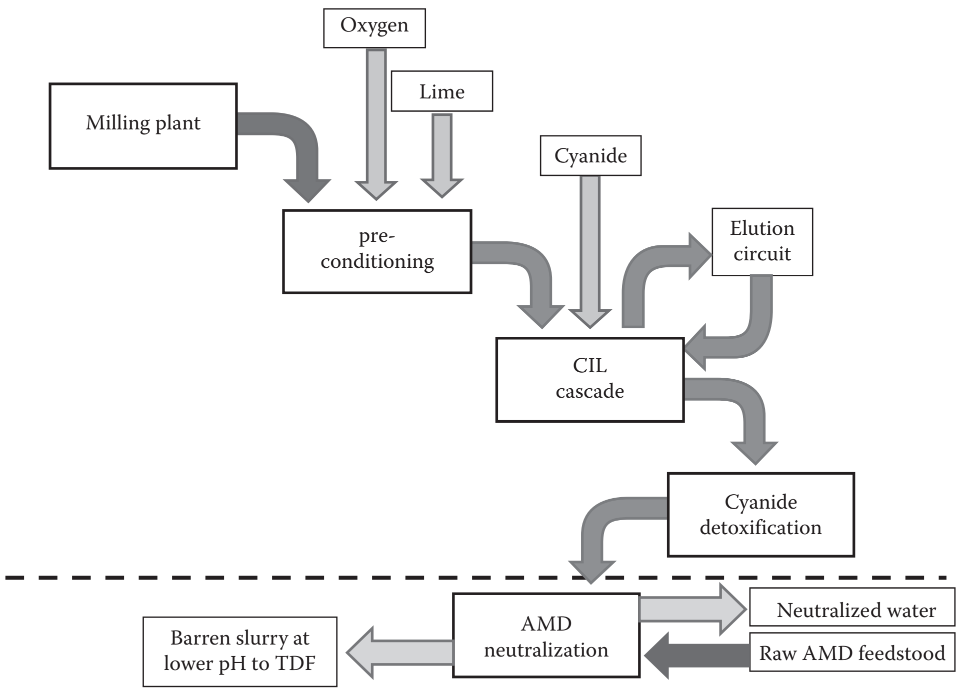


FIGURE 46.5 Closure mining as a conceptual model showing the core elements of the overall process.

6.2 million, but over the next decade (1994–2004) that population exploded with 25% growth to 7.7 million inhabitants living in 2.4 million households of which 0.6 million were in informal settlements [24]. In fact, 1.6 million people are now living in close proximity to uraniferous mine residues and that number is growing exponentially, so government has a hard choice to make—either move the people from the dumps or move the tailings from the people [9]. The population is set to grow at a rate of 6.7% per annum, which will yield a population of 20 million by the year 2020. More significantly, however, this will drive the demand for 4.7 million households, or 200% growth off the 1994 baseline. The only land left to settle is mining impacted, so the water resource management problem is intimately linked with the mine rehabilitation issue, with uranium sequestration as a central feature to any viable strategy.

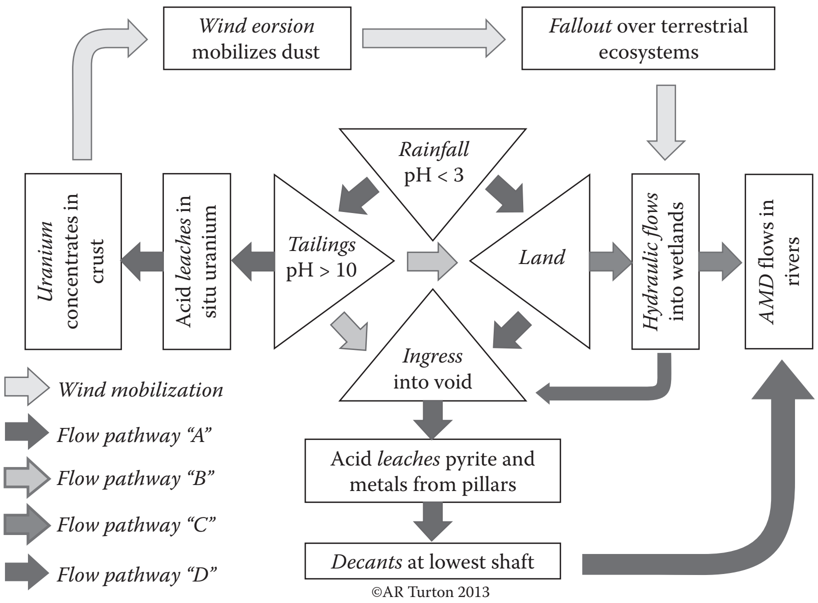
The biggest lesson is that closure mining is an appropriate adaptive response, so it is important to explain how this differs from conventional mining. Stated simplistically, conventional mining as practiced in South Africa maximized profits at the level of the shaft or pit, by externalizing costs in collusion with the Apartheid-era government, which essentially left the industry to self-regulate in order to survive as a pariah state [12,27,29]. This increasingly placed the outcome of mining—a highly impacted landscape in which uranium is a persistent hazard and water pollution a central feature—at odds with the broader interest of society. Closure mining is about realigning the outcome of the mining process—a rehabilitated landscape that is safe to use—with the broader interests of society, thereby reducing the conflict potential inherent to the conventional mining model. This is achieved by aligning the processes shown in Figure 46.5 in order to lower the breakeven point derived from falling grades of ore.

The essential idea behind closure mining is the recovery of gold from the existing tailings dams, which contain around 0.3 g of gold per tonne of tailings. This means that in order to recover 1 kg of gold, in excess of 3333 tonnes of tailings have to be reprocessed. This is a low-grade high-volume business with viability driven by the availability of low cost water and the constant throughput of tailings into the processing plant. However, for every tonne of tailings moved in the gold extraction process, between 50 and 200 g of uranium are also moved. This means that for every kilogram of gold recovered, up to 600 kg of uranium can also be processed or sequestered. The existence of significant bodies of ore, no longer in sufficient quantities to sustain conventional mining, but enough to change the economics of a marginal operation by increasing the grades through the milling circuit, remains a potential resource. Known reserves of surface striking reef (Figure 46.1) and pillars left in underground operations are of a grade that averages around 5 g/t, with sweet spots of higher value that can be selectively targeted. This is blended with the tailings stream at the mill in order to bring the run of mine grade up to 1 g/t, which is the breakeven point for the operation. In the process, the following key objectives are reached, thus representing a realignment of the outcome of closure mining with the broader interests of society:

- The remaining surface dumps are removed and consolidated using state-of-the-art processes that are designed to twenty-first century standards.
- The void is closed out as far as possible with high-density paste backfill in order to remove as much of the surface waste as possible.
- Geotechnical stability is ensured through the backfilling of high-density paste into the void, as well as the removal of surface striking reef in shallow undermined areas (Figure 46.1).
- Ingress points into the void are closed out, thereby reducing the future flow of surface water into sub-surface flow pathways.
- Access points for illegal artisanal miners are permanently closed out, reducing the presence of criminal syndicates linked to the fencing of stolen goods and the laundering of money across international borders.
- Livelihoods are created in an industry currently shedding jobs, as the life of marginal mines is extended by up to 20 years, buying time to complete the rehabilitation process.
- The mining industry becomes part of the solution, so the burden on the state and taxpaying public is substantially reduced.
- An integrated rehabilitation process is enabled, with multiple intervention points at key parts in the complex hydrogeological and hydrochemical cycle underpinning AMD.

More importantly, in the context of this specific chapter, closure mining is centered on the reuse of highly contaminated industrial water because the very foundation of the process is hydraulic mining and aqueous metallurgical processes. In fact, inherent to the concept of closure mining is the neutralization of AMD by means of exposure to barren tailings at a naturally high pH as shown in Figure 46.6.

Figure 46.6 shows the overall TWT technology in schematic format [18]. Blended paste enters the circuit from the mill with a grade value of ≥1 g/t. This is preconditioned by raising the pH through the addition of calcium hydroxide and oxygen in order to precipitate out the iron. This slurry is then pumped across to the carbon-in-leach (CIL) cascade where activated carbon and cyanide are both introduced. The cyanide captures the gold, which is adsorbed into the activated carbon matrix, to be stripped out and recovered during the elution phase. The barren slurry is then sent though a cyanide detoxification process, at which time the highly alkaline barren tailings, still at a pH value of ≥10.5, are exposed to raw AMD pumped in from the void. This exposure causes the low levels of residual cyanide to complex with other metals in the tailings stream, while also precipitating out metals in the form of HDS, which is seeded onto each individual tailings particle. The uranium in the AMD and tailings stream also becomes a chemically stable complex, thereby sequestering it onto the tailings particle. The neutralized AMD is used as process water for the hydraulic mining and related circuits, while the barren tailings are returned to their final resting place to be rehabilitated to twenty-first century engineering and environmental management standards.



Q5 **FIGURE 46.6** Schematic diagram of the tailings water treatment (TWT) technology that uses alkaline mine tailings to neutralize AMD.

46.8 Summary and Conclusions

South Africa was once the home of some of the most innovative mining engineering in the world. The result of over more than a century of mining has been a mixed blessing to the citizens of the country. On the one hand, the country has rapidly industrialized into a modern diversified economy capable of competing in a global market, with the transition from low paid agricultural subsistence livelihoods into higher paid industrial jobs supported by a range of benefits. On the other hand, the externalities of mining, mostly the result of the Apartheid-era survival tactics of an embattled pariah state, are now manifesting as significant constraints to future economic growth and job creation policies being rolled out by the first democratically elected government. Johannesburg is now one of the most uranium-contaminated cities in the world, but it remains the economic capital of the African continent. It remains to be seen how water resource management, most notably around the pressing need to mitigate the AMD risk, will become the catalyst for future economic wellbeing. The regulatory authority is now confronted by a difficult set of trade-offs, defined in this chapter as being the interaction between two different business models with two different operational process models. The decisions that are made in the near future will define the future of the city of Johannesburg. This chapter is offered in the sincere hope that it can inform that process of decision-making.

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