The ***Paradigm Shifter*** series of Discussion Papers being launched by SAWEF is designed to elicit new thinking about seemingly-intractable problems facing society. By their nature such papers will push boundaries and take us out of our comfort zone in order to explore alternatives. The intention is to encourage interaction between enlightened citizens, consistent with the SAWEF vision of constructive engagement, underpinned by a respect for a diversity of views.

Debunking Persistent Myths about AMD in the Quest for a Sustainable Solution



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Introduction

The AMD debate has raged on for a decade now, often manifesting as a series of messy public spats in which attempts have been made to apportion blame and seek redress by well-meaning activists. Central to this debate have been images of chaos, often perpetuated by the media, which include the notion of buildings that are likely to collapse[1] and the city of Johannesburg being in grave peril[2]. Significantly, despite a concerted effort by environmental and social justice activists, all attempts at the apportionment of liability have largely been rejected by the regulator through a protracted legal process. While the *status quo* has prevailed to the frustration of government, the mining industry and the enlightened public, this decade of contestation has also prevented viable technical solutions from being developed and implemented. It can safely be assumed that a general loss of confidence has resulted – in the government as an arbiter, in the industry as a responsible corporate citizen, in Gauteng as a region of future developmental potential, and in the economy as a safe place to invest foreign capital and create jobs – making us all collectively less well off. This is a classic lose-lose outcome, so how can we turn this into a win-win solution instead?

When reflecting on this process, a significant and persistent element has been the creation of a chain of logic, woven by environmental activists and eagerly propagated by the media as a seductive narrative, presented to a non-technical public in sound-bite sized chunks as an alluring truth. On closer examination this compelling narrative is based on four persistent myths that are simply untrue if examined in the cold light of reason and science. This paper seeks to debunk these myths, which have impeded the emergence of a viable solution to a seemingly intractable issue. It will be argued that the AMD issue is a classic dilemma[3], so its solution is within our collective reach as a nation, *only* if we break it into a set of distinct sub-problems[4]. The logic of the paper is predicated on the assumption that the way you define any problem determines the selected solution, so if the initial definition is wrong, then the chosen solution will be inadequate for the stated purpose. This paper starts off by presenting these four myths. It then presents a suggested solution in the form of four discreet **flow pathways** (see glossary), based on the best available facts, derived from a scientific approach to field observation by the author. These **flow pathways** represent distinct sub-sets of the overall dilemma, so they are soluble if understood in their unique context. The object of this paper is to stimulate enlightened debate, in the belief that it is in our collective best interest to shift from blame-seeking to solution-seeking as a means of restoring lost confidence in government as a regulatory authority, the mining industry as an important stakeholder in our national economy, in Gauteng as a region that will see rapid urbanization in the next decade and in our young democracy still finding its direction in an unpredictable and sometimes confusing post-Apartheid world. In so doing we need to acknowledge the role played by environmentalists that have raised awareness of

1 **Tempelhoff, E**. 2007(a).
2 **Segar, S**. 2013(a).
3 A dilemma arises when one is confronted by a situation requiring a choice between equally undesirable alternatives, hence the saying, "sitting on the horns of a dilemma" when confronted by one.
4 A problem is defined as a question to be considered, solved or answered. In this context, problems are more desirable than a dilemma.

the issue. The proposed solution of thinking in terms of **flow pathways** is not presented as a new dogma to replace the old debunked myths, but rather as a potential approach that we may collectively choose, if we want to navigate ourselves out of the aimless wilderness in which we are now apparently lost.

Four Persistent Myths about AMD

When one evaluates the public-domain material reported in the media it seems that four myths have persisted over the last decade. Despite the absence of credible scientific facts to support the argument being presented, the narratives they provide remain remarkably resilient. The time is now ripe to challenge these myths in order to collectively move forward.

Myth No. 1: The AMD is Radioactive

This myth is most eloquently captured in one of the most recent articles on the subject, which starts off by confidently stating that, *"By October (2013), the acidic, radioactive liquid lurking under central Johannesburg is expected to pass a critical point"*[5]. Stated so confidently as fact, is AMD actually radioactive?

The answer to this is …. it depends …, but such an answer is unconvincing, so let us trace the logic backwards. AMD is a liquid, mostly water, characterized by a low pH, a high concentration of dissolved salts (mostly sulphate), a high electrical conductivity (EC) and a potentially elevated level of metals, depending on the host geology through which the flow occurs. The significant defining factors for AMD are therefore the following:

- It is a liquid, consisting mostly of water.
- It is acidic[6], sometimes with a pH value as low as 3.
- It has a high concentration of salts, typically sulphate (SO_4), with values in the Western Basin decant potentially exceeding 3,500 parts per million (ppm)[7].
- It often has a metal content, sometimes including uranium[8], but this is dependent on the pH and consequently the prevailing **redox conditions** (see glossary).

AMD in and of itself, is not radioactive. However, under certain conditions uranium can be present, and it is this metal that suggests a possible source of radioactivity. We thus need to dig deeper into the mystery of uranium. The first question we need to answer is whether uranium is radioactive on its own? The answer is a simple yes. Uranium occurs in various chemical formats, but it has three isotopes – U-234, U-235 and U-238 – all of which are mildly radioactive[9]. Of these three isotopes it is only the latter (U-238) that is fissionable, and this consists of 0.7204% of naturally occurring uranium, which is insufficient to sustain nuclear fission[10]. It is therefore logical to claim that uranium is radioactive.

5 **Segar, S**. 2013(a).
6 **Hobbs *et al.***, 2008.
7 **Hobbs, P.J. & Cobbing, J.E.**, 2007.
8 **Winde, F. & Van Der Walt, I.J.** 2004; **Winde, F.** 2005; **Winde, F.** 2009.
9 See http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Uranium-and-Depleted-Uranium/#.UbbavvIaLIU

So the next question is how much uranium is found in the AMD-producing areas? Here it becomes interesting, because both coal and gold production are associated with radioactivity.

Coal is often associated with the presence of thorium, with global levels around 2.5 times higher than uranium[11]. This means that a potential by-product of coal combustion is radioactivity, typically associated with the presence of thorium. In fact, one author[12] concludes that, "*although trace quantities of radioactive heavy metals are not nearly as likely to produce adverse health effects as the vast array of chemical by-products from coal combustion, the accumulated quantities of these isotopes over 150 or 250 years could pose a significant future ecological burden and potentially produce adverse health effects, especially if they are locally accumulated. Because coal is predicted to be the primary energy source for electric power production in the foreseeable future, the potential impact of long-term accumulation of by-products in the biosphere should be considered*". This means that coal combustion, in the context of radioactivity, is of greater significance than radioactivity arising from gold-based AMD, yet this nuanced fact never finds its way into the public discourse.

Gold-bearing reef, on the other hand, is closely correlated to uranium in the Witwatersrand Goldfields[13]. As a general value over the life of the Witwatersrand Goldfields, approximately 430,000 tonnes of uranium has been produced, mostly discarded as waste and now present in the many tailings dams that litter the Gauteng landscape[14]. The combined reefs found across all seven gold mining basins in the Witwatersrand complex contain 10 – 100 times more uranium than gold, so for every tonne of gold produced, between 10 and 100 tonnes of uranium were brought to surface, where it was exposed to a more aggressive oxidizing environment[15]. So clearly there are vast quantities of uranium in the various gold **mine residue areas** (MRA's)(see glossary). Uranium is highly reactive, so it is never found in its pure elemental form in the environment, mostly manifest as triuranium octoxide (U_3O_8), but sometimes also as uranium dioxide (UO_2), also known as uraninite. Significantly uranium is also highly sensitive to acid, which dissolves it easily. It is also widely accepted in technical circles that uranium is not particularly dangerous[16] with substantial research having been done that shows no significant harmful effects arising from natural exposure to uranium[17]. In fact there is no significant published material from mainstream AMD researchers active in South Africa that reports on radioactivity as a significant risk. Where it is reported in the South African literature, it is mostly related to the presence of mine tailings that have migrated into aquatic systems where it manifests as a potential hazard[18] with limited exception[19]. It is this migration of

10 For a simple explanation see http://education.jlab.org/itselemental/ele092.html
11 See http://www.mindfully.org/Energy/Coal-Combustion-Waste-CCW1jul93.htm
12 **Gabbard, A**. 1993.
13 **Werdmüller, V.W**. 1986.
14 **GDARD**, 2011.
15 **Winde, F**. 2006.
16 **Barthel R**. 2007.
17 See http://www.lenntech.com/periodic/elements/u.htm
18 A non-exhaustive list of this includes the following: **Coetzee *et al.***, 2002; **Coetzee *et al.***, 2006; and **Wade *et al.*,** 2002.
19 **Winde, F**. 2009.

uranium that needs to be understood, hence the introduction of the concept of **flow pathways** (expanded on later). The density of uranium is a factor in the lower risk. Its high density makes it more effective than lead in halting radiation from strong energy-emitting sources such as radium[20].

Having said this, uranium is soluble in water under certain conditions, and it is this solubility that determines the inherent danger, so we need to understand this aspect better, most notably by focusing on two specific factors:

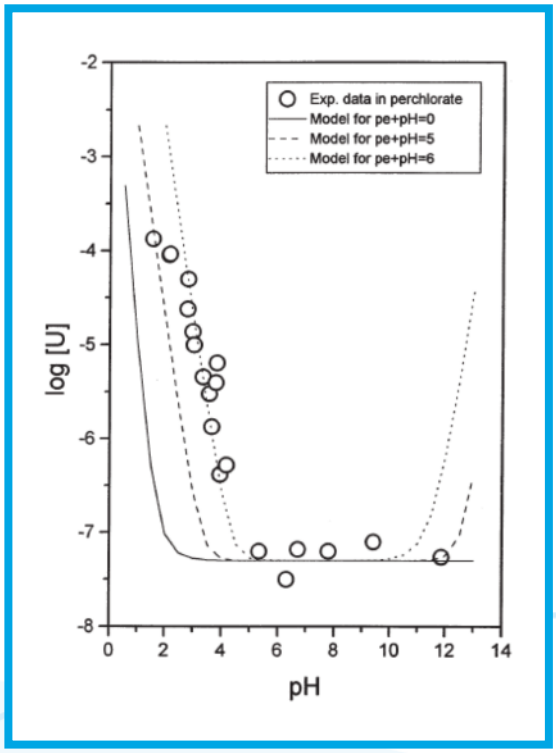
- The role of pH in mobilizing uranium.
- The prevailing **redox conditions** (see glossary) at different pH levels.

In nature, different forms of uranium can be mobilized by water at different pH values, hence the relevance of **flow pathways**, because each step in a complex series of episodic events does not have the same prevailing **redox conditions**. The essential aspect to understand in this context is that the water solubility of uranium is highly correlated to pH values. At high pH values, typically in alkaline waters containing carbonates, highly soluble uranium complexes can exist, dependent on oxidization states, but typically found as U(VI)[21]. The converse holds true for low pH values, typically containing sulphates, which often manifest as sulphuric acid to which uranium is highly susceptible. However, this is a simplistic view of a complex reality, because it is not only pH that is relevant, but also the different levels of oxygen availability at different pH ranges. The latter is known as **redox conditions**.

It is an empirically verifiable fact that uranium behaviour is clearly determined by the oxic/anoxic conditions of the host aquatic environment[22]. In layman's terms, this refers to the available oxygen, which in the presence of differing pH values, result in a wide range of uranium species. Across the acidic range of the pH scale, the predominance of uranyl ion complexes is the most common form of solution, whereas in the alkaline range uranyl-hydroxo complexes tend to occur. Stated differently, depending on both the pH and availability of oxygen, different forms of uranium are present, each with a different risk profile. **Figure 1** shows this in simple graphic format, where the total solubility of various uranium specie concentrations at different **redox conditions** is shown on the vertical axis (expressed in logarithmic[23] values). On the horizontal axis we have a range of potential pH values. This graph thus shows the relationship between **redox conditions** (vertical scale) and pH values (horizontal scale). **Figure 1a** (left) shows solubility as a total uranium concentration for uranium dioxide (UO_2), while **Figure 1b** (right) shows the results under nominally **reducing conditions**. From both curves it is evident that a sharp attenuation occurs with two transitional thresholds at a pH of 5 and 10 respectively. Below the pH of 5, uranium is highly soluble as a uranyl ion complex, whereas above the pH of 10, it is again mobilized as a uranyl-hydroxo complex. Between these values, the

[20] See http://en.wikipedia.org/wiki/Uranium
[21] See http://en.wikipedia.org/wiki/Uranium
[22] **Casas *et al.***, 1998.
[23] Logarithmic values are non-linear, so each step in value represents an exponential shift in that value.

fourth hydroxo-complex U(VI) occurs as a highly stable phase. **More importantly, between these two values, uranium is not readily mobilized in aquatic environments and this is a central fact in understanding AMD and radioactivity**. This is also why **flow pathways** are important as a concept.



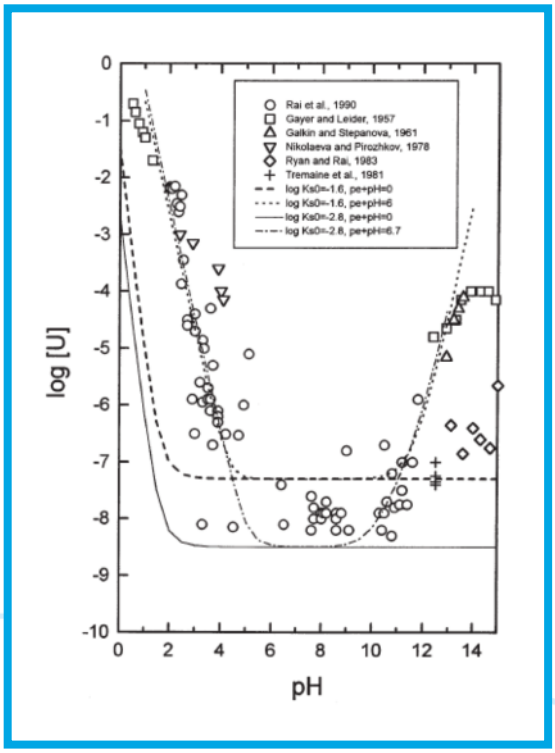


Figure 1a (left). Experimental solubility as total uranium concentrations in solution for the dissolution of uranium dioxide (Casas *et al.*, 1998:2225). Figure 1b (right). Uranium dioxide solubility data under nominally reducing conditions (Casas *et al.*, 2228). Note the clearly defined transitional thresholds in solubility at pH values of 5 and 10. If the receiving aquatic environment is between these two values, then uranium solubilisation is not possible, so AMD at such pH values cannot be radioactive.

The same thing can be shown in other formats, but for the layman these become exceedingly complex, so let us accept this simplification for purposes of the logic being developed. This logic states that while uranium might be present in solid form, this does not mean that it is present in the receiving aquatic environment in soluble form, because of the uniqueness of discreet **flow pathways**. Uranium, manifesting as residue in mine tailings, might well be present in insoluble form, but if the water in the receiving environment is in a pH range between 5 and 10, then that uranium cannot be mobilized aquatically. **Simply put, for uranium to be present in AMD, the pH is critical**. In highly acidic forms of AMD, uranium is mobilized in liquid form, but as soon as the pH 5 threshold is reached, then this is no longer possible, and if present at all, will be found as a precipitate in the sediment pile, rather than in the water column. In order to make a clear distinction for the purposes of this logic, we can more accurately define AMD as being water emanating from a mine void or an MRA

that is at a pH value below 5. In similar vein we can define mine impacted water as being water emanating from a mine void or an MRA that has a pH value of greater than 5. The former is acidic and may contain uranium in soluble form, whereas the latter is approaching a neutral value, so it does not contain elevated levels of uranium, but it will still contain high levels of salts, most notably sulphate.

Another significant component of this technical argument is the relationship between iron (Fe), uranium (U) and oxygen (O_2). One of the essential ingredients in AMD is the presence of high levels of iron. This is caused by the fundamental chemical reaction that oxidises iron pyrite (FeS_2), also known as Fools Gold, which is the actual genesis of AMD. In general all AMD has elevated levels of iron, which is highly reactive to oxygen. This is why a typical manifestation of AMD results in **anoxic conditions** (the absence of free oxygen), hence the absence of biological life that can only survive under aerobic conditions. It has been clearly shown that even if a large release of uranium occurs from a **reduced zone** (see glossary), its movement as a pollution plume is retarded and mitigated because of **adsorption** (see glossary) onto multiple iron oxide phases, which provide prolific adsorption sites[24]. When groundwater rich in oxygen containing U(VI) species flows through a reduced sediment zone (**anoxic** or **redox conditions**), then uranium species are first reduced and subsequently precipitated out as U(IV) species (typically uraninite (UO_2)) in a very short space of time (usually within minutes). Significantly, the amount of uranium accumulated in the reduced sediment zone (as precipitate) depends on the mass of reduced iron, as well as the mechanisms that eventually oxidize the zone. More importantly, the uranium accumulation varies in direct relationship with the spatial availability of the reduced iron content[25]. **This is one of the reasons why the neutralization of AMD with alkaline mine tailings, rich in iron, can potentially yield the added benefit of tying up available uranium in more stable forms**. Tests to enhance our understanding of this are currently on-going.

The important take-home message from this complex chemistry is the following:

- Gold mining is closely associated with uranium, but during much of the life of gold mining, uranium had limited commercial value and was often discarded as waste.
- Gold tailings dumps are rich in uranium species, most notably triuranium octoxide (U_3O_8) or uranium dioxide (UO_2).
- The mobilization of uranium in an aquatic form is highly dependent on prevailing **redox conditions**.
- Redox conditions are correlated with pH.
- **Flow pathways** are thus a critical interceding variable that need to be understood if viable mitigation strategies are to be developed.

[24] **Szecsody *et al.***, 1998.
[25] **Szecsody *et al.***, 1998.

- Under acidic conditions normally associated with AMD flows, a transitional threshold exists at a pH value of 5, above which uranium is no longer mobilized into aquatic environments as a soluble form.
- It is therefore only technically possible for AMD to be radioactive if the decanting water has a pH value of less than 5; and is physically impossible within the pH range of 5 – 10.

It thus becomes necessary to understand the pH trend over time. In this regard the only actual decanting of AMD has been in the Western Basin, where an accurate dataset has been developed from a range of monitoring points. The pH of the void water in the West Wits Pit (WWP) was consistently less than 3, until the Department of Water Affairs (DWA) issued a directive to neutralize the decanting water and deposit alkaline tailings directly into the pit, as emergency measures. Part of this intervention occurred in April 2010 and the observed effect was dramatic and rapid, with the pH in the pit itself shifting from 2.8 to 6.8 in one week (**Figure 2**).

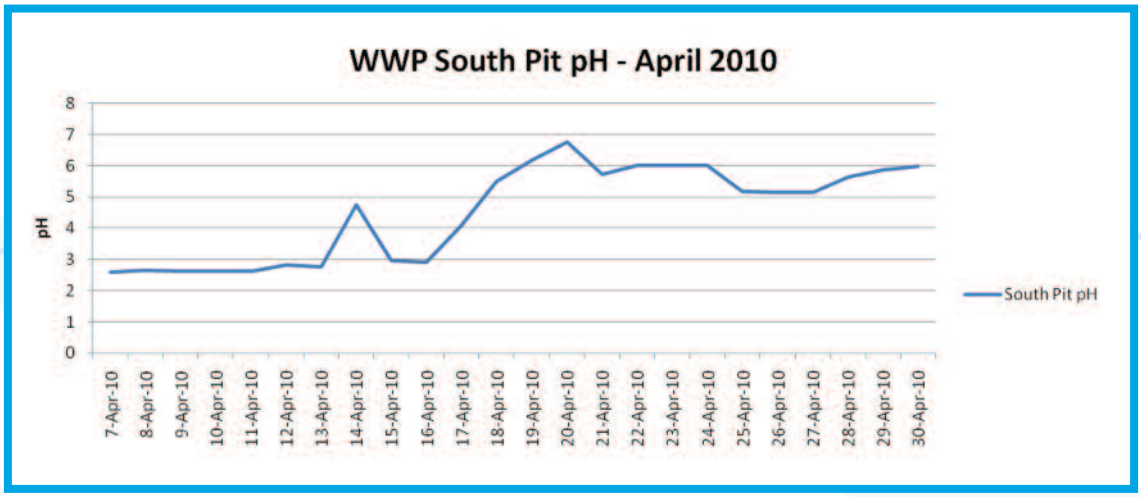


Figure 2. The pH of water in the West Wits Pit shifted dramatically from being highly acidic (pH 2.8) to near-neutral (pH 6.8) in one week after tailings deposition commenced in April 2010 as per DWA Directive. (Data courtesy of Mintails (Ltd)).

The pH of water in the WWP has consistently remained above a value of 5 (the solubility threshold of uranium) since then (**Figure 3**), hovering around a value of 6, well within the range noted above. Active monitoring of 17 Winze started in August 2011, with data from that point showing a close correlation with the WWP (see **Figure 3**).

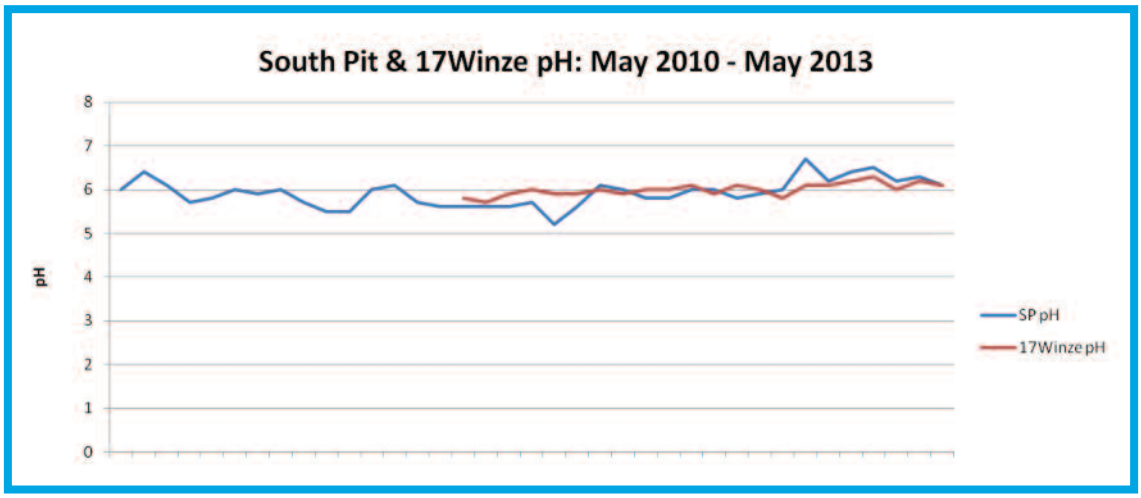


Figure 3. The pH of water in the WWP South Pit has remained above the threshold value of 5 since part of the DWA directive was enacted in April 2010, with 17 Winze showing a close correlation (Data courtesy of Mintails (Ltd)).

Data from other monitoring points in the Western Basin (Black Reef Incline Shaft, No 8 Shaft, No 9 Shaft, No 9 East, 18 Winze) is consistent with this trend, so we can safely conclude that the pH of a **major** portion[26] of the void has now been fundamentally shifted to a neutral state that will remain stable as long as the deposition of alkaline tailings into the WWP continues. More importantly, the last significant decant was recorded on 25 September 2012, so not only is the water neutral and uranium-free, but it has also stopped flowing to surface in a radiologically hazardous state.

Testing during April 2013 confirmed that this pH range is consistent across a number of sample sites including Turk Shaft, which is far removed from the traditional decant point. Sampling in the recently re-opened "D" Shaft and Emerald Shaft (August 2013) has shown the presence of highly acidic pockets of water still occurring along the Witpoortjie fault. What this means is that the neutralization of AMD in the WWP with alkaline tailings, initially as an emergency measure, has made a significant impact on large portions of the void, with the initial change being dramatic and rapid until a new steady state was reached. This has consistently been maintained from April 2010 until the time of writing (August 2013). Technically speaking we therefore no longer have AMD in the entire Western Basin, but we do still have **mine impacted water** (see glossary), with high sulphate values and pockets of acidic water in areas away from the main flow path between the WWP and the draw-down point at No. 8 Shaft.

[26] The flow path between the WWP and the decant (BRI) and abstraction point (No. 8 Shaft), will be the fastest to reflect this change, but areas in the void isolated from this flow will take longer to react.

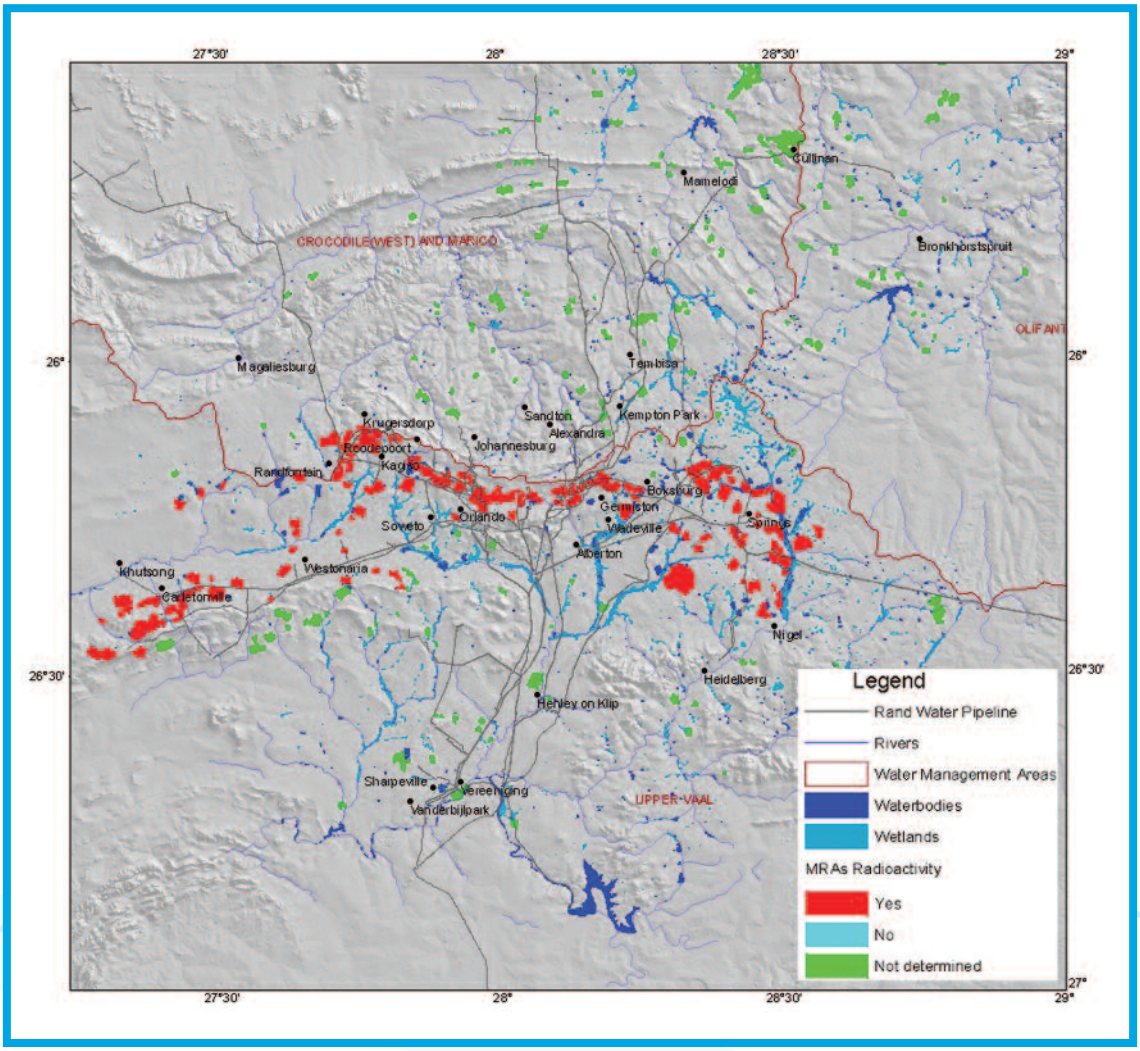


Figure 4. Radioactive (red) and non-radioactive (green) mine residue areas in Gauteng[27]. The presence of radioactivity on surface, closely associated with uranium in dumps, should not be confused with radioactivity in the AMD flows.

What this means is that there can be no radioactivity in the Western Basin decant, as long as the void pH remains above a value of 5, despite the presence of uranium in the surface tailings dams (see **Figure 4**). This again raises the critical issue of **flow pathways** as conceptually discreet, but significant management intervention points, if we are to develop a viable AMD mitigation strategy that is socially acceptable.

[27] **Hartnady *et al.***, 2012.

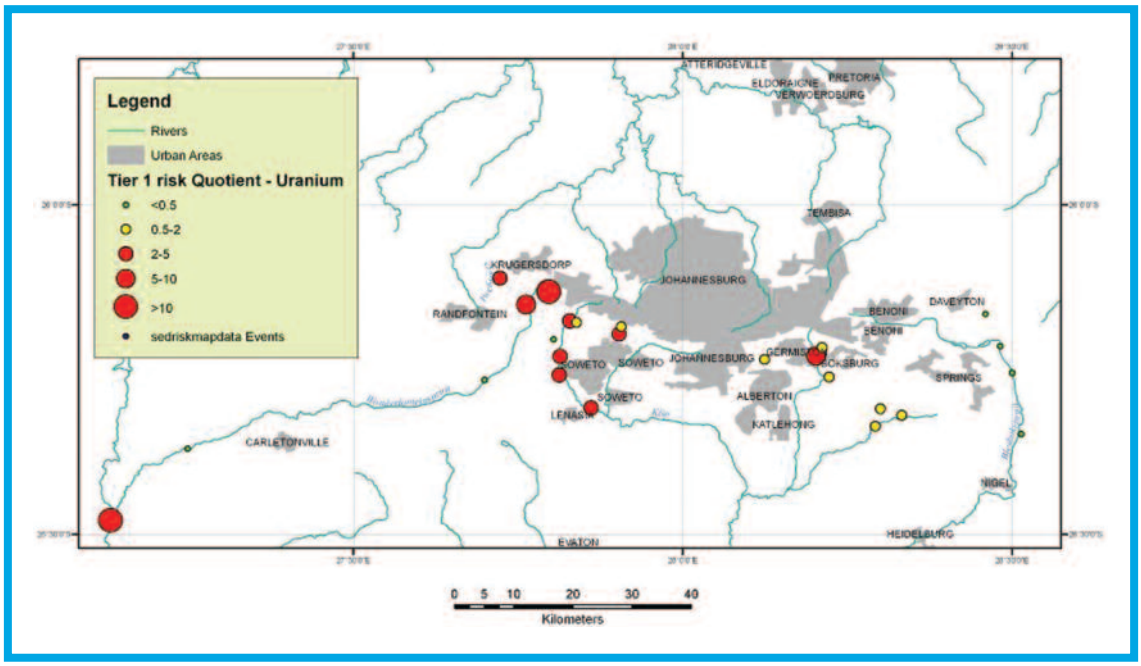


Figure 5. Tier 1 Risk Assessment Classes for uranium found in wetlands draining MRA's in the Witwatersrand Mining Basin[28]. The author is of the opinion that this is a classic manifestation of Flow Pathway "B" (see Figures 12, 14, 15 & 17).

The same logically holds true for the data often cited as "proof" of the radioactivity of AMD, shown in **Figure 5**. In this specific case, the data is from a Tier 1 Risk Assessment, which is designed to do a rapid survey of a given region with a view to informing future, more refined studies if needed[29]. This specific dataset refers to all forms of uranium found in wetlands[30] draining MRA's, including surface tailings dams, so it mostly represents migration by wind and rainfall events. Uranium is clearly present, but it is not necessarily from AMD decant, certainly after April 2010 in the rivers receiving the Western Basin decant. This potentially represents a classic example of the end manifestation of what is later defined as **Flow Pathway "B"** (see **Figures 12 & 14**), with a fundamentally different set of biophysical conditions within each discreet circuit, but invisible unless one is aware of their existence. Once again, the presence of uranium from surface dumps is not the same thing as soluble uranium in the AMD decant. These are two clearly different conceptual entities – made visible only *via* a clearer understanding of **flow pathways** – so they must not be confused if we intend to develop a sustainable mitigation strategy.

More importantly, the data shown in **Figures 2 & 3** also validates the decision by DWA to initiate the emergency neutralization of AMD in the Western Basin in 2010, and the subsequent position taken by the Inter Ministerial Task Team on AMD to implement a Short Term Solution that simply neutralizes the water, before a Long Term Solution can be implemented. The emergency intervention has clearly

[28] **Coetzee *et al.***, 2005.
[29] **Wade *et al.***, 2002.
[30] **Coetzee *et al.***, 2005.

stabilized the situation, buying time to implement the Short Term Solution, but more importantly, it has so altered the pH in large portions of the Western Basin, that whatever uranium used to exist in solution, has now precipitated out in the void, thus rendering the resultant surface flow non-radioactive and thus less hazardous. This must be evaluated by the reader in the context of persistent criticism from some environmental NGO's that neutralization is an inadequate response[31] by the state. Similarly, the technical work showing the mobilization of uranium in aquatic systems and resultant health risks[32] must be contextualized within the significant pH shift that occurred as a result of the implementation of the DWA directive in April 2010 and the emerging knowledge of **Flow Pathway "B"** (see **Figures 12, 14 & 17**).

Myth No. 2: Radon Gas is a Hazard Arising from AMD

The second persistent myth is that of radon gas. Radon-222 is a daughter by-product arising from the decay of U-238 and it is well known and understood in the South African gold mining sector. As such monitoring is deeply embedded in standard operating procedures for all mining where uranium is present. Taken out of context, the issue of radon gas often finds its way into the public domain as an element of the AMD discourse[33], where it logically evokes a primordial response. This is probably why it is used by activists who want to mobilize public opinion in a given direction. Let us therefore unpack this issue with a view to understanding how it has become one of the enduring myths that hinder progress.

While radon is the product of decaying uranium, it is widely found all over the world. Often associated with granites, by virtue of the fact that within granite there is some uranium, it is not only a mining-related hazard[34]. In Europe, radon is found in elevated levels, often in the basements of homes. In many cases radon monitors are in widespread use for this very reason. Studies in Europe indicate that radon exposure is the second highest cause of lung cancer[35], so it is a hazard that is both significant and understandably emotive. In the South African gold mining sector it is potentially associated with the non-hydraulic mining of surface tailings dumps, known to have elevated levels of uranium in them.

Radon is therefore real, but is it a hazard directly related to AMD? To answer this question we need to understand more about the physical and chemical properties of the gas. Radon has the following characteristics[36], some of which are unique to the hazard potential:

- It is an odourless, colourless and tasteless gas.
- It is chemically inert and thus non-reactive.

[31] See http://www.miningweekly.com/article/no-consultation-process-for-amd-2011-11-18
[32] **Winde, F**. 2009.
[33] **Tempelhoff, E**. 2007(b).
[34] **Lindsay *et al.***, 2008.
[35] See http://www.bizcommunity.com/Article/196/323/40512.html
[36] See http://enhs.umn.edu/hazards/hazardssite/radon/radonintro.html

- It is the heaviest of all noble gasses (a key characteristic).
- It is moderately soluble in water (a key characteristic in an AMD risk profile).
- It is capable of diffusing through soil and rock.
- It rapidly decays *via* alpha particle emission with a half-life of 3.8 days (the most significant characteristic in an AMD risk profile).
- The daughter products arising from natural decay have an extremely short life-span ranging between 0.2 milliseconds and 26.8 minutes.
- Charged radon progeny can attach to air particles.

With this as a background, we can now assess the actual risk in the context of AMD. A known study conducted by a national science council attempted to determine the presence (or absence) of radon gas in AMD decant water. This project was hampered by the fact that the gas has such a short half-life. In fact, it was found that the period of time needed to take the sample from the decant point and then test it in the laboratory, was greater than the half-life of 3.8 days. The testing had to be abandoned until more sophisticated apparatus capable of real-time field testing could be procured. From this we can distil the first significant element of risk, because as a gas dissolved in AMD decant water, the half-life is a significant mitigating factor. If we evaluate this factor in the context of the **redox conditions** noted in the previous myth, we can safely assume that without uranium as a feedstock in AMD water, then the production of radon will be greatly attenuated, so even if the gas is present by some inexplicable process, then the short half-life will become the key mitigating factor.

Where it is most likely to manifest as a potential public risk is during non-hydraulic mining operations. Significantly, this action is tightly controlled by standard operating procedures, so levels are constantly monitored, and if legal buffer zones are actively enforced, then the risk remains extremely low. Hydraulic mining mitigates this risk, which is why it is preferred by responsible mining companies. Assuming that some gas is found however, the key physical characteristics of radon then become relevant, even if this is no longer an AMD-related hazard. This explanation must not be confused with an attempt to minimize the risk, but rather to contextualize it more accurately. Given that radon is heavier than air, it flows like water and sinks into valleys and depressions. This will significantly slow the flow, which only needs to be done for ≥ 3.8 days in order for the gas to naturally decay into short-lived progeny. As a result, where there might be a risk is not related to AMD, but rather to non-hydraulic mining. Where the re-mining of surface dumps is allowed, it is therefore better to do this hydraulically (see picture on front cover), as this has a known lower risk profile. Consequently the best risk mitigation strategy is to ensure that the monitoring protocols are being strictly enforced, most notably around buffer zones, while preferring hydraulic mining over a conventional front end loader.

The important take-home message regarding radon is the following:

- In the context of AMD it is not a real hazard.
- The short half-life naturally reduces the hazard rating.
- Being heavier than air, the gas flows like water, so is unlikely to travel great distances in the time when it is still hazardous. While this is not an AMD-related risk, it is potentially applicable to non-hydraulic mining operations that recover gold from tailings, so it needs to be understood in that context.
- Responsible hydraulic mining uses neutralized AMD water (image on front cover), thereby reducing the risk of mobilizing uranium and thus radon.
- Radon is well known in the gold mining industry, so monitoring protocols are sophisticated and strictly enforced by the regulatory authority.
- The issue of radon gas as a perceived risk arising from surface mine dumps must not be confused with AMD, as these are two separate manifestations.
- The conceptual distinction between different **flow pathways** is highly relevant.

Myth No. 3: Uncontrolled Decant of AMD will Flood the Streets of Johannesburg

This myth was initially cited by the media[37] and simply recycled without any active attempt at verifying the factual basis of this assertion[38]. The most recent manifestation states confidently that, *"With each rainy season the levels rise inexorably and by October (2013) the … [AMD] is expected to break surface in the Eastern Basin near Boksburg"*[39]. In order to counter the seductive allure of this myth, we need to separate two critical aspects:

- The uncontrolled aspect of the decant.
- The capacity of this uncontrolled flow to flood streets anywhere in the Witwatersrand mining basin.

Let us first deal with the uncontrolled aspect of the AMD decant. In 2002 the first water rose from the flooded mine void in the Western Basin and reported to surface in a small wetland that is the source of the Tweelopies Spruit, located in a dolomite outlier (shown as the colour purple in **Figure 6**), upstream of the Krugersdorp Game Reserve. This received much media attention and was initially met with a confused response ranging from denial that it actually existed, to attempts at controlling the flow by inserting a balloon down the shaft to seal it off permanently. None of these interventions worked and images of the flow became a regular feature in the media from that time onwards. Arising from this apparent debacle is the fact that this decant is now probably the most studied in the country, so our knowledge of how the process works is improving with time.

37 **Tempelhoff, E**. 2007(c).

38 **Segar, S**. 2013(a).

39 **Segar, S**. 2013(b). This specific statement indicates that the journalist has no conceptual understanding of the basic difference between breaching of ECL (see glossary) (scheduled to occur around Sept/Oct 2013) and active decant to surface (see glossary) (likely to occur only if the pumping fails and then only at a future date). The more the author engaged with this specific journalist in an attempt to correct these factual errors, the more his actions were perceived as presenting a biased case in favour of irresponsible mining companies. It is clear that one cannot debate the intricacies of empirical science in a magazine that exposes scandal.

Figure 6 is a cross section of the Western Basin along the surface line between the WWP and the Hippo Dam / Lodge Spring in the Krugersdorp Game Reserve. This is part of a current programme designed to develop an accurate groundwater model capable of predicting the movement of AMD plumes in various future rehabilitation scenarios currently being considered for the WWP. The data shown in this cross section is the *status quo* situation as it currently stands, without any rehabilitation of the WWP, and can thus be used as a baseline. The current decant point is from the Black Reef Incline (BRI) shaft, not shown on the cross section, but located upstream of the Hippo Dam near the 1,665 metre above mean sea level (mamsl) contour. It is immediately apparent that the level of water in the WWP, clearly visible in all photographs in the public domain, is slightly higher than the level at the BRI decant point. This difference in elevation provides the hydraulic head that drives all flow through the system.

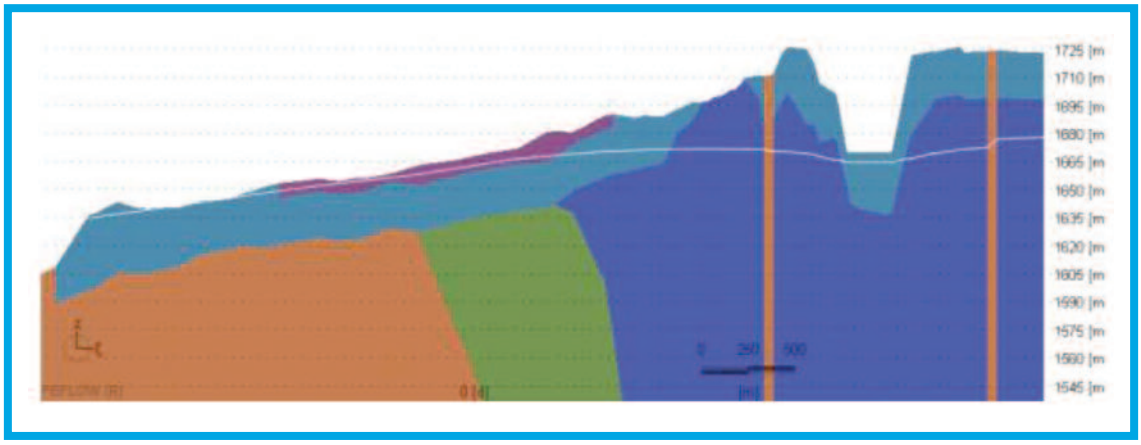


Figure 6. Cross sectional view of the Western Basin decant point along the line between the West Wits Pit and the Hippo Dam / Lodge Spring in the Krugersdorp Game Reserve showing the current water table (zero pressure isoline presented in white)[40].

AMD has continuously decanted from the BRI since it first began in September 2002, so it is the best studied analogue for what uninformed media commentators confidently state will happen elsewhere (without the benefit of that technical insight). This decant initially started at 18 Winze Shaft, later migrating to 17 Winze which is higher in elevation, giving an indication that there is sufficient resistance to the underground flow of water to create a hydraulic head. One day, without forewarning, a new decant point occurred as the increasing hydraulic pressure moved the plug that had sealed the entrance to the BRI shaft. From that moment onwards, the BRI shaft became the primary decant point, but with sufficient hydraulic head to still decant from 18 Winze during times of high flow; and occasionally from 17 Winze for intermittent periods after major rainfall events caused peak flow conditions.

The primary source of water for the Western Basin decant is twofold[41], again raising the significance of **flow pathways** as conceptually discreet elements of the overall manifestation of AMD. Precipitation patterns show a spatial variability along the Witwatersrand, which is also the continental watershed divide between the Limpopo River basin (flowing to the north and east) and the Orange River basin (flowing to the south

[40] **Hartnady *et al.***, 2013.

and west). **Figure 7(a)** shows a relatively high level of rainfall distributed at a localized scale in the Randfontein and Krugersdorp areas. This translates into high levels of groundwater recharge in that same area **(Figure 7(b)),** a combination of elevated levels of localized precipitation and the existence of dolomite close to the surface. The first source of recharge into the Western Basin in general is thus relatively high rainfall on the dolomites, which occurs predominantly around Randfontein. (This is an example of **Flow Pathway "C"** interacting with **Flow Pathway "D"** as defined in **Figures 12, 15, 16 & 17**). The significance of this being that surface flows in that area report to the Orange River basin *via* the Wonderfontein Spruit and Mooi River, whereas some of the groundwater flows report to the Limpopo River basin *via* the Tweelopies Spruit, that also drains the Western Basin decant point at BRI and 18 Winze. This is a classic case of a groundwater compartment that does not coincide with a surface water catchment area.

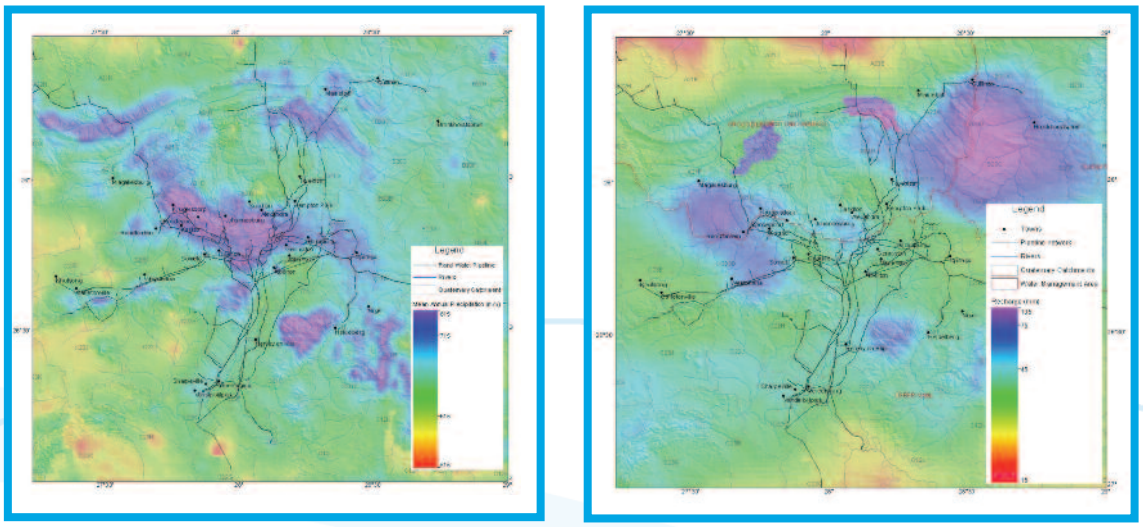


Figure 7(a) (left) shows the spatial distribution of rainfall along the Witwatersrand ridge. Figure 7(b) (right) shows groundwater recharge across the same area. The area of highest groundwater recharge in the Western Basin is located in the dolomites around Randfontein[42] and is an example of the interaction between Flow Pathway "C" and Flow Pathway "D" (see Figures 12, 15, 16 & 17).

The second source of water for the Western Basin decant is the WWP, shown in Figure 6 (as an example of **Flow Pathway "D"** – see **Figures 12, 16 & 17**). In this regard the reader needs to be aware of the fact that the water visible in the WWP is indicative of the water level in the entire Western Basin void, with a slight hydraulic gradient between the WWP and the BRI decant point. This gradient is no more than 15 metres (the difference between 1,650 mamsl at the Hippo Dam downstream of the decant point, and 1,665 mamsl in the WWP). We also know, from close observation of the Western Basin behaviour, that as soon as the pressure differential gets too large, then alternative decant points are opened up naturally in order to equilibrate the growing internal stresses.

41 **Hartnady *et al.*,** 2012.
42 **Hartnady *et al.*,** 2012.

Using this as an analogue we can safely conclude that the water level in a given mining basin, is capable of building a hydraulic gradient, at least of 10-15 metres (1-1.5 bar of pressure), with the actual pressure differential determined by a balance between the volume of water flowing into the void and the resistance to that flow created by underground blockages such as falls of ground. With this knowledge we can now examine the Central Basin, which lies beneath the city of Johannesburg, in order to determine whether it is possible for water to actually flow in the streets.

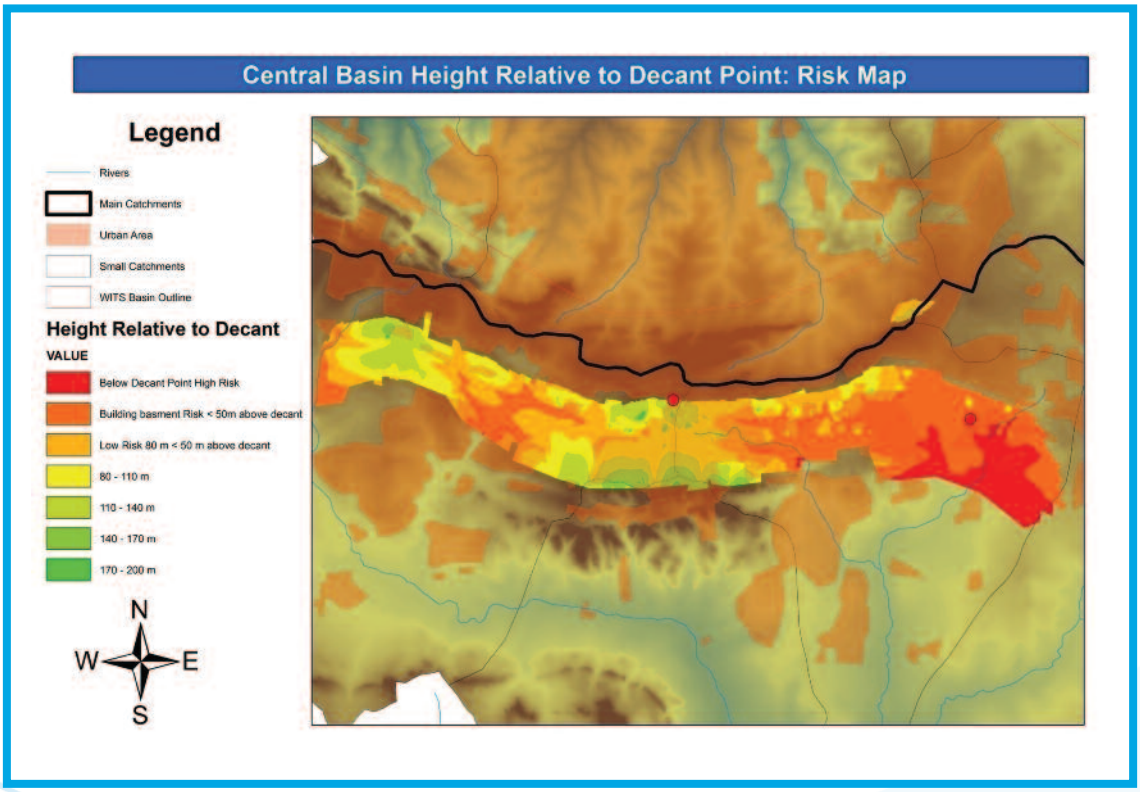


Figure 8. Map of the Central Basin showing elevation above the lowest point from which decant will occur if the flow is left uncontrolled (courtesy of Danish Hydrological Institute).

The Central Basin is shown in **Figure 8**, with contour lines represented as colour bands using the lowest elevation, shown in red, as the baseline. The first observation is the elongated nature of the Central Basin, physically occurring to the south of the Witwatersrand Ridge. The second observation is that three natural rivers drain the area, all flowing into the Klip River system, but all originating in the void from different elevations. The third observation is the lowest elevation that is shown in red. This is the area most likely to be flooded if the decant remains uncontrolled. From this it is evident that the only significant area of flooding exists around Cinderella Lake, where the actual decant point is shown as a red dot. Given the prevailing geohydrological conditions, which are similar to those found at the Western Basin decant point used as an analogue, we can safely believe that they are both likely to behave in a similarly predictable manner (allowing for some degree of localized

variability). Finally, note the difference in elevation between the decant levels (shown in red) and the general level of the city centre (shown in light green). The streets of downtown Johannesburg are 80 – 140 metres above the level at which decant will occur if left uncontrolled, and two alternative decant points will be reached (shown in red/orange) long before that moment. So in a worst case scenario we can expect a second decant point to open up in a different river as forewarning that void levels are rising dangerously.

Using our knowledge of the behaviour of the Western Basin decant as an analogue, we can conclude confidently that for water to flow in the streets of the city centre, there must be a pressure differential across the void of more than 10 times that known to be possible (100 metres of hydraulic head or 10 bars of pressure). The probability of this occurring is remote enough to be considered negligible. Yes, we can expect a 10 metre hydraulic head to occur as we have noted in the Western Basin, and possibly even double that if some localized underground condition exists that we do not yet know about, but that will not push the level back to any point where it poses a direct risk to the streets of the city. Of interest is the Standard Bank Building (shown as a red dot in the middle of the basin), often cited in the media as being at great risk, which is actually located close to a watershed divide between two quaternary catchments and thus at one of the highest elevations of all. Even if the basements of such buildings are 10 storeys deep, they will still be perched between 50 and 110 metres above the water in the void at decant level. From this we can safely conclude that even under the worst conditions of uncontrolled decant from the Central Basin, the following are physical impossibilities:

- Flooding of the streets of Johannesburg.
- Flooding of basements unless they go 80 – 140 metres below surface.
- Corrosion of metal in foundations.
- Collapse of buildings caused by the failure of foundations and corrosion of structural steel.

Returning now to the uncontrolled nature of the decant, we can safely say that even under a worst case scenario where the Central Basin pumps cannot be installed in time and the void water rises fast enough to reach the decant point at Cinderella Lake, then what we will have is a situation similar to that in the Tweelopies Spruit, possibly with a second decant point opening up in a different tributary of the Klip River system. While it will certainly be a localized environmental catastrophe, at no time will AMD ever flow in the streets of the city, or even in any suburb. **Figure 9** shows the area where the Central Basin decant will occur and it is evident that it is a large wetland, with no housing development that is at imminent risk.



Figure 9. Image of the area downstream of the most probable Central Basin decant point at Cinderella Lake. Hydrogeologically this is similar to the Western Basin decant point, so its future behaviour can be predicted with some confidence.

Confidence for this statement is boosted by the recent completion of a significant project[43] that developed a risk assessment methodology capable of objectively quantifying the actual risk that might arise to infrastructure from AMD flows. From this study we now know, with a high level of accuracy, exactly how AMD plumes pose a risk to infrastructure. Significantly, there were five findings relevant to the current context:

- **It is not the AMD in the void that poses the greatest risk, but rather the slow insidious movement of acidic saline plumes out of surface tailings dumps**. It is thus not uncontrolled flowing water coming out of the void, but rather the insidious seepage of plumes from the base of tailings dams that pose the greatest risk.
- All surface tailings dams do not have the same risk profile when a number of biophysical factors - age, size, localized geology, precipitation, gradient and proximity to wetlands - are quantified. It is now known with high confidence that the Western Basin contains the most hazardous dumps, with MRA's 172, 188 & 189 being extremely hazardous, leaving all of the rest classified as highly hazardous except MRA 177, which is moderately hazardous. The western portion of the Central Basin has three areas rated at high hazard (MRA's 190, 192 & 196), with the rest scoring quite low. The eastern portion of the Central Basin has only one dump featuring as a high hazard (MRA

[43] **Hartnady *et al.***, 2012.

293), with the rest showing as low or moderate hazard. The Eastern Basin shows no MRA's of a high hazard, with five as moderate (MRA's 319, 325, 365, 366 & 389) or moderate-low and low (the rest) in terms of the multiple criteria (and relative weightings) used in the assessment methodology. The Far Western Basin only shows MRA's as low and moderate-low hazard, with the highest rating being moderate for MRA's 150, 151 & 220.

- The major risk in this regard is associated with a change in the electrical conductivity of the earth, which has implications for buried infrastructure that makes use of cathodic protection. Galvanic action plays a major role where two different metals are immersed in an electrolyte, thereby setting up an electrical current that corrodes metal.
- Where plumes from tailings dams intersect buried infrastructure in close proximity to elevated high voltage power lines, there is a significant increase in risk arising from the existence of spurious flux currents caused by electromagnetic forces now operating under a different set of parameters.
- The Western Basin is an environmental catastrophe because the **Environmental Critical Level** (ECL) (see glossary) has been breached, which in the presence of dolomite, has allowed for the rapid movement of two distinct pollution plumes. The prevention of the breaching of ECL is thus a key management objective in basins where active decanting has not yet occurred.

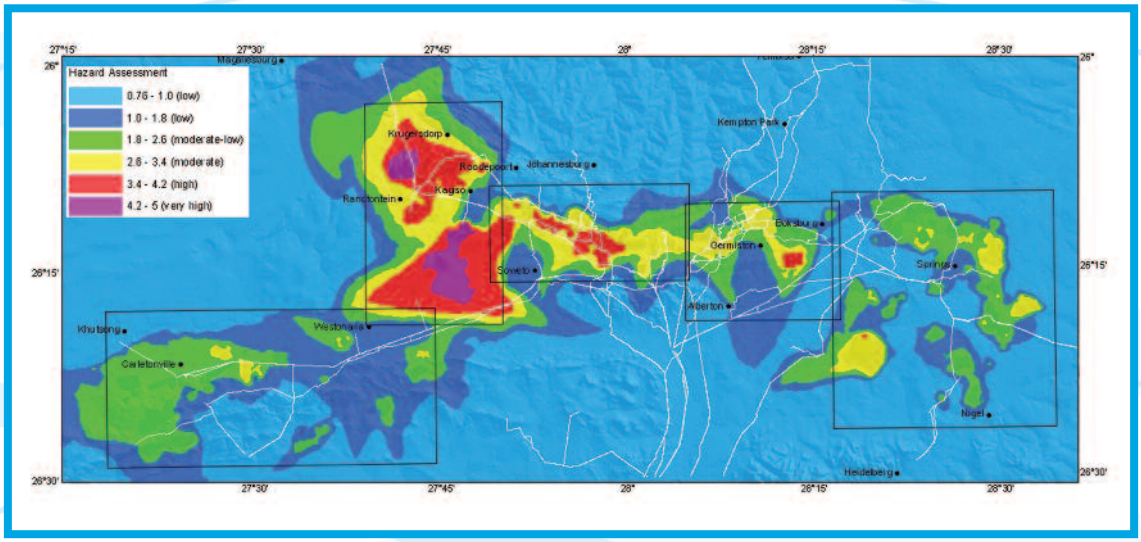


Figure 10. Hazard Diffusion Model of the Witwatersrand Mining Basin showing the conditions that prevailed in 2012[44].

In the context of lessons learned from the uncontrolled aspect of decanting AMD, specifically how that translates into specific risk, let us dwell for a moment on the last bullet point. **Figure 10** shows the hazard diffusion model that was developed in order to quantify the risk to infrastructure arising from AMD. For conceptual purposes the Witwatersrand Mining Basin was divided into the Far Western Basin, Western Basin, Eastern Basin with the Central Basin sub-divided into Central West and Central East.

[44] **Hartnady *et al.***, 2012.

The first aspect that arises from this hazard diffusion model is the extent to which AMD-impacted plumes have moved in the Western Basin. This is a direct consequence of the presence of dolomite, which enables the rapid lateral movement of water as soon as ECL has been breached. It is evident that there are two major pollution plumes, one driving northwards into the Limpopo River basin via the BRI decant in the dolomite outlier into the Tweelopies Spruit (see **Figure 6**), the other driving southwards into the Vaal River system via the dolomites associated with the Wonderfontein Spruit. This tells us that the prevention of ECL breach is an important management objective. Shifting our attention now to the next hydrogeological unit to potentially breach the ECL – the Central Basin – it becomes patently obvious that a catastrophe has not yet occurred in that basin. More importantly, no other basin is at risk of imminent catastrophe. This teaches us two important lessons:

- Current efforts designed to prevent the breach of ECL in the Central Basin are entirely justified and in fact the best thing to do at this stage of the process.
- The failure to prevent ECL breaching in the Western Basin does not mean that we must simply write it off, because the delicate hydrological balance shown in **Figure 6** tells us that with limited effort, we can reverse the flow of the pollution plumes and begin rehabilitation fairly easily. This will occur naturally as soon as the void level is drawn down to ECL, thereby changing the piezometric gradients in the system.

Stated simplistically, the government has made the right decision to focus all attention on the prevention of the breach of ECL in the Central Basin by installing a pump and neutralization capability there. Conversely, we must collectively not allow all relevant parties to simply leave the Western Basin as it is, because it is an unmitigated environmental disaster as it currently stands. All available knowledge suggests that we are making progress, with a reversal of the *status quo* being possible in the near-term future, more specifically as we start to draw void levels down once again.

The important take-home messages regarding the risk of uncontrolled decant flooding the streets of the city of Johannesburg are the following:

- It is a physical impossibility for AMD decant in the Central Basin, even under uncontrolled conditions, to ever flood the streets or basements in the city of Johannesburg.
- Under worst case conditions where ECL is breached in the Central Basin, then it will resemble the Western Basin with active decant occurring into the wetland downstream of Cinderella Lake. There is a possibility of a second decant point opening up in an adjacent tributary. While this will be a localized environmental disaster, it is not the same thing as having streets flooded.
- The structural stability of buildings is not at risk from AMD decant.
- The AMD risk is now well defined and consists mostly of the movement of plumes in the soil, out of surface tailings dams into local wetlands, which serve to alter the electrical conductivity of the earth, thereby elevating the risk to any buried infrastructure that needs cathodic protection.
- There might be localized risk to structural steel if key elements are in direct contact with shallow acid plumes adjacent to mine dumps.

- Once ECL has been breached, in the presence of dolomite, the basin concerned rapidly deteriorates as the acidic plume moves laterally.
- It is therefore correct to focus all attention on the prevention of ECL breach in the Central Basin by installing a pumping and neutralization plant.
- It is incorrect to write the Western Basin off as a disaster that has already happened, as available data suggests that the remediation of that situation is possible and practical.
- The only place where a street might be flooded is in Nigel in the Eastern Basin, where it has been built in close proximity to the likely decant point, but this is a remote possibility in terms of the current timelines, and is still a far cry from the image of flooded streets in a city centre.

Myth No. 4: AMD is Created in the Mine Void

This brings us to the last of the four myths. It is significant that the prevailing assumption underlying the public discourse on AMD is that it is created in the mine void. This probably arises from the association with the first decant from the void in 2002 and the resultant media coverage that created the mental connection between AMD and the cessation of underground mining. As this assumption underpins a lot of the current efforts at solution-seeking, let us examine it in greater detail.

The chemistry of AMD is now very well known[45]. In essence we know that pyrite (FeS_2) oxidises to form an acidic solution of ferrous iron and sulphate (s = solid; l = liquid; g = gas; aq = aqueous). This is chemically described as follows:

$4FeS_2\ (s) + 14O_2\ (g) + 4H_2O \rightarrow 4Fe^{2}+\ (aq) + 8SO_4^{2}-\ (aq) + 8H+\ (aq)$

(This is what happens on the surface of the tailings pile, specifically the relase of hydrogen, which can be defined as **Flow Pathway "A"** (see **Figures 12, 13 & 17**), as this is the genesis of the majority of future AMD in the entire downstream portion of the overall system).

Ferrous iron then oxidises to ferric iron, more slowly at lower pH values, which is descibed as follows:

$4Fe^{2}+\ (aq) + O_2\ (g) + 4H+\ (aq) \rightarrow 4Fe^{3}+\ (aq) + 2H_2O\ (l)$

(This is what happens when the acidic water leaves the tailings pile, again noting the role of hydrogen in the process, which is defined as **Flow Pathway "B"** (see **Figures 12, 14 & 17**).

Ferric iron then precipitates as ferric hydroxide, producing further acid, which is described as:

$4Fe^{3}+\ (aq) +12H_2O\ (l) \rightarrow 4Fe(OH)_3\ (s) +12H+\ (aq)$

(This is what happens when the acidic water enters a local wetland or river, again with hydrogen as a key element, which is defined as **Flow Pathway "C"** (see **Figures 12, 15 & 17**).

[45] **Hartnady *et al.***, 2012.

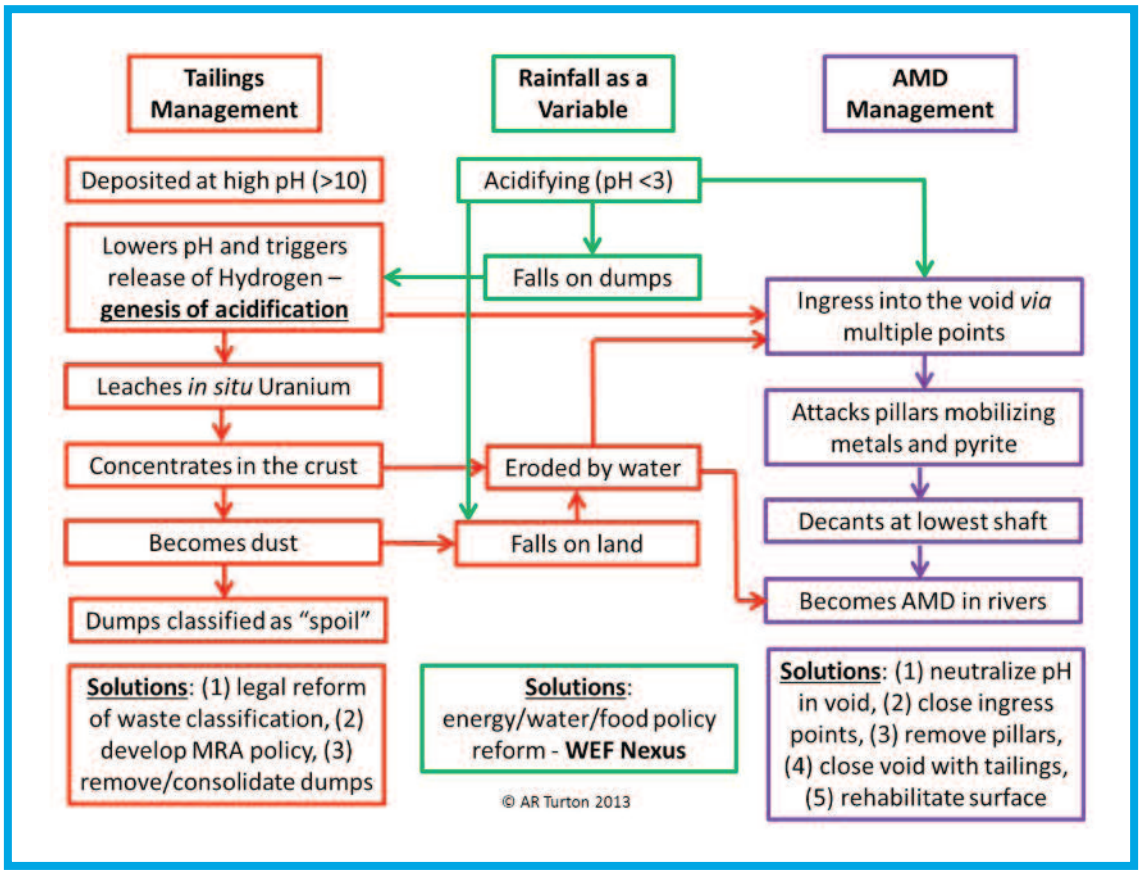


Figure 11. Schematic diagram of the relationship between the management of tailings and AMD as conceptually different entities, with rainfall as an independent variable.

What is now better understood is that in order to initially trigger the formation of acid, you need pyrite, water and oxygen. This was thought to be the "normal" condition in a mine tailings dam. On closer examination we now know that an additional factor is also relevant, because **barren tailings** (see glossary) are deposited at a very high pH (in the order of pH 10.5), simply because this is the required metallurgical condition for the extraction of gold. The question therefore arises how the genesis of AMD occurs? The assumption has been that it must happen when the pyrite is oxidised in water[46]. Current work suggests a more complex situation, noting the existence of discreet but conceptually unique **flow pathways**. Recent pH readings of rain falling on flat-topped mine dumps suggests that it is often highly acidic, with a value of 3 in some cases. While we have long records of rainfall in the country, those records do not include pH, so we do not have an accurate understanding of the trend in acidification of rain over time. Current tests, limited to localized mine sites on the West Rand, show that the rain is often highly acidic, and it is now being hypothesized that this creates exacerbating conditions for the acidification of the surface of mine tailings dams. Once the localized conditions in the tailings pile become acidic, then the chemistry of AMD kicks in and becomes virtually self-propelling unless a major intervention occurs to shift the prevailing conditions back to a neutral pH. While this is only a hypothesis

[46] Typically pyrite particles are encased in alkaline (calcium hydroxide) salts. When these are sun-dried they become fragile and blow away in the wind, exposing the pyrite to oxygen. Acid rain exacerbates this by enhancing the oxidization process.

at this time, it deserves to be researched further, as it can change our view of whether we must manage AMD in perpetuity. This thinking is at the core of the notion of discreet **flow pathways**, each with a fundamentally different set of cause-effect linkages as shown in **Figure 11**.

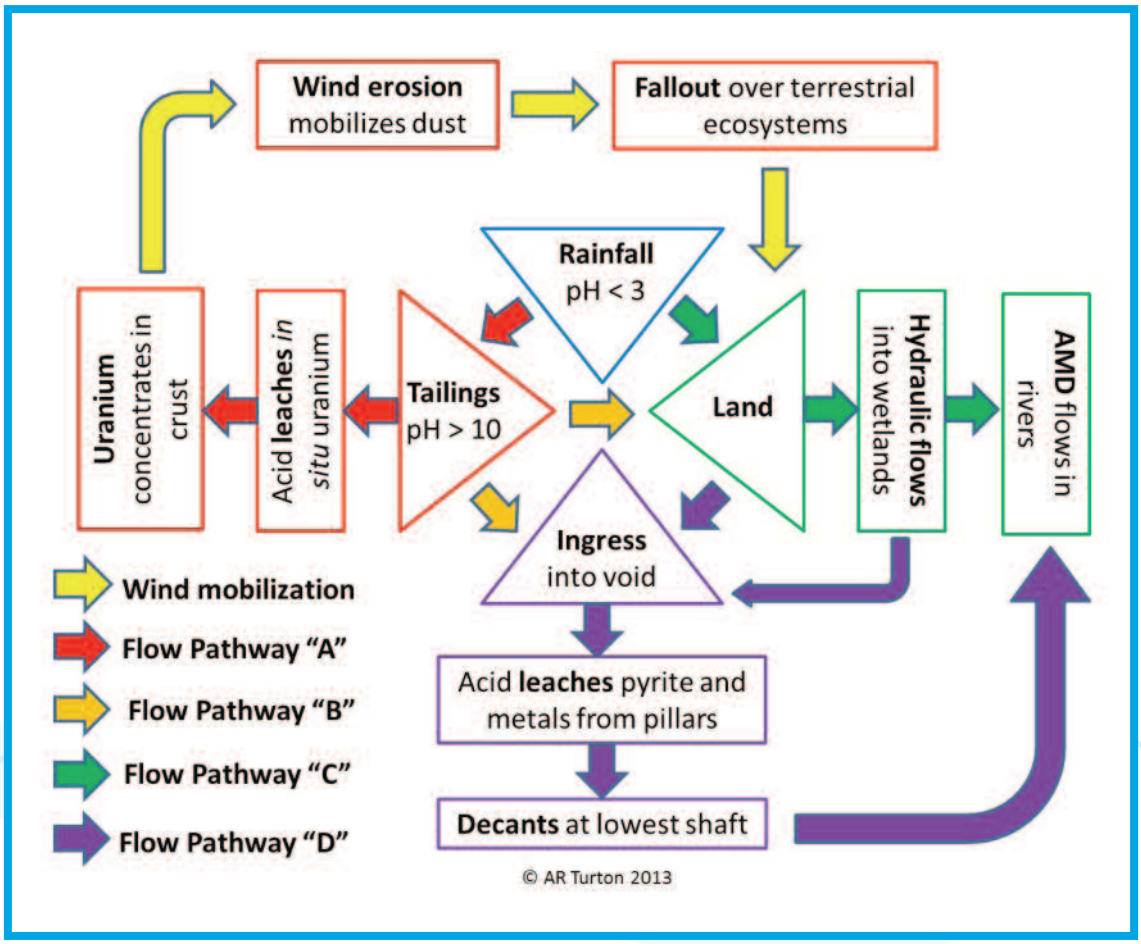


Figure 12 shows the four discreet but unique flow pathways associated with AMD. Our failure to identify these as separate sub-systems has contributed to our inability to separate myth from reality.

In terms of the assumption that AMD is created in the mine void[47], we can now safely say that the acidification of tailings on surface, exacerbated by acid rain, is the probable genesis of the process in the entire system. We can go even further by identifying at least four discreet but unique **flow pathways** as shown in **Figure 12** in more detail. Only by understanding these as separate sub-systems, each with a fundamentally different set of relationships between key biophysical processes involving aspects of wind circulation, hydraulics, pH and **redox conditions**, can we begin to develop viable mitigation strategies capable of dealing with the uniqueness in each **flow pathway**. This is how we convert the dilemma of AMD into a set of soluble problems!

[47] The presence of calcium in many AMD samples is evidence that a linkage exists with the tailings dams, because the Witwatersrand quartzite's that make up the host geology, do not naturally contain calcium. Calcium is used in the metallurgical process to extract gold, as either unslaked (CaO) or slaked ($Ca(OH)_2$) lime, so it is found in high concentrations in barren tailings piles.

For conceptual clarity we can now define **Flow Pathway "A"** as being the genesis of AMD (**Figure 13**). This can be described as acid rain falling onto alkaline tailings dumps (with an initial pH ≥ 10) containing pyrite, lowering the pH and triggering the release of hydrogen, fuelling the acidification process in the dump itself. Rainfall is thus probably the genesis of the acidification process, and NOT the mine dumps in and of themselves, which are initially deposited as highly alkaline **barren tailings**, but acidify over time in response to the chemistry and physics of precipitation. This hypothesis needs to be validated by credible independent scientists in the national interest. Once a pH threshold of 5 is breached, then uranium starts to leach. This leachate is concentrated in the crust that is later mobilised by either wind or rain, hence the need to isolate those two pathways as being unique and discreet in their own right.

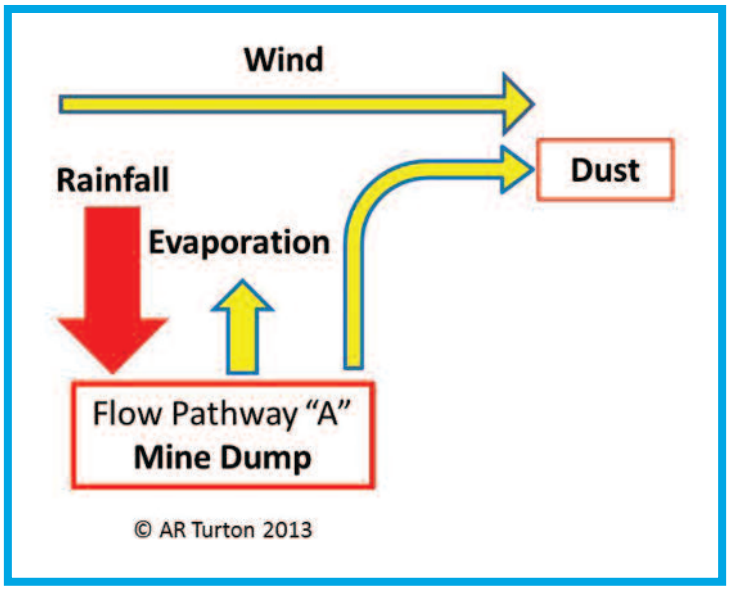






Figure 13 shows surface ponding on tailings after a rainfall event, leaving highly acidic water that leaches uranium (left), with resultant crust (right) before being wind eroded. Flow Pathway "A" is the Genesis of Acidification.

Flow Pathway "B" consists of the movement of water off the tailings dam as a result of episodic weather events, hydraulically moving particulate matter, most notably from the uranium-rich crust, which makes its way *via* multiple ingress points into either the void or adjacent wetlands, after flowing across MRA land (**Figure 14**). The ability of this flow to mobilize uranium is dependent on prevailing pH and **redox conditions**. An example of this is shown in **Figure 5**.





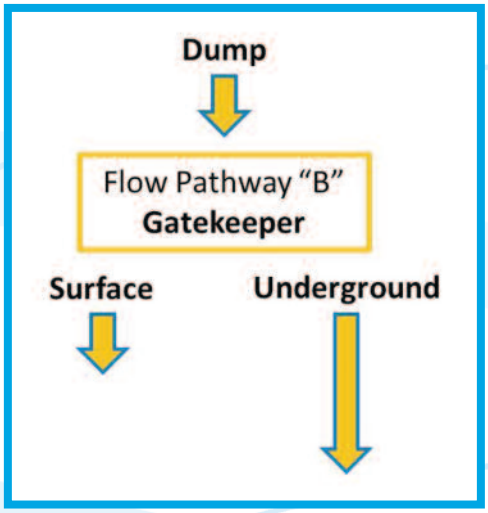


Figure 14 shows erosion off a tailings dam because of the runoff of surface flows (left) and the ingress of water into a stope deep inside the void (right). Flow Pathway "B" is a Gatekeeper because it divides flows into either surface or underground pathways.

Flow Pathway "C" consists of: dust fallout, primarily originating from the dried crust on the tailings dam that also contains uranium by virtue of the natural leaching process that has occurred, which then blows uncontrolled over the landscape; and sediment that has been eroded off tailings dams adjacent to wetlands (**Figure 15**). Rainfall occurs in a series of episodic weather events, and this dust and sediment, along with all other particulate matter including uranium, is mobilized hydraulically, entering rivers by means of natural hydrological processes. The prevailing pH and **redox conditions** will determine the extent to which the uranium remains soluble as it transitions through the many small steps in this complex and lengthy process. An example of this is shown in **Figure 5**.





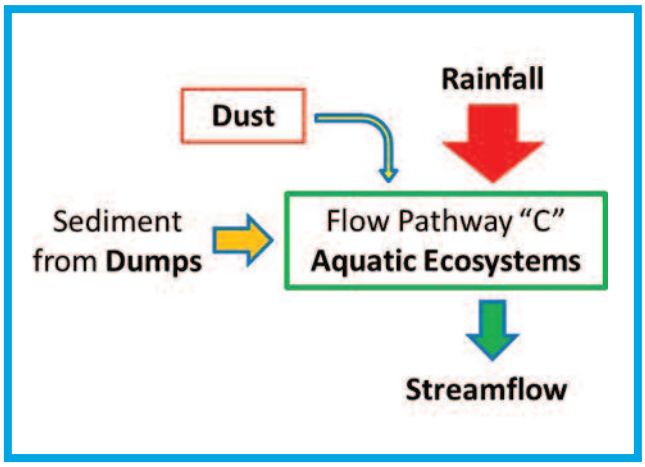


Figure 15 shows sediment that has been eroded off a surface dump into a wetland (left), and Yellow Boy encrustation in a river bed downstream of the Western Basin decant point (right). Flow Pathway "C" is centred on aquatic ecosystems on the surface involving either sedimentation (left) or precipitation (right) as process mechanisms.

Flow Pathway "D" consists of the runoff of water from land (other than directly from tailings dams) due to episodic rainfall events (**Figures 7 & 16**). This flow enters the void and starts to mobilize heavy metals and oxidize pyrite found in the remaining underground **pillars** (see glossary), dependent on the prevailing pH and the **redox conditions**. This eventually reports to surface as **decant** that enters rivers *via* natural wetlands that can potentially accumulate the heavy metals in the peat, if anoxic conditions are maintained (shown in **Figure 5**) (again **redox conditions** are significant). If these rivers or wetlands are intersected by preferential pathways into the void (faults, dykes or karstic structures), then water can be recirculated within that unique but discreet sub-system.





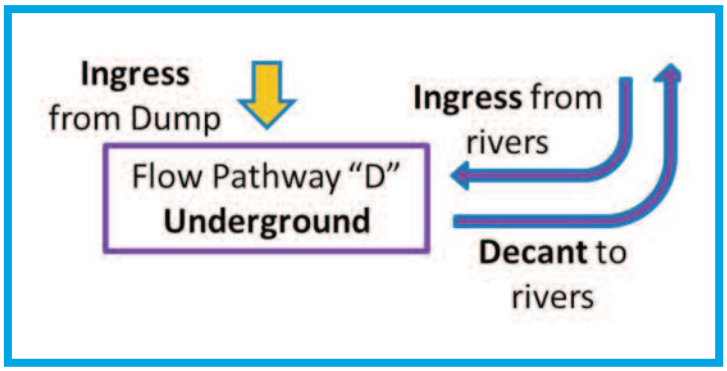


Figure 16 shows the water table in an incline shaft ("D" Shaft at Luipardsvlei Estate Gold Mine) in the Western Basin (left) and the decant point at 18 Winze (right). Flow Pathway "D" is entirely underground.

Comparatively speaking, the mass and volume of pyrite on surface, mostly in the form of tailings, is far greater than the mass or volume of pyrite still left underground. In fact, it is common knowledge in mining circles that even in defunct gold mines, only around 10-15% of the gold-bearing reef is still underground (in many cases less than this), mostly in the form of shaft and crown **pillars** holding the roof up. It is this remaining reef that is being exploited by illegal artisanal miners, known as Zama Zama's. Yet while this reef is known to exist, it is significantly less than the mass of pyrite that is found in the surface tailings. More importantly, the area of exposure to **oxidizing conditions** is far greater in tailings than in uncrushed rock, simply because of the known mathematical relationship[48] between the volume and surface area of small versus large particles. Smaller objects have a larger surface area relative to volume than large objects have, which is exactly why rock is crushed into fine particles in the first place – it creates a larger surface area for the chemical processes to occur.

We can therefore accept, with a reasonable degree of confidence, that the majority of AMD is created on surface rather than in the void, until the contrary is proven by credible scientists. We therefore need to understand how it moves from surface into the void, which has been eloquently illustrated in a GCRO Provocation Paper[49] and enhanced here in the form of at least four discreet but unique **flow pathways**:

- **Flow Pathway "A"** = rainfall → lowers pH on alkaline dump → leaches uranium → concentrated in the crust. (Purely a hydraulic process occurring only on dumps, but underpinned by chemistry).

[48] See http://en.wikipedia.org/wiki/Surface-area-to-volume_ratio for more information.
[49] McCarthy, T.S. 2010.

- **Flow Pathway "B"** = drainage off dumps after episodic rainfall events → moves sediment rich in uranium from the crust dependent on prevailing pH and **redox conditions** → enters the void *via* multiple ingress points, but also finds its way onto land. (Purely a hydraulic process manifesting on surface only at localized scale, but with elements of chemistry).
- **Flow Pathway "C"** = wind mobilizing dried crust often rich in uranium → blown as dust across the landscape → deposited onto the land → mobilized by runoff from episodic rainfall events dependent on prevailing pH and **redox conditions** → enters the rivers via natural hydrological processes with uranium being concentrated in wetlands where present → decant from **Flow Pathway "D"** is a unique input into this sub-system. Both sedimentation and precipitation are relevant. (Combined wind and hydraulic process underpinned by chemistry with all significant components occurring on the surface at a larger scale).
- **Flow Pathway "D"** = water enters the void via multiple ingress points from the landscape including rivers that intersect geological features like faults and karstic systems → emerging as decant where it becomes a unique input into **Flow Pathway "C"**. (Purely a hydraulic process but defined by chemical and biological (notably the bacteria *Thiobacillus feroxidans*) parameters only occurring underground).

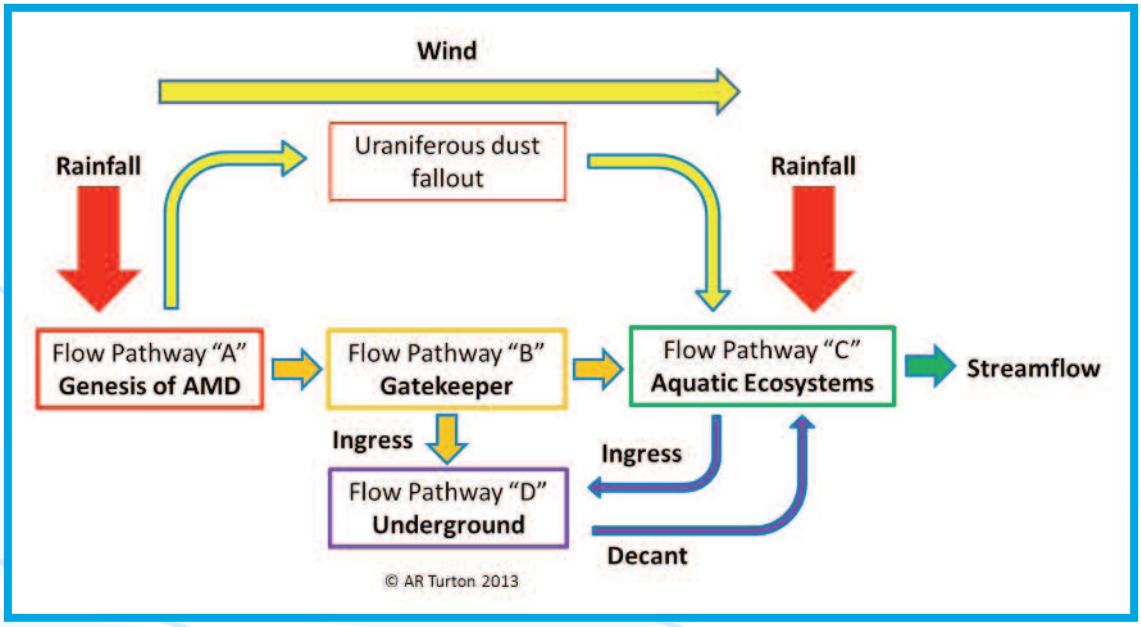


Figure 17 shows AMD flows as a total system, illustrating how each of the discreet Flow Pathways relates to one another as unique sub-systems. Viable mitigation of AMD will depend on designing interventions at key points in the overall system.

In summary, AMD moves from the surface, by means of multiple **flow pathways (Figure 17),** each containing a fundamentally different set of cause-effect relationships, into the void through open shafts, shallow stopes that often break through to surface and geologically defined preferential

pathways such as faults, dykes and karstic structures. **Figure 18** shows a shallow haulage, less than 20 metres below surface, that has been revealed by open cast operations. Such workings are common all along the surface striking reef within a defined package. **Figure 19** shows a surface opening to one of these shallow stopes, dating back to early mining more than a century ago. Such openings typically occur every 100 metres or so all the way from Krugersdorp/Randfontein in the West to Springs/Brakpan in the East. All of these provide active ingress points for acidic water to move from surface tailings dams and rainfall into the void. If one also considers the presence of dolomite (see **Figures 7(a) & 7(b))** then this ingress potential is greatly enhanced.





Figure 18 (left) shows a shallow haulage that has been revealed by open cast operations. Note the fracture planes propagating to surface created by the systematic collapse of these old workings, each providing preferential pathways for water to enter the void. Figure 19 (right) shows a surface holing on the West Rand.

What We Collectively Need To Know

What has emerged from this analysis is that the AMD issue is a classic dilemma, in which science clearly has a problem when it comes to transferring factual information to the general public and decision-making executives. The media and certain activists have been helpful in raising public awareness of the problem. They have equally been a constraint to progress by presenting narratives that are seductively simply in their logic, but factually flawed in their final message. They simply cause confusion in the mind of the non-technical public by attacking those seeking to clarify this complexity, branding them as untrustworthy puppets of an irresponsible and greedy mining industry[50]. This has increasingly manifest as noise in the system, rising in volume to the point where doomsday scenarios are being presented in which four perpetual myths continue to restrict progress by confusing decision-makers and raising the risk for scientists and engineers foolish enough to engage in that space.
What we collectively need to know about AMD is best summarized as follows:

[50] See Segar, S. 2013(b) for an example.

- It is complex so we need to have a clear conceptual understanding of the problem, specifically with respect to **flow pathways**, as these are discreet but unique sub-systems within the greater whole. This Discussion Paper has offered a clear model (**Figures 11 - 17**) that non-technical people should be able to grasp.
- We can accept that AMD is created mostly on the surface, originally out of alkaline tailings dumps that acidify in response to the ingress of rain at a naturally low pH, until proven otherwise by credible scientists.
- To mitigate AMD we therefore need to embed the technical aspects associated with the different engineering, design and costing's, within a broader strategy of mine closure that embraces surface rehabilitation.
- AMD is not necessarily a perpetual problem, provided we purpose design mitigation measures that are cognizant of the **flow pathways**.
- In essence, AMD is a manifestation of an unplanned transition from an extractive economy in which costs were externalized for reasons of state survival, to a new and as yet ill-defined post-mining regional economy (at least for Gauteng province). It is therefore a manifestation of a fundamental failure of policy, so any viable solution has to be embedded in policy reform, most notably around those issues identified in **Figure 11** (the legal classification of mine waste, MRA policy with respect to human settlements and the removal/consolidation of tailings dams).
- Technically we can solve the AMD dilemma, but the solutions will not be sustainable unless we combine them with the final rehabilitation of tailings dams (**Flow Pathway "A"**), with both dust and water ingress/erosion control as two fundamental management objectives. Again there is a clear policy element to this aspect, most notably in the areas of ingress point management (**Flow Pathways "B" & "D"**), void closure by means of pillar extraction and backfilling with **barren tailings** and cement, and the permanent rehabilitation of the surface of all MRA's. This element thus deserves to be elevated to an open public debate with a view to initiating policy reform.
- The existence of large amounts of uranium poses a complex hazard that cannot be ignored. **Johannesburg is potentially the most uranium-contaminated city in the southern hemisphere, if not the world**, and we will increasingly see manifestations of this. If mining companies go bankrupt, then the dumps that they are liable for will simply succumb to the combined forces of wind and rain, distributing uranium far and wide. This will not be a desirable outcome for us as a society.
- It is therefore not in the public's best interest for marginal mining companies to close down before they have adequately removed all surface tailings as far as possible, and closed all voids and ingress points as much as possible.
- **There is a strong case to be made for a subsidy from the fiscus, in order to sustain the sequestering of uranium, while remaining mining companies reprocess surface tailings**. This issue deserves to be analysed in greater depth and fully debated in the best interest of the growing population of Gauteng, all of whom are directly impacted by uranium fallout from dust (the end result of **Flow Pathway "A"** and wind-borne input into **Flow Pathway "C"**) .

- The presence of uranium in the tailings must not be confused with radioactivity in AMD, as these are fundamentally different manifestations of unplanned mine closure.
- The legal definition of mine residue needs to be re-visited, because as it currently stands, it is not defined as waste. This means that by legal definition, **no mine dump is ever in its final resting place, so the capital that has been set aside to offset liability, cannot be used for any final rehabilitation**. This is a critical issue that deserves increased debate in all professional domains working on AMD as a problem.
- There is a strong case to be made for the public and regulatory authorities to embrace the remaining mining companies as part of the solution, as they alone have the physical ability to close ingress points, backfill the void and consolidate remaining surface tailings dumps. Clearly this will need a fundamental shift in attitude, as well as a significant change in the relationships between all parties. The risk to scientists trying to promote convergence is high[51], so these unfortunate individuals need some support from enlightened people if they are to remain willing to engage.
- Smart mining companies will realize that their core business is actually environmental rehabilitation, thereby aligning their corporate objectives with the best interests of society in general, bringing mine-impacted land back into safe social and economic use. This will increase revenues to local authorities and the fiscus, thereby funding future development.
- We need to work with the Water Research Commission (WRC) and other science bodies to develop a national program for the rehabilitation of mine-impacted ecosystems. At present this technical work is not adequately coordinated and funding is haphazard. The bio and phytoremediation of uranium-impacted landscapes should receive priority attention, as should the rehabilitation of wetlands, as these remain vital management tools for the accumulation of otherwise hazardous toxins.
- The risk assessment methodology that has already been developed for infrastructure[52] needs to be refined, as this shows great promise as a management tool with predictive capabilities.

Conclusion

The AMD issue is a classic example of a dilemma, which is why it has not been adequately solved. A dilemma, by definition, is something for which no apparent solution exists. This is why the public debate has been so confused and increasingly angry. It is thus in the best interest of society in general, and the government and mining companies in particular, to break this insoluble dilemma into smaller but clearly defined problems, because a problem, by definition, can be solved. This paper has attempted to do that by debunking the four persistent myths that have underpinned the public discourse over the AMD dilemma. The notion of **flow pathways** has been offered as a vehicle capable of distinguishing the discreet but unique sub-sets of the dilemma. It is suggested that these four (and maybe more) **flow pathways** each identify distinct problems, but are now capable of adequate solution.

[51] See Segar, S. 2013(b) for an example.

[52] Hartnady et al., 2012.

These solutions are as follows:

Flow Pathway "A" is a critical one, because it speaks to the whole issue of acidification of all water resources in general. Central to this is the policy reform process underpinning industrialization, which has a direct impact on our comparative advantage as an economy, and thus on our capacity to create sustainable jobs in a post-mining future. More importantly it speaks to the national debate on energy, currently based on coal combustion, which has as an unintended consequence, the release of sulphur dioxide (SO2) and carbon dioxide (CO2), both of which result in acid rain. This is clearly a vexing issue that deserves robust debate, underpinned by the most brilliant minds we can mobilize as a young nation, which is why we created SAWEF as a vehicle. We will also need to legally redefine mine spoil as waste, because only then will we be able to adequately rehabilitate dumps that have been moved to their final resting place. The concept of the **Water – Energy – Food Nexus** that was introduced by SAWEF is useful in framing the debate over the need for this policy reform, as it embraces all of the key trade-off's that will need to be considered.

Flow Pathway "B" is centred on the natural hydraulic process associated with the erosion of fine particulate matter off man-made structures that were designed on a flawed assumption that there would always be a cash flow to sustain the need for bulldozers and mechanical diggers to maintain the flat-topped step-sided structures called tailings dams. We now know that as soon as the company concerned is unable to fund this constant maintenance, then the dumps succumb to the laws of physics and simply collapse. One shudders to think what the consequence of this might be when one looks at the mega-dumps that lie adjacent to the soccer stadium outside Soweto, which push the very envelope of engineering design. This issue speaks to the need for clear thinking about the safe rehabilitation and possible removal of dumps, away from areas of high human population density. It also speaks to the clear need to close out all ingress points as a matter of stated public policy.

Flow Pathway "C" is centred on the fallout of dust originating from wind erosion off unrehabilitated dumps, as well as sediment moved from mine dumps by rainfall. Significantly, the geochemical process of uranium leaching, resulting from acid rain falling on flat topped structures and being held there for safety reasons, is a clearly defined but unintended consequence of this engineering design. The presence of uranium in vast quantities, now being dispersed across a wide landscape by wind, later to be mobilized hydraulically by water, is a truly vexing problem. Elements of the solution will entail the safe rehabilitation of mine dumps to prevent wind and water erosion, as well as the use of wetlands as key components for the entrapment of heavy metals as they migrate. The need to prevent artisanal miners from illegally mining gold from the peat in these wetlands will require a robust enforcement capability. The possibility of phytoremediation of uranium contaminated land will also need to be explored with greater commitment from all parties. The issue of sequestering uranium, most notably when tailings dams are reprocessed and repositioned for final rehabilitation, needs to also be considered and subsidized if necessary.

Flow Pathway "D" centres on the ingress of water into the void from multiple points, including rivers that cross geological faults or karstic structures. This issue is already being dealt with in some locations. We need to expand on this knowledge by carefully mapping all intersections between rivers and known preferential pathways into the void. Once this has been done we can then design appropriate engineering solutions, preferably embracing the emerging thinking around landscape architecture[53] and paste backfill to permanently close out the void. The objective must be to remove as many uraniferous tailings deposits as possible from surface and prevent future ingress and AMD generation underground.

If we break up the dilemma of AMD into these unique problems, then we are well on the way to resolving them. It is hoped that this Discussion Paper contributes towards an enlightened engagement capable of shifting us from blame-seeking to solution-seeking in the best interests of society. **The hypotheses presented here are now open for validation or refutation by credible scientists and graduate students looking for potential thesis topics**.

Glossary

Acid Mine Drainage (AMD). This is water emanating from a mine void or an MRA that is at a pH below 5, which is likely to contain a range of heavy metals as soluble species, dependent on the host geology and prevailing **redox conditions**.

Adsorption. This refers to the process by which molecules or particles bind themselves to a particular surface by means of chemical bonds. Carbon is an example of adsorption used to extract gold after it has been exposed to cyanide in a high pH environment (≥ 10.5). **Barren tailings** also provide natural adsorption faces for cyanide and iron, both elements central to gold processing and recovery. This is distinct from absorption, which involves the filling of pores in a solid.

Anoxic Conditions. A set of biophysical conditions characterized by the absence of free oxygen. (See **Reducing Conditions**).

Barren Tailings. These are tailings that are of a high pH (˃ 10) from which all gold has been recovered, which are then pumped onto tailings dams.

Classified Tailings. Mine tailings naturally consist of different particle sizes that emerge from the milling and recovery circuits in a processing plant. When a tailings stream is put through a cyclone, centrifugal forces separate the coarse from the fine material. The latter is better referred to as slimes, whereas the former is called classified tailings by virtue of the fact that it is more sand-like with a lower water carrying capacity and a higher structural strength than slimes. It is these characteristics that make it useful in the context of **pillar extraction**, because when placed inside a Hyson Cell[54] and vibrated *in situ*, classified tailings provide great structural load carrying capacity at low cost.

[53] See Tang, D. & Watkins, A. 2011; and Toffa, T. 2012.

[54] See www.hysoncells.co.za for more details.

Decant. When water rising in a mine void reaches the lowest point at which it can flow to surface without mechanical assistance, usually via an old shaft or a natural wetland, it is said to be decanting.

Environmental Critical Level (ECL). A threshold is presumed to exist at an agreed depth below the lowest contact point of an aquifer and any known vertical preferential pathways for contaminated water such as mine shafts. The ECL is designed to protect the aquifer from ingress of AMD from below, so it is defined as a level measured in metres above the mean sea level (e.g. 1450 mamsl), as this is a known constant. It is therefore not measured from surface, as this value changes with topography.

Flow Pathway. This is a discreet but unique sub-system within the overall AMD process, with specific cause-effect linkages that differ fundamentally from different sub-systems. At least four (but possibly more) flow pathways exist. **Flow Pathway "A"** is driven by acid rain falling onto tailings dams and is highly site specific. **Flow Pathway "B"** is the hydraulic flow off tailings dams, either onto the adjacent land or into the void, so it too is highly localized in scale. **Flow Pathway "C"** occurs at a larger geographic scale, above that of quaternary catchments, incorporating dust mobilized by wind off tailings dams and deposited onto the land, and the subsequent hydraulic movement of sediment on the surface into wetlands and rivers. **Flow Pathway "D"** occurs mostly underground within a geologically defined basin, but with some surface manifestation as decant into rivers and wetlands, or ingress from rivers and wetlands that intersect preferential pathways into the void.

Mine Impacted Water. This is water emanating from a mine void or an MRA that is at a pH value approaching neutral (>5), which is likely to contain a high level of dissolved salts, most notably sulphates, but without the presence of heavy metal species typically found in the host geology.

Mine Residue Area (MRA). This is an area of land surrounding mining operations that is often associated with surface outcroppings of reef, open shafts and holings, and the existence of mine tailings dams. In the case of derelict and ownerless mines, the MRA is no longer protected by the security guards employed by the company, so it often becomes the site of illegal mining activity and informal settlements.

Oxidizing Conditions. A set of biophysical conditions characterized by the presence of free oxygen. When an atom or molecule combines with oxygen, the resultant chemical bond is characterized by the loss of electrons to the oxygen atom.

Oxidation-Reduction Reactions. Also referred to as redox reactions, this is a balance of electron loss (by reduction) and electron gains (by oxidization). The substance gaining electrons is undergoing reduction and is therefore an electron acceptor or oxidant. Conversely the substance losing electrons (by oxidation) is an electron donor (or reductant) since its lost electrons reduce the other substance.

Paste Backfill. An emerging international best practice is the backfilling of stopes with classified tailings that are hydraulically placed *in situ* as an integral part of retreat mining. Sometimes cement is added, but this is not always necessary. The end result is the permanent closure of the stope with a high level of geotechnical integrity maintained, while also preventing ingress of water and the generation of future AMD.

Pillar. When mining operations are developed, protection is needed for critical areas such as those found around shafts, haulages, drives and within stopes. This is done by means of pillars, which consist of reef that is left in place with the express purpose of providing geotechnical integrity. These pillars often contain high grade ore and can thus be mined on a retreat basis when that specific portion of an underground mine is permanently closed out. Pillars typically become the target of artisanal miners who lack the engineering skills to calculate the stresses resulting from their removal, which accounts for a significant number of deaths for illegal miners.

Pillar Extraction. Modern mining engineering has advanced to the point where pillars can be safely removed on a retreat mining basis. Many methods exist and this is emerging as international best practice in the industry. One method makes uses of a Hyson Cell[55], which is a geotextile fabric that has been woven into a cell-like sock into which classified tailings are pumped, sometimes with cement to act as a binder. This distributes the load from the pillar, thus allowing for its safe extraction and subsequent permanent closure of the void with **paste backfill**.

Redox Potential. This corresponds to the least oxidized zone of a host aquatic environment into which uranium is of potential concern.

Reducing Conditions. A set of biophysical conditions characterized by the absence of free oxygen. When an atom or molecule loses oxygen it is said to have been reduced, with the resultant chemical bond being characterized by the gain of electrons from the oxygen atom. (See **Anoxic conditions**).

Stope. This is an underground working face that follows the reef band away from haulages used to transport men, equipment and rock. Some stopes are very steep and extremely narrow. They are only designed to be temporary working places as mine development moves into a defined resource. Support for the roof (known as a hanging wall) is by means of temporary wooden packs, or permanent pillars, left in place at carefully defined intervals.

Tailings. This is the fine powdery residue from the milling and mineral recovery process. In the case of gold mining as it was practiced in the Witwatersrand Mining Complex, these tailings are deposited at a high pH (> 10) because of the carbon-in-leach (CIL) process used. (See **Classified tailings**).

[55] See www.hysoncells.co.za for more details.

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