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METHODS TO ASSESS THE IMPACTS OF TAILINGS DAMS ON THE GROUNDWATER SYSTEM IN SOUTH AFRICA

Ingrid Dennis*, Jennifer Pretorius*, Piet van Deventer and Gideon Steyl*#**

*Institute for Groundwater Studies, University of the Free State,
Bloemfontein 9300, South Africa
**Department of Environmental Geology, North West University,
Potchefstroom, South Africa

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Abstract

The production of waste materials, such as tailings, from mining activities can have a significant impact on the environment. Most tailings dams contribute to the pollution of subsurface waters. Assessing the potential effect that the construction of a tailings dam will have on an area's groundwater system is of great significance. The eventual impact can be evaluated from construction methods of the tailings dam, the tailings chemical and physical composition, hydraulic conductivity of the tailings itself and the groundwater systems that are present in the underlying systems. South African aquifers consist largely of fractured rock (> 90%) which can serve as conduits while rock matrices serve as storage reservoirs for water and pollutants. This paper includes methods to assess the seepage of pollutants into the subsurface aquifers. These include a risk based approach and mathematical modeling to determine the possible impact on groundwater systems.

Key words: *groundwater, risk assessment methodology, tailings dam.*

1. Introduction

Mining activities have played a significant role in the economic development of South Africa [8]. Since the 1960's, the possible environmental impacts of mining has grown increasingly controversial, to the point that environmental objections are often an obstacle to the development of new mines [6]. A major cause of concern is the impact of tailings dams on the environment, and in the case of this paper, the impacts of tailings dams on the groundwater system.

[#] ***Corresponding author:*** *steylg.sci@ufs.ac.za*

Tailings dams can consist of a variety of environmentally toxic chemical species (i.e., cyanides, chlorides, nitrates and sulphates) which can form a source of groundwater pollution. The construction of the tailings dam also plays a significant role in the rate by which the pollutants reach the groundwater system. The chemical and physical properties of the tailings can also affect the scope of the pollution in these subsurface regions. The impact of the pollution can be magnified by the nature of the aquifer systems underlying these tailings dams. The geological composition of South Africa's aquifer systems consist largely of fractured rock (> 90%), which can increase the transport rate of pollutants in the local region.

South African law requires that a long-term groundwater management and monitoring plan must be compiled in order to achieve the environmental goals as set out in the National Water Act of 1998 and must be complaint with the Mineral and petroleum resources development amendment bill. In this regard, the assessment of tailings dams on the groundwater reservoirs will be discussed. In this paper special reference will be made to the procedure of South African groundwater management, mining conditions and assessment strategies.

2. Groundwater in South Africa

Up until 1977 groundwater management fell in South Africa under the Groundwater Division of the Geological Survey. In this time groundwater was regarded as a 'mineral'. Only after the establishment of the Directorate for Geohydrology at the Department of Water Affairs and Forestry did the focus of groundwater as a potential water resource increase. The Water Act of 1956 regarded groundwater as privately owned water and management and usage was uncontrolled. The introduction of the National Water Act in 1998 reflected the start of a new era in the management and protection of groundwater [4]. The most significant change was that groundwater was no longer classified as privately owned but rather owned by the state [2].

South African groundwater conditions are, however, complicated because of the nature of the aquifers. The aquifers are often multi-layered, multi-porous and fractured. Fractures often serve as conduits for the movement of water and pollutants, while the rock matrices act as a storage facility for the respective components. This behaviour is further compounded due to the arid nature of large parts of South Africa, with an average groundwater recharge ranging from 0,22 – 0,0001 m per annum [7]. In addition the scarcity of surface water causes small towns and settlements to rely largely on groundwater sources for potable water.

3. Mining impact on groundwater resources

There are very little, if any, mining activities that do not have an impact on groundwater in some way. The impacts vary with the different stages of mining, i.e.

- Operational phase: Dewatering of a mining area, groundwater exploitation for use in the mining operations, construction of tailings dams and waste rock dumps which can pollute the underlying groundwater system.

- Closure and post-closure phases: Flooding and decanting of mines, acid water drainage and associated water quality problems. The impact of waste facilities should also be included due to drainage into the groundwater system.

Until the early 20th century, virtually all tailings were simply released in the closest watercourse. Where mining continued for a number of years this could sometimes lead to surface water features such as rivers, dams and even estuaries becoming clogged with tailings. This in turn had a devastating impact on the riparian zone and as such prompted the development of alternative tailings disposal methods. By the 1940's the sedimentation dams, also known as tailings dams were becoming common practice in the mining industry world-wide [6], although this practice has been used in South Africa from the outset of gold mining on the Witwatersrand.

Though tailings dam failures are amongst the most spectacular causes of pollution, they are not the most common or widespread. The alteration of regional water flow patterns (as a tailings dam can form a recharge point) and pollution thereof is far more common. A typical example is the re-vegetation of tailings dams to reduce surface erosion and stabilization of the topsoil in these dams. This rehabilitation however does not reduce the leaching of contaminants into the groundwater system or surface environment.

The tailings dam design and the nature of the tailings plays a large role in the impact of the tailings dam on the groundwater system. These effects can be summarized into the following main groups:

- The inclusion of a lining beneath the dam.
- The long-term rehabilitation plan of the tailings dam.
- The chemical and physical properties of the tailings.
- The water level in the tailings dam.
- The hydraulic conductivity of the tailings dam. Tailings are predominantly fine-grained with a grain size of less than 1 mm. The hydraulic conductivity often falls into the same range as those of clay and silt ($1 \times 10^{-8} - 1 \times 10^{-3}$ m/d). Tailings conductivities generally range from $1 \times 10^{-1} - 1 \times 10^{-5}$ m/d.

The magnitude of the groundwater related issues is not only related to the design of the tailings dam and types of tailings but also to the nature of the subsurface. These effects can be assigned to different parameters which influence the groundwater system:

- Recharge, directly from precipitation or artificially *via* the tailings dam aids in the movement of pollutants and dilution.
- The consolidated, unconsolidated or karst rock matrices that serve as water-bearing units. The fractures that occur in the rock matrix must also be taken into account.
- The unsaturated zone which is the portion of the rock matrices which occurs between the base of the tailings dam and the groundwater (piezometric) level [1]. All infiltrating water must pass through this zone before it reaches the groundwater system. The deeper the groundwater

level the less chance it has of being polluted due to attenuation of possible pollutants by means of chemical reactions, dilution etc. In many cases a freatic water level develops underneath the tailings dams if it is in operation for many years and a confined layer is present between the groundwater level and the original ground surface.

- The hydraulic conductivity of all subsurface media has a direct influence on the rate at which water and associated pollutants can transverse the aquifer.

Examples of related hydraulic conductivity effects include:

- When water moves through the tailings dam, the rate at which it moves is depended on the water level in the dam and the hydraulic conductivity of the tailings. If the hydraulic conductivity is too low then the water might not be able to drain through the system fast enough, causing seepage along the banks of the tailings dam, see Figure 1. This is exacerbated by anisotropic hydraulic conductivity, often 2 to 10 times greater in the horizontal direction than the vertical owing to the layering arising from the deposition practice. If a lower hydraulic conductivity layer is overlain by a higher conductivity layer, seepage can occur at the contact of these two layers (see Figure 1).

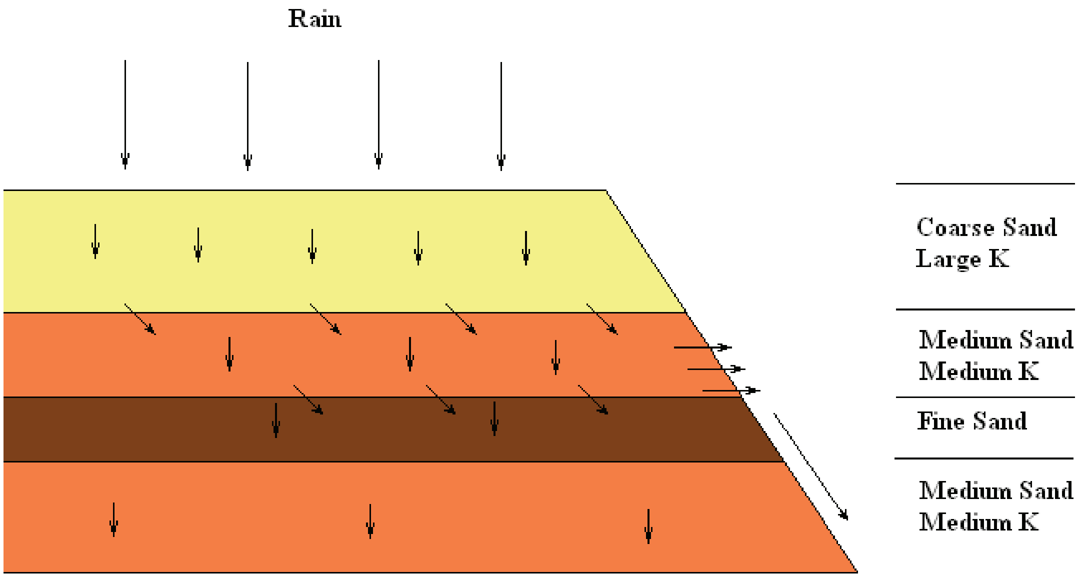

Fig. 1. Seepage due to different hydraulic conductivities (K) in a tailings dam

- Marshes can occur in the vicinity of a tailings dam if the underlying soil and rock media have a very low hydraulic conductivity when compared to that of the tailings dam. Seepage at the toe of tailings dams is also a consequence of low hydraulic conductivity below the dam. An example of this is shown in Figure 2. The water collected in the marsh can contain high levels of dissolved solids and other polluted species.

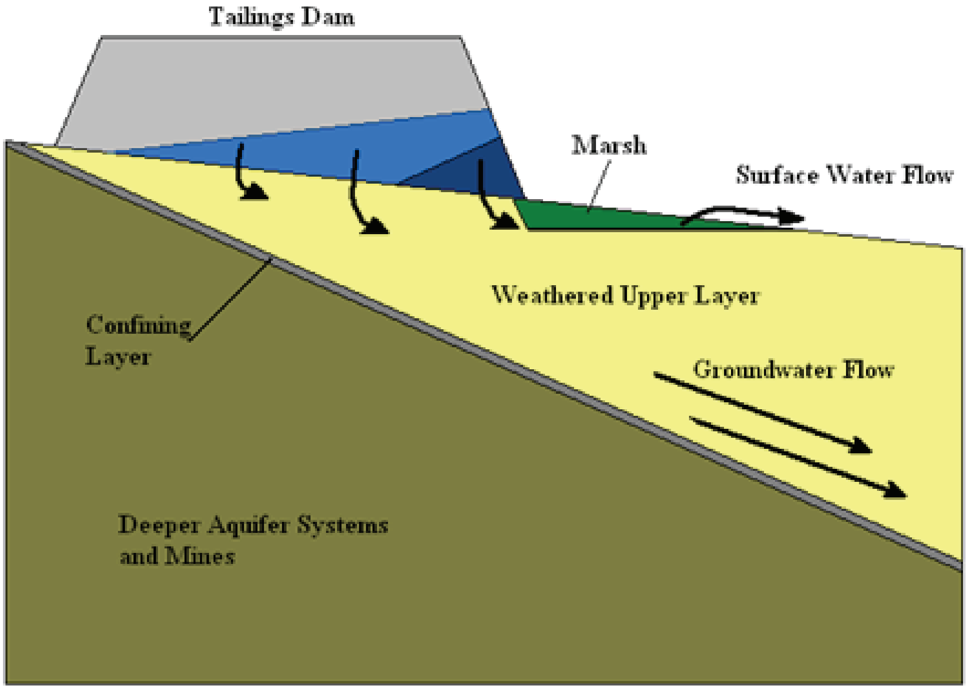

Fig. 2. Diagram showing the effect of drainage water from a tailings dam into the subsurface layer, water rises to the surface creating a marshy area

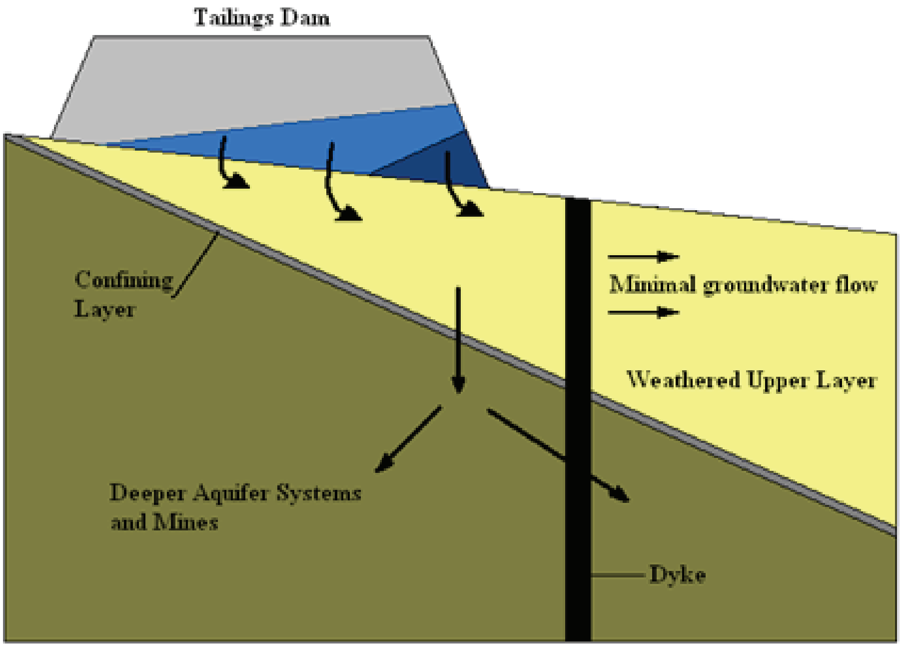

Fig. 3. Effect of a dyke on the water drainage from a tailings dam. Waste water penetrates the confining layer to seep through to deeper aquifer systems or mines

- Groundwater levels in the vicinity of tailings dam can also increase if there is a barrier such as a dyke in the vicinity of the tailings dam and the water seeping into the groundwater system is at a faster rate than the movement of the groundwater see Figure 3. In this scenario water can flow either into deeper aquifer systems or redirect into mining operations flooding the mining area with contaminated water.
- Some gold tailings dams with high pyrite content develop an impermeable thin layer with an extremely low infiltration rate of < 0,05 m/d comparing to others with an infiltration rate of > 0,24 m/d [5]. In the case of other tailings dams the infiltration rate could be as high as 0,5 m/d.

4. Methods to assess the impact of tailings dams on groundwater systems

In order for a mine to obtain a mining license, an environmental impact study has to be performed on the area. The most important step in this assessment is site characterization. Site characterization can be seen as the process whereby all relevant data concerning the site and the problem at hand is collected and interpreted to form a conceptual model. The following questions must be addressed during site characterization:

- What is the spatial extend and height of the tailings dam?
- What is the piezometric level in the tailings dam?
- What are the composition, size and hydraulic conductivity of the tailings?
- Is the tailings dam lined, if so what are the properties of the lining?
- Is the tailings dam capped, if so what are the properties of the capping?
- What are the properties (including hydraulic conductivity) and thickness of the unsaturated zones?
- What is the piezometric level of the groundwater system?
- What is the hydraulic conductivity of the groundwater system?
- Are there any aquifer boundaries and, if so, what type of boundaries?
- Is there any groundwater abstraction is the vicinity of the site?
- What is the natural groundwater recharge?

Once this information is available then a conceptual model for the site can be developed. The conceptual model forms the basis for understanding groundwater related problems. It is important at this point to highlight the effect of data shortages in the conceptual model and gathering of data if it is needed to complete the analysis framework. Once all required data have been collected the conceptual model can be refined and assessments made.

There are numerous tools available for assessing the impact of a tailings dam on the groundwater system. Two of the most widely used tools Risk assessments and Mathematical models.

Firstly, a risk can be defined broadly as the probability that an adverse event will occur in specified circumstances. There are numerous commercial risk assessment packages such as Risk Workbench that can be used to perform groundwater related risks. However, the Institute for

Groundwater Studies at the University of the Free State has developed a fuzzy logic based risk assessment tool (South African Groundwater Decision Tool - SAGDT) that can be used to determine the impacts of mining including tailings dams on the groundwater system [3]. This freeware can be obtained from the Department of Water Affairs and Forestry at the following website: www.usersupport.co.za.

The main usage of this software is to include pre-selected weights into the system for specific hydrogeological parameters which can then be evaluated to determine the risk factor to the groundwater system.

Secondly, mathematical models are generally divided into analytical and numerical models. There are many analytical models based on Darcy's Law that can be used to determine seepage of water and associated pollutants; however these models are usually idealized and empirical in nature. MODFLOW is one of the most-used numerical models to simulate the impacts of tailings on the groundwater system. If the conceptual model is correct, the results of the assessments based on this modeling package are usually of a high quality, however there are major assumptions that are usually overlooked when using this package.

i. It assumes that the tailings dam and the groundwater system are directly connected, since MODFLOW only takes into account saturated flow conditions.

ii. In order to simulate the unsaturated flow more accurately numerical model software such as FEFLOW should be considered.

iii. Many of the models developed are for porous flow conditions and therefore the simulation of fracture zones is quite difficult or impossible in some cases.

iv. Similarly there are many assumptions on which the mass transport models are based. These assumptions are usually neglected and this can cause some serious errors in the results obtained if the movement of pollution is considered.

A vital step in determining the correctness of the evaluation process is the calibration of the data which can include further site monitoring processes, updating and review of simulation results. The Risk Assessment and Mathematical Models should be rerun after each evaluation cycle, calibrated and verified against field data. Once this iterative process is completed can a risk assessment be made on the groundwater system.

5. Conclusions

The construction, composition, conductivity and water management of the tailings dam play a large role in assessing the potential impacts on the groundwater systems and therefore quantitative impacts are very site specific. There are numerous tools available for assessing the impact of a tailings dam on the groundwater system, the most popular methods are Risk Assessments and Mathematical Models.

Wherever new tailings dams are built, one should determine the hydraulic conductivity of the soil and rock material at the proposed footprint and the tailings material by means of simulations and laboratory assessments rather than by predicting from geotechnical models. This information together with the operational design of the tailings dams, one should be able to predict the potential pollution effects on the groundwater and regional area.

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