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TECHNICAL ARTICLE

Estimating the Decant Rate from a Rehabilitated Opencast Colliery Using a Water Balance Approach

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Abstract The long-term average decant rates from rehabilitated opencast collieries in South Africa are often estimated by assuming effective recharge rates through the spoils. However, large uncertainties are associated with these assumed recharge rates. Furthermore, this approach assumes that groundwater inflows and pit water outflows are negligible compared to the volumes of water recharged through the spoils. To obtain an estimate of the decant rate at a particular colliery, I used rainfall figures, pumping rates, and water elevations measured over a period of 6 months as well as estimated evaporation rates to construct a water balance. I then calculated a decant rate, independent of assumed recharge rates, that was significantly higher than a previous long-term estimate, despite the lower than average rainfall experienced during these 6 months. This discrepancy suggested that groundwater inflow was indeed contributing to the decant volumes. The decant rate during years of average rainfall was subsequently calculated by adding the estimated groundwater inflow to the recharge volumes found with the method based on assumed recharge. This decant rate was approximately 49 % greater than a previous estimate obtained by assuming negligible groundwater inflow. This study shows that the decant rates at rehabilitated opencast collieries could be significantly underestimated if the decants are assumed to be recharge-driven without considering the possibility of groundwater inflow. Underestimation of the decant rates will lead to flawed water management strategies, which could result in adverse environmental impacts.

Keywords Effective recharge · Groundwater inflow · Salt balance

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Introduction

Pit water overflowing (decanting) from rehabilitated opencast collieries can pose a serious threat to the environment. This water typically has a high concentration of total dissolved solids, and often has a low pH due to the formation of acid mine drainage (AMD) from the oxidation of pyrite in the discarded rock material (spoils). The interaction of acidic water with the spoils in the pit can also mobilize trace metals, which may cause the water to acquire acute and chronic toxicity to both human users and the environment (Coetzee et al. 2006). Furthermore, AMD production may continue for many centuries after mining ceases (Younger 1997).

The National Water Act (NWA) (Act 36 of 1998) is the principal statute providing the legal basis for water management in South Africa (DWAF 2008). Water use for mining and related activities is controlled through regulations that were updated after the promulgation of the NWA (Government Notice GN704 of 1999). Between 2006 and 2008, the Department of Water Affairs and Forestry (DWAF) issued several separate documents, which together constitute the *Best Practice Guidelines (BPGs) for Water Resource Protection in the South African Mining Industry*. The BPGs for surface mines are described in *Guideline A5—Water Management for Surface Mines* (DWAF 2008). The BPGs are not regulatory, and only serve as guidelines to the mining sector on issues related to the use and management of mine water. According to the BPGs, mine management is expected to ensure that the potential future impacts from a mine have been identified and are addressed in the closure plan and the closure financial provisions. A further requirement is that a post-closure water management plan be developed that addresses the likelihood and positions of future decants, as well as the possible impacts of such decants on receiving water bodies. Mine management is also expected to consider possible post-closure uses of the decanting pit water.

The BPGs advise mine management to obtain estimates of the expected volumes and qualities of decanting water. However, specific methods for the estimation of decant volumes are not stipulated. Often the long-term average decant rates at opencast collieries of South Africa are estimated by using an approach based on assumed effective rates of rainfall recharge through the spoils of the backfilled pits. Although some authors (e.g. van Tonder et al. 2003) have included lateral groundwater inflow when using this approach, most often the decant volumes at opencast collieries are assumed to be primarily due to rainfall seeping through the spoils and runoff reaching the pits. The contributions from seepage and runoff are usually considered together as a single parameter, the *effective recharge*, expressed as a percentage of the mean annual precipitation (MAP). This method is referred to as the *%RF approach* in this paper.

During 2012, I investigated the decant rate at a rehabilitated colliery in the Mpumalanga Province of South Africa. A previous estimate obtained with the %RF approach had put the long-term average decant rate at approximately 4 megalitres per day (ML/day) (Hodgson 2009). For this estimate, an effective recharge rate of 20 % of the MAP had been assumed. However, considering the fact that, to prevent decant, approximately 20 ML of pit water was daily recycled through a recirculation system, mine management felt that the estimate was too low and required an independent estimate of the decant rate that was not based on the %RF approach. For this independent estimate, I used the water balance approach described in this paper.

Description of the %RF Approach

The elements that may contribute to the water balance of a rehabilitated opencast pit are shown in Fig. 1. Pre-mining, the natural groundwater level is not horizontal, unless conditions of zero groundwater flow occur. After mining and rehabilitation, a horizontal water level exists in the pits due to the high permeability of the backfilled spoils. This water level corresponds to the decant level, i.e. the level at which the surface of the water in the pit intersects the ground surface. Inflows to the pit consist of the effective recharge (*Re*) through the spoils and groundwater inflows (GW_{In}). The latter term may consist of inflow from the geological units below the decant level [marked (a) in Fig. 1], as well as seepage through the boundary between the saturated geological units and the unsaturated spoils [the *seepage face*, marked (b) in Fig. 1]. Outflows from the pits comprise the decant and pit water outflows (PW_{Out}) to the surrounding geology.

The %RF approach is based on the assumption that the groundwater inflows and pit water outflows through the surrounding geology are negligibly small compared to the volumes of water entering the pit in the form of effective recharge through the spoils. The basis of this assumption is that the geological units in which the coal seams of Mpumalanga occur are known to have low permeabilities (Hodgson and Krantz 1998). The %RF approach furthermore assumes that the volume of groundwater entering the pit along secondary features such as faults, fractures, joints, and dykes, remains negligible compared to the effective recharge (Grobbelaar et al. 2004; Hodgson and Krantz 1998). With these assumptions, it follows that the decant volumes are approximately equal to the volumes recharged through the spoils.

Although recharge estimation in surface mining environments is difficult and associated with large uncertainties (NRC 1990), various authors have estimated the percentage of the rainfall recharged through the spoils at South African opencast collieries. In a mine water simulation model developed by Wilkens and van Niekerk (1993), the authors used different values for unrehabilitated spoils (15 %), topsoiled and seeded spoils (8 %), and rehabilitated spoils (5 %). However, the authors provided no justification for these estimates.

In a report to the Water Research Commission, Hodgson and Krantz (1998) estimated the effective recharge percentage through rehabilitated spoils from observations made at nine opencast collieries in Mpumalanga Province. Their results indicated recharge rates of 10–25 %. The authors suggested using an average value of 18 % for future estimates at rehabilitated collieries. However, in the same report, the authors concluded that the effective recharge at opencast collieries averages 20 % of the MAP. Of this recharge, 12 % was attributed to runoff reaching the pits and 8 % to seepage through the spoils. Several authors have since based their recharge calculations on these values, including: Annandale et al. (2007), du Plessis (2010), Grobbelaar et al. (2004), Hough (2003), Lukas and Vermeulen (2014), Usher (2003), Usher and Vermeulen (2006), Vermeulen (2003, 2006), Vermeulen and Usher (2006a).

Three years after the 1998 report, Hodgson (2001) used slightly different values for the contributions from runoff

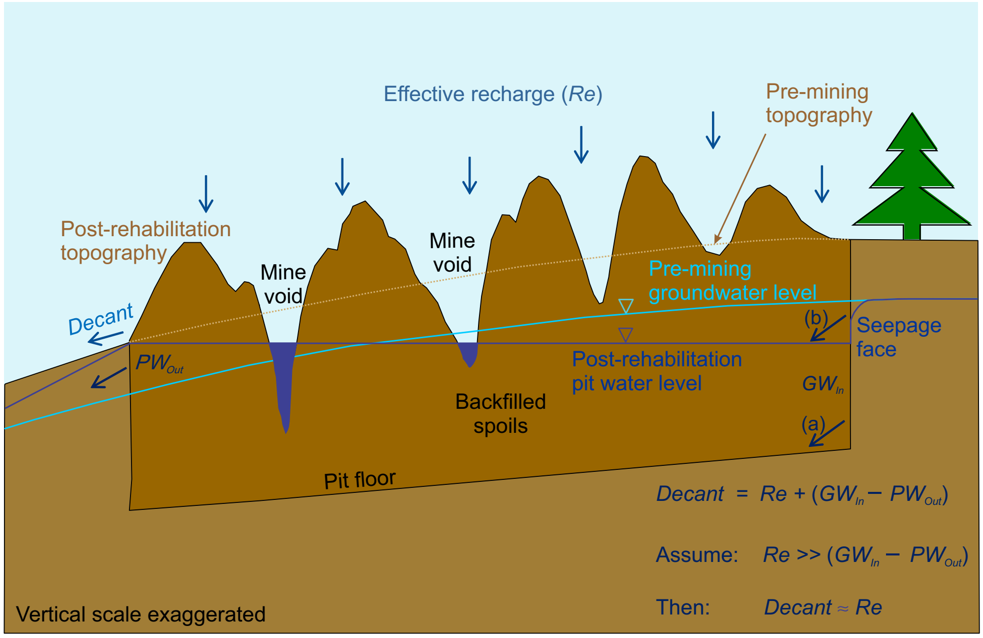

Fig. 1 Elements of the water balance of a rehabilitated opencast colliery. GW_{In} represents all groundwater inflows to the pit, while PW_{Out} represents all pit water outflows through the subsurface

(14 %) and seepage (6 %) at another opencast colliery. Havenga (2002), Hodgson et al. (2007), and Vermeulen and Usher (2006b) used effective recharge rates of 14-20 % in their investigations of inter-mine flows and decant volumes. Van Tonder et al. (2003) used a recharge rate of 17 % to predict decant volumes from an opencast coal mine. Vermaak et al. (2004) reported recharge percentages through soil covers of rehabilitated spoils that ranged between 12 and 20 %. This range was also used by Coleman et al. (2014) in their investigation into the potential use of mine water for urban supply. Repinga (2010) employed a recharge rate of 15 % without further explanation.

The assumptions on which the %RF approach is based have important implications. Since the contribution of groundwater inflow to the pit water is assumed to be negligible, the residence time of groundwater within the aquifers surrounding the pits is immaterial. Only the residence time of rainwater within the topsoil covering the spoils and within the spoils is relevant. Due to their high permeabilities, very short residence times are expected within the spoils (Moustafa 2014). The thickness, permeability, and moisture content of the topsoil cover are therefore likely to be the determining factors when considering the delays between rainfall events and the resulting increases in the volumes of pit water. These delays are less than 24 h at the rehabilitated opencast colliery investigated in this paper (personal communication, mine manager).

The recharge rates proposed by Hodgson and Krantz (1998) were derived from long-term observations at opencast collieries in the Mpumalanga Province. These recharge rates are therefore only applicable when estimating long-term average decant rates at collieries in this province. Recharge through the spoils during and after an individual rainfall event will depend on a number of factors, including the intensity and duration of the rainfall, the humidity, and the moisture content of the topsoil cover prior to the rainfall event. The %RF approach is not concerned with these distinct factors, but only considers the long-term average contribution of rainfall to the pit water volumes.

Site Information

Location and Climate

The colliery is located in the Mpumalanga Province of South Africa. It occurs within the Eastern Highveld, in a summer rainfall region. Rain occurs as mild to heavy showers and thunderstorms. The highest rainfall normally occurs between the months of November and January (Midgley et al. 1994), while the winter months (May to August) are usually dry. Sleet may occur during cold spells, but the occurrence is rare and the falls are usually light. The mean monthly rainfall figures recorded at a rain gauge at the colliery between 1981 and 2010 are listed in

Table 1. The mean annual rainfall amounts to 649 mm. The rainfall figures recorded during the first 6 months of 2012, when this investigation was conducted, were below average (Table 1).

The mean monthly Symon's Pan evaporation figures for the study area are listed in Table 2. These figures represent water losses due to evaporation from an open pan with a surface area of 0.56 m^2 (6 ft^2) and a depth of 0.61 m (24 in.), sunk into the ground. The corresponding lake evaporation figures, calculated by multiplying the Symon's Pan values by the appropriate pan factors (Haarhoff and Cassa 2009; Midgley et al. 1994; Pretorius 2011), are also listed in this table. The mean annual evaporation (MAE) from lakes (open water bodies) amounts to 1256 mm (Midgley et al. 1994). This value is significantly higher than the mean annual rainfall. Large evaporation losses can therefore be expected from open water bodies at the colliery.

Table 1 Rainfall recorded at a rain gauge at the colliery, January to June 2012

Month	Rainfall (mm)	
	Mean (1981–2010)	January–June 2012
January	106	98
February	78	59
March	72	64
April	33	11
May	8	0
June	10	0
July	3	–
August	11	–
September	23	–
October	84	–
November	105	–
December	116	–
Total	649	232

– No measurement

Table 2 Mean monthly Symon's Pan evaporation figures and corresponding lake evaporation figures

Month	Symon's Pan evaporation (mm)	Pan factor	Lake evaporation (mm)
January	164	0.84	138
February	140	0.88	123
March	135	0.88	119
April	104	0.88	92
May	86	0.87	75
June	67	0.85	57
July	78	0.83	65
August	108	0.81	87
September	137	0.81	111
October	155	0.81	126
November	150	0.82	123
December	170	0.83	141
Total	1494		1256

Geological Setting

The colliery is located within the Witbank Coalfield. The geology in the colliery area is dominated by rocks belonging to the Ecca Formation of the Karoo Supergroup. These rocks predominantly consist of various shales (including carbonaceous shales), sandstones, conglomerates, and coal layers. The southern and northern boundaries of the opencast pits run approximately parallel to exposures of volcanic rocks of the Pretoria Group of the Transvaal Supergroup. These exposures occur at positions where the major rivers have eroded away the overlying Karoo rocks and coal seams. The volcanic rocks are predominantly red rhyolites with some andesites. Drilling results and geophysical investigations have revealed the presence of dolerite structures in the vicinity of the opencast pits. Minor faults, displacing the coal seams by 1 or 2 m, were encountered during mining.

The weathered zone consists of varying proportions of topsoil, subsoil, clay, and silty sands, with the nature of this zone depending largely on the original lithology. Clays are thought to be derived from weathered shales and siltstones, while the more sandy materials are most probably due to the weathering of sandstones. The topsoil is typically a well-developed loamy soil horizon and may have a considerable thickness (>6 m).

Hydrological and Geohydrological Setting

The colliery is situated near the lowest point of a quaternary sub-catchment (unnamed, for reasons of confidentiality), close to the confluence of the river systems draining the sub-catchment. As such, the colliery is located at a surface elevation that is lower than 78 % of the sub-catchment. This implies that groundwater recharge within most of the sub-catchment is likely to be associated with hydraulic heads greater than the elevation of the colliery. The surface area of the sub-catchment is approximately 1066 km^2, while a first estimate of the average annual recharge within the sub-catchment is 52 mm (8 % of the MAP) (Midgley et al. 1994). The above figures translate into an average daily recharge volume of 152 ML. Groundwater is expected to flow according to the regional hydraulic gradient towards the lower parts of the sub-catchment and the colliery.

Three distinct aquifer systems have been identified in the colliery's catchment, namely the weathered Ecca aquifer, fractured aquifers within the unweathered Ecca rocks, and pre-Karoo aquifers (Hodgson and Krantz 1998). The aquifers in the weathered Ecca formations are typically perched and low-yielding (100–2000 L/h). The pores of the unweathered Ecca rocks are usually well cemented, allowing only limited groundwater flow through the rock matrix. Groundwater migration predominantly takes place along secondary structures, such as joints, fractures, and faults (Hodgson and Krantz 1998). The pre-Karoo aquifers occur below the depths of coal mining, and are rarely exploited due to their depth, low yield, and inferior water quality.

Dolerite intrusives in the Karoo are generally associated with host rock alteration. Due to the high pressures and temperatures that occurred during intrusion, the sedimentary rocks adjacent to the intrusives are often extensively fractured (Botha et al. 1998). These fractured zones may act as preferential pathways for groundwater migration. The dolerite intrusives themselves may act as aquifers if they are extensively jointed and fractured.

Mining History

Opencast mining at the colliery commenced in the early 1970s and continued until 1992. Production took place from two main opencast pits, here referred to as Pits A and B (the latter consisting of two smaller pits, Pits B1 and B2). The No.1 and No.2 coal seams of the Witbank Coalfield were mined and the floors of the opencast pits at the colliery roughly correspond to the depths at which the bottom contact of the No. 2 seam was encountered (<35 m below surface). During mining, spoils were used to backfill the mined-out parts of the pits. When mining ceased, the pits were rehabilitated by sloping the spoils and covering them with topsoil. The topsoil was subsequently seeded with indigenous grass species. The footprint of the three rehabilitated pits totals approximately 10.57 km^2.

Materials and Methods

I studied the water recirculation system at the colliery as well as the groundwater and pit water levels to gain an understanding of the hydraulic gradients driving flows in and around the pits. From this data, I developed a conceptual model of the pits and surrounding geology that was consistent with the observed water levels.

An estimate of the decant rate, independent of assumed recharge rates, was obtained for the 6-month period from January to June 2012 during which the investigation was conducted. This decant rate was estimated by constructing a water balance for the colliery, using information on measured quantities (rainfall data, pumping rates, and pit water levels) and estimated quantities (evaporation losses from open water bodies). A rain gauge at the colliery provided daily rainfall figures. During this period, the colliery was operating a water recirculation system within one of its pits to maintain the pit water level below the decant level. Daily measurements of the volumes of water pumped between various voids in the pit, as well as the water levels in the voids, were recorded. I estimated the evaporation losses from the open water bodies at the colliery by using the lake evaporation figures for the area (Table 2).

The results of the decant estimation for the period January to June 2012 indicated that groundwater inflow to the pit constituted a significant component of the decant volumes at the colliery. Estimates of the daily volumes of groundwater inflow and pit water outflow were obtained by assuming an effective recharge rate for the period January to June 2012, and by applying Darcy's law using the observed hydraulic gradients and estimated hydraulic properties of the geological units surrounding the pits. Since below-average rainfall was recorded during these 6 months, I had to adjust the decant rate estimated with the water balance approach upwards to correspond to years of average rainfall. For this adjustment, I was again obliged to make assumptions regarding the recharge rate through the spoils.

The large groundwater component of the decant suggested that the pits were intersected by preferential pathways for groundwater migration. Since dolerite intrusives are known to occur in the vicinity of the pits, and since these intrusives are often associated with preferential flow paths, I conducted a magnetic survey in selected areas along the boundaries of the pits to investigate the presence of such intrusives. Measurements of the total magnetic field of the earth showed prominent anomalies, indicating the presence of magnetic bodies in the subsurface. Boreholes sited on these anomalies confirmed the presence of a dolerite dyke intersecting one of the pits. Groundwater level measurements in the boreholes on the dyke revealed a large hydraulic gradient that could drive flows along the dyke towards the pit.

Based on the results of the water balance, I constructed salt and sulphate balances for the colliery and compared my prediction for the rate of sulphate generation within the pits with previous estimates obtained by different authors for sulphate generation at South African collieries.

Water Recirculation at the Colliery

As part of the water management strategy at the colliery, a water recirculation system is operated within Pit A, in which a number of voids were left after mining and

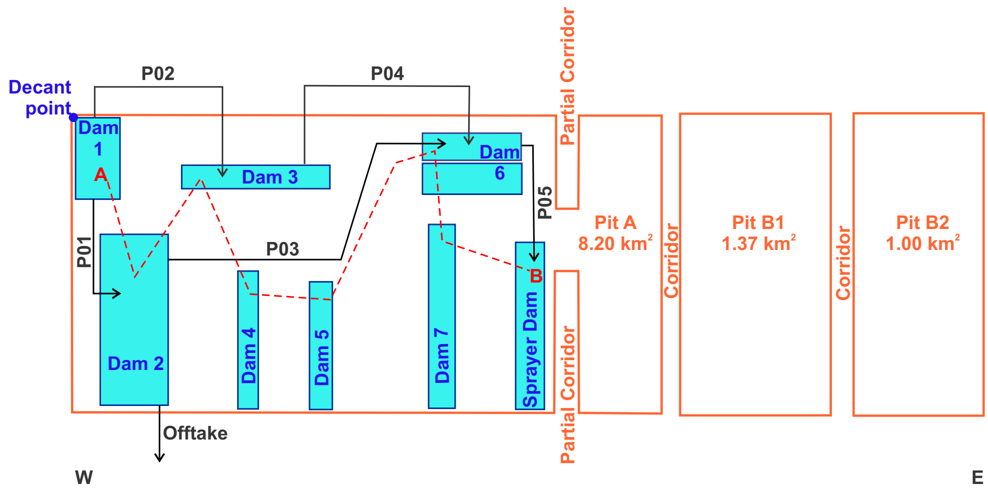

Fig. 2 Schematic plan view of the colliery showing the current water recirculation system within Pit A. The pumps forming part of the recirculation system are numbered P01 to P05. Water pumped to a nearby colliery is referred to as the *offtake*. Line A–B represents a trace through the dams of Pit A, used to evaluate the water levels in these dams

rehabilitation. The water recirculation system is shown schematically in plan view in Fig. 2. In accordance with the terminology used at the mine, the voids in the pit are referred to as *dams*. Also shown in Fig. 2 is the position of a trace (A–B) crisscrossing the pit, connecting all the dams within the pit. A cross-sectional view through the pit along this trace is presented in Fig. 3.

The purpose of the water recirculation system is to maintain the water level of Dam 1 below the decant level. Water is circulated through the spoils by pumping from Dam 1 to Dams 2 and 3. From these dams, water is pumped to Dam 6, from where it is pumped to 20 mist sprayers still further east, away from the decant point. The sprayers are used to increase evaporation losses during irrigation of the spoils. The ponded water near the sprayers is referred to as the *Sprayer Dam*. In addition, water is abstracted from Dam 2 and pumped to a nearby colliery to be used as process water (this water is referred to as the *offtake*). The pumps used for water recirculation are numbered P01 to P05 in Figs. 2 and 3. During the period of this investigation, an average of 19.87 ML/day was pumped from Dam 1, while the offtake averaged 0.96 ML/day.

Water Levels in Boreholes Within and Surrounding the Pits

During June 2012, I measured the pit water levels in boreholes within the three pits as well as the groundwater levels in monitoring boreholes surrounding the pits (Fig. 4). The horizontal axis of the graph represents the distance from the decant point, as measured along a west-east trace through the pits. The positions of the boreholes are simply projected perpendicularly onto this trace; no account is taken of the distances between the groundwater boreholes and the pits.

It is clear from Fig. 4 that the pit water elevation exceeds the groundwater elevation along most of the length of the trace through the pits. Only towards the eastern parts of Pit B2 is the groundwater elevation greater than the pit water elevation. Groundwater inflow can therefore be expected along the eastern parts of this pit (Fig. 1), while pit water outflow into the surrounding geology is likely to occur through the walls of Pits A and B1, and the western parts of Pit B2.

The water levels shown in Fig. 3 are the levels during January 2012 when the mine had a digital terrain model (DTM) compiled for the rehabilitated pits and surrounding areas. From Fig. 3, a number of observations may be made regarding the water levels in the dams of Pit A:

1. The water level of Dam 1 was well below the decant level when the DTM was compiled. This dam has a storage capacity of only 71.8 ML. Considering that approximately 20 ML/day was pumped from this dam to Dams 2 and 3 at the time of the DTM, the low water level is to be expected.
2. The water levels in Dams 3, 6, and the Sprayer Dam were well above the decant level. These dams all receive water, directly or indirectly, from Dam 1. The Sprayer Dam had a water level more than 17 m above the decant level. The existence of this perched dam shows that the permeability of the topsoil used during rehabilitation of the backfilled pits is low enough to allow ponding of the irrigated water.
3. The water level in Dam 5 was slightly higher than the decant level. This elevated water level is

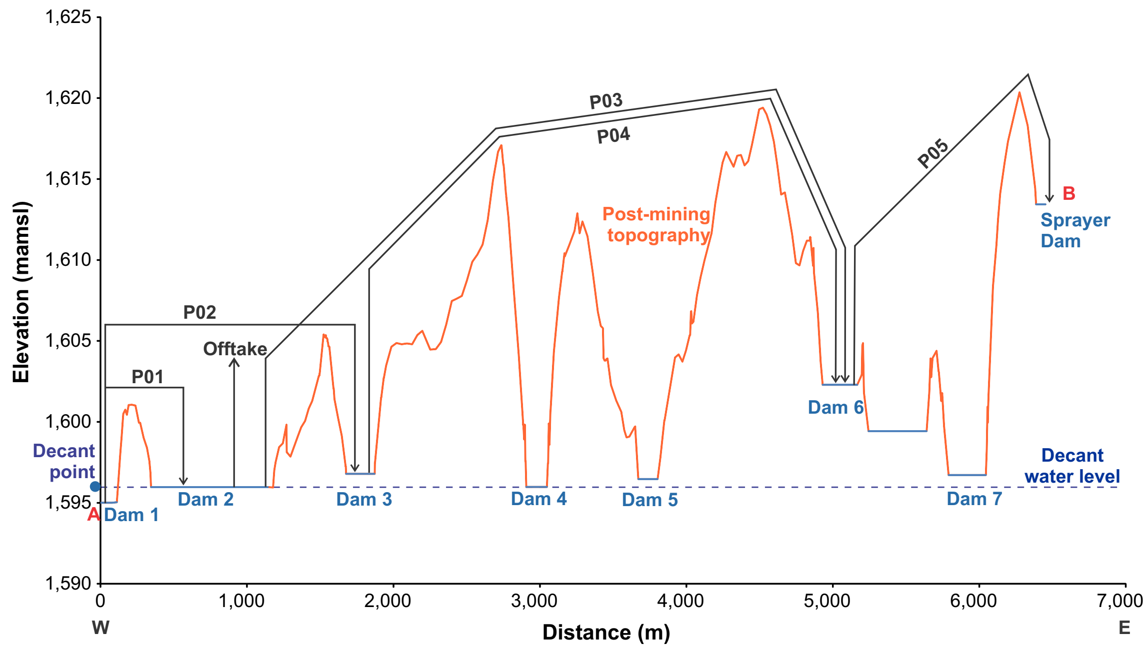

Fig. 3 Cross-sectional view of Pit A along trace A–B through the dams within the pit. Elevations are shown in metres above mean sea level (mamsl). The pumps forming part of the recirculation system are numbered P01 to P05. Water pumped to a nearby colliery is referred to as the *offtake*

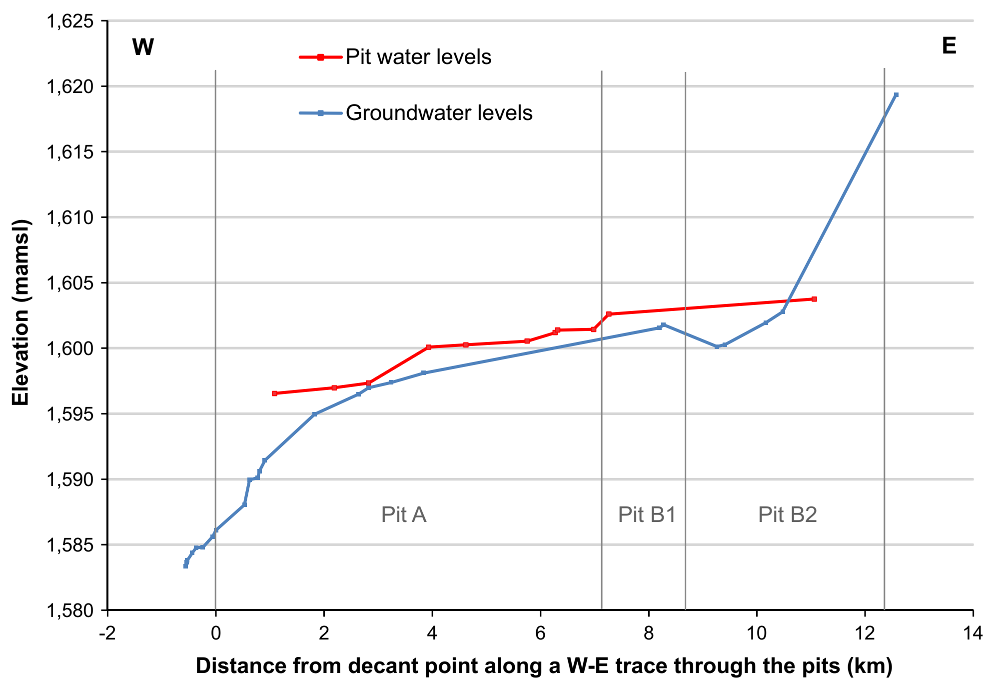

Fig. 4 Water level elevations measured in boreholes within the pits and the surrounding geology

unexpected since Dam 5 is located more than 800 m from Dam 6. Due to the high permeability of spoils, water from Dam 6 is expected to seep vertically downwards with very little lateral movement. It is therefore highly unlikely that seepage from Dam 6 was responsible for the raised water level in Dam 5. This suggests that Pit A is compartmentalised, and that each compartment has its own decant level.

4. The water level in Dam 7 was also above the decant level, again pointing towards compartmentalisation of Pit A.

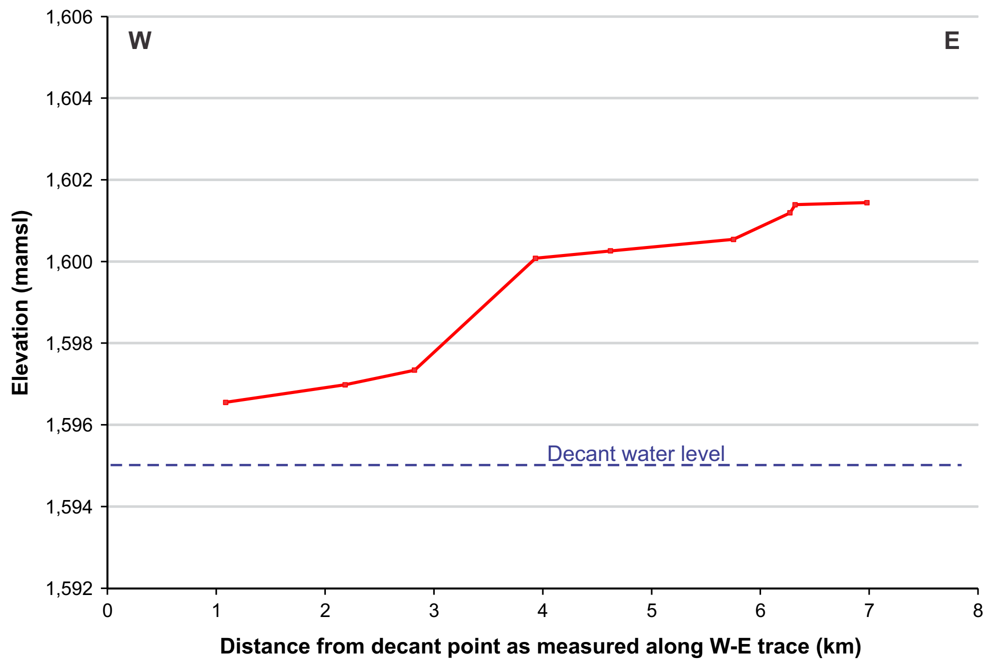

Fig. 5 Water elevations measured in boreholes within Pit A

The notion that Pit A is compartmentalised is supported by the water elevations measured in the boreholes within Pit A (Fig. 5). Water elevations above the decant level were measured in all of the boreholes, with an increase in the water elevation towards the east, away from the decant point. The compartmentalisation of Pit A was also mentioned in a note to the mine manager (dated Sept. 1998), in which it was explained that the coal hauling ramps formed impermeable boundaries to in-pit water flow.

Decant Estimation with a Water Balance Approach

A water balance for the period January to June 2012 can be constructed for the colliery by considering all water contributions to the system (inflows) and all water losses from the system (outflows). If the sum of the inflows exceeds the sum of the outflows, decant will occur:

$$\begin{aligned} Decant &= Inflows - Outflows \\ &= (Re_D + Re_S + Ro_D + GW_{In}) \\ &\quad - (Ev_D + Ev_S + Ev_{Spr} + PW_{Out}) \end{aligned} \tag{1}$$

where Re_D is the direct recharge to the system from rainfall on the dams; Re_S is the recharge to the system from rainfall percolating through the spoils; Ro_D is the surface runoff from the spoils reaching the dams; GW_{In} is the groundwater inflows to the system; Ev_D is the evaporation from the dams; Ev_S includes the evaporation from the spoils and topsoil, as well as the evapotranspiration from the vegetation planted during rehabilitation; Ev_{Spr} is the evaporation losses at the sprayers, and; PW_{Out} is the pit water outflows from the system.

Since the decant is the volume of water that would flow from the pits if no water management were done, this volume may also be calculated as the volume of water actively removed from the system by the mine, plus the change in water storage within the pits that occurs as a results of the water recirculation:

$$Decant = OT + Ev_{Spr} + \Delta S \tag{2}$$

where OT is the offtake, and ΔS is the change in water storage in the system. While Eq. 1 describes the decant in terms of the individual components contributing to the water balance, Eq. 2 views the decant from the perspective of the ongoing water management at the colliery. These equations both contain known or readily estimable parameters (Re_D, Ev_D, OT) and unknown parameters (Re_S, Ro_D, GW_{In}, Ev_S, Ev_{Spr}, PW_{Out}). The assumption is now made that the storage change in the system (ΔS) can be approximated by the change in water storage in the dams (ΔS_D) within Pit A:

$$\Delta S \approx \Delta S_D \tag{3}$$

This assumption implies that changes in the water storage in the spoils (ΔS_S) can be considered negligible compared to ΔS_D. In terms of pit water levels, this means that the water level within each compartment of Pit A is taken to be the decant level of that particular compartment. The assumption is justifiable for the following reasons (see Fig. 6):

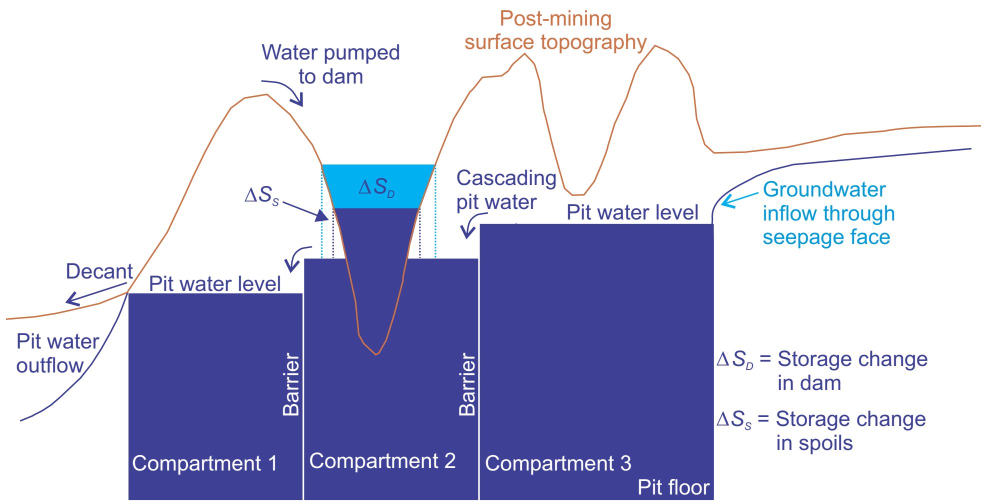

Fig. 6 Conceptual model of the dams within Pit A, used to motive the assumption that changes in the water storage in the system may be approximated by changes in the water storage in the dams

1. If the water level in any one compartment is below the decant level of that particular compartment, no water would cascade into the adjacent downstream compartment. In this case, none of the upstream compartments would contribute to the volumes of water encountered at the decant point. Given the large volumes of water actively managed by the mine (approximately 20 ML/day), this scenario is unlikely.
2. The steep slopes of the banks of the dams (old mine voids) imply that small changes in the water levels of the dams do not lead to significant changes in the surface areas of the open water bodies, nor in the volumes of water stored in the spoils below the dams.
3. The high permeabilities of the spoils imply that very little lateral seepage of water occurs through the spoils. Water is expected to drain nearly vertically downwards from the dams to the decant levels of the particular compartments in which the dams occur.
4. The effective porosity (the porosity available for fluid flow and storage) of the spoils is expected to be well below 0.20 (Hodgson and Krantz 1998), while an open water body has unit porosity. Less than a fifth of the bulk volume of the spoils below the dam floors is therefore available for water storage.
5. As discussed earlier, flow through the topsoil lining the dams is expected to be slower than through the spoils. This means that the spoils below a dam (but above the pit water level) may be unsaturated.

Equation (1) may be rewritten by grouping together the two quantities that are known (Re_D) and readily estimable (Ev_D), and those that are unknown:

$$\begin{aligned} Decant &= (Re_D - Ev_D) + [(Re_S + Ro_D + GW_{In}) \\ &\quad - (Ev_S + Ev_{Spr} + PW_{Out})] \\ &= (Re_D - Ev_D) + [unknown\ inflows \\ &\quad - unknown\ outflows] \end{aligned} \tag{4}$$

Instead of estimating each of the unknown components individually, their combined influence may be estimated from the measured dam water levels and pumping rates by considering the measured storage changes in the dams within Pit A in terms of the volumes of water received and lost. With this approach, no assumptions are needed regarding the recharge rate through the spoils. The change in the water storage in the dams may be written as:

$$\begin{aligned} \Delta S_D &= \Delta P + (Re_D - Ev_D) \\ &\quad + [unknown\ inflows - unknown\ outflows] \end{aligned} \tag{5}$$

where ΔP is the difference between the measured volumes of water pumped to and from the dams. Substituting Eq. 5 into Eq. 4 shows that the decant volume may be calculated directly from the measured storage changes in the dams and the pumped volumes:

$$Decant = \Delta S_D - \Delta P \tag{6}$$

From Eqs. (2), (3), and (6), it follows that the net volume of water actively displaced by pumping is equal to the volume of water actively removed from the system through the offtake and evaporation losses at the sprayers:

$$-\Delta P = OT + Ev_{Spr} \tag{7}$$

The measured and estimated water losses and gains at the various dams within Pit A during the 6-month period of the investigation are listed in Table 3. Also included is information on water losses and gains at an evaporation dam (Evap Dam) located adjacent to Pit A. This dam occasionally receives water from Dam 3 when the water level of Dam 6 approaches its decant level. The term [*unknown inflows* − *unknown outflows*] is estimated for each dam by applying Eq. (5). From the values presented in Table 3, it is seen that the *unknown inflows* exceeded the *unknown outflows* by more than a thousand megalitres over the 6-month period. The calculated difference corresponds to a daily volume of approximately 6.09 ML.

Table 3 Measured and estimated water losses and gains (in ML) at the various dams within Pit A, January to June 2012

Item	Dam 1	Dam 2	Dam 3	Dam 4	Dam 5	Evap Dam	Dam 6	Dam 7	Sprayer Dam
ΔS_D	8	11	23	0	0	0	5	−1	0
$-\Delta P$	3576	−1372	659	0	0	0	−481	0	−1,547
$-Re_D$	−9	−104	−21	−5	−17	−2	−11	−18	−8
Ev_D	18	218	45	11	36	5	23	38	17
Unknown inflows – unknown outflows	3593	−1247	706	6	19	3	−464	19	−1538
Grand total	1097								

Three dams exhibit greater outflows than inflows (Table 3). The large deficit at Dam 2 is probably due to the water percolating through the spoils to Dam 1 where the water level is kept artificially low by pumping almost 20 ML/day to Dams 2 and 3. Dam 6 and the Sprayer Dam receive large volumes of water from the dams closer to the decant point, either directly or indirectly (Figs. 2, 3). At the time of the DTM, the water levels in these dams were more than 6 m (Dam 6) and 17 m (Sprayer Dam) above the decant level. The high hydraulic heads in these dams are expected to cause large water losses through the spoils.

Using Eq. (6) and the data listed in the first two rows of Table 3, the total decant volume at the colliery is estimated at 881 ML for the 6-month period from January to June 2012. This value translates to an average decant rate of 4.89 ML/day which, according to Eqs. 2 and 3, is equal to the sum of the storage increases in the dams (0.26 ML/day, as calculated from Table 3), the offtake (0.96 ML/day, a measured quantity), and the estimated volumes of water lost to evaporation at the sprayers (3.67 ML/day).

The above estimate of the decant rate (4.89 ML/day) was derived from the water balance compiled for the period from January to June 2012, during which lower than average rainfall was experienced (232 mm over 6 months). With the %RF approach, using a recharge rate of 20 %, an average long-term decant rate of 3.76 ML/day is calculated for a MAP of 649 mm. Even with this higher rainfall figure, the long-term average decant rate estimated with the %RF approach is 23 % less than the estimate obtained with the water balance approach for a period of low rainfall. This observation strongly suggests that the assumption of negligible groundwater inflow is wrong for this particular colliery.

Estimating Groundwater Inflows and Pit Water Outflows

To obtain a first estimate of the rate of groundwater influx during the 6-month period, it was assumed that the recharge percentage (20 %) used in the %RF approach is still applicable during years of below-average rainfall. This assumption is likely to lead to an overestimation of the volumes of recharge and decant, since the percentage of rainfall recharged through the spoils during years of below-average rainfall is expected to be less than during years of average rainfall, given that a greater percentage of the incident rainfall is lost to evaporation and soil moisture in drier years. When the assumed recharge percentage was applied to the rainfall received (232 mm) during the 6-month period, the decant rate was estimated at 2.70 ML/day. The large volume of water (2.19 ML/day) unaccounted for when comparing this decant rate to the rate estimated with the water balance approach (4.89 ML/day) points towards significant groundwater influx, particularly when considering that the recharge volume is most likely overestimated.

However, earlier it was seen that pit water elevation at the colliery exceeds the groundwater elevation in the vicinity of the pit, except for the eastern parts of Pit B2 (Fig. 4). Based on the observed hydraulic gradients, pit water outflow is therefore expected to exceed groundwater inflow. This apparent contradiction is the first indication that groundwater inflow to the pits must occur along preferential pathways connected to remote recharge zones at elevations higher than the pit water levels. A conceptual model of the hydraulic heads and flows towards and away from a compartmentalised pit is presented in Fig. 7.

By using the water balance approach, the difference between the groundwater inflow and the pit water outflow (the *net underground inflow*) was estimated at 2.19 ML/day. To obtain a first estimate of the magnitudes of the groundwater inflow and pit water outflow, Darcy's law may be applied. From water level measurements, I estimated the average hydraulic gradient (i) between the pit water and the groundwater in the surrounding sedimentary rocks at 0.016. Estimates for the hydraulic conductivities (K) of the sedimentary rocks were obtained from slug tests performed on 11 monitoring boreholes around the pits. The geometric mean of the hydraulic conductivities was found to be 0.039 m/day. Using a cross-sectional area (A = 574,200 m^2) corresponding to the combined surface area of the sides of the pits below their decant water levels, the pit water outflow (Q) was estimated from Darcy's law ($Q = KiA$) at 0.36 ML/day. Groundwater inflow to the pits (net underground inflow + pit water outflow) was thus estimated at 2.55 ML/day, which includes the inflow through the eastern sides of Pit B2 and along the preferential pathways.

Estimating the Decant Rate for Years of Average Rainfall

During the 6 months from January to June 2012, only 232 mm of rainfall was recorded at the colliery; however, the MAP at the colliery is 649 mm (Table 1). The decant rate estimated with the water balance approach should therefore be adjusted upwards to be more representative of years of average rainfall. To do this, the %RF approach with a recharge of 20 % of the MAP was used to estimate the volume of water reaching the pits through recharge alone (3.76 ML/day), while it was assumed that net underground inflow occurred at a similar rate (2.19 ML/day) as during the 6-month period used for constructing the water balance. The estimated decant rate for years of average rainfall then amounts to 5.95 ML/day. This estimate is approximately 49 % higher than a previous estimate obtained with the %RF approach alone (4 ML/day, for an assumed MAP of 700 mm) (Hodgson 2009).

The above estimate of the decant rate during years of average rainfall may still be slightly less than the true value, since it was assumed that the net underground inflow into the pits will remain similar to the inflow experienced during the first 6 months of 2012. However, higher rainfall figures are likely to increase the elevations of the groundwater and hence the hydraulic heads in the aquifers from which flow occurs towards the pits along the preferential pathways. Due to the resulting small increases in the hydraulic gradients towards the pits, slightly greater groundwater inflows can be expected during years of higher rainfall. A similar argument suggests that slightly higher groundwater levels in the geological units surrounding the pits will lead to slightly less pit water outflow, due to decreases in the hydraulic gradients (the pit water levels cannot exceed their decant levels).

Pathways for Groundwater Inflows

The water balance constructed for January to June 2012 indicated that significant groundwater inflow contributes to the decant volumes managed at the mine. This suggests that the pits are intersected by pathways of high hydraulic conductivity along which groundwater is mobilised from remote locations at elevations higher than the pit water elevations (as shown conceptually in Fig. 7). Dolerite intrusions are known to abound in the coal field in which the colliery is located. These structures are often associated with preferential pathways for groundwater migration. Since dolerite is generally highly magnetic, I undertook a magnetic survey to detect and locate possible dolerite structures intersecting the pits.

Due to the size of the pits and the lack of information in the mine archives on intrusive structures encountered in the pits, the magnetic survey focused only on those areas where the shapes of the pits suggested the presence of structures that had interrupted mining. I therefore recorded

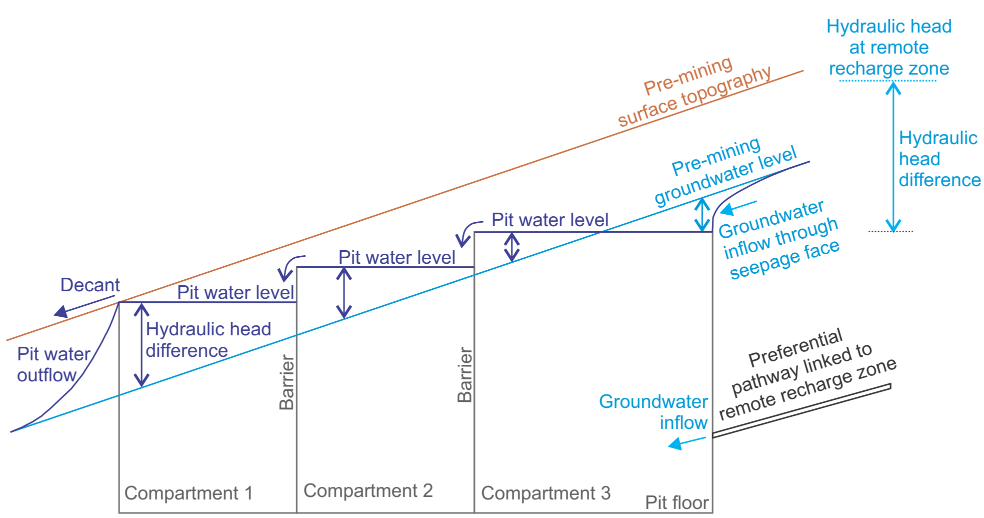

Fig. 7 Conceptual model of the hydraulic head differences driving flows towards and away from a compartmentalised pit intersected by a preferential pathway

magnetic data on traverses parallel to the boundaries of the pits, perpendicularly across the corridors between the pits, and across the partial corridor within Pit A (refer to Fig. 2). Large magnetic anomalies with amplitudes greater than 350 nT confirmed that the partial corridors in Pit A were due to the presence of a linear magnetic intrusive (less prominent anomalies were also recorded across the corridors between the pits).

After the magnetic survey, two percussion boreholes were installed in the northern and southern partial corridors in Pit A. Both boreholes intersected dolerite at depths of approximately 20 m below ground level, confirming that the linear magnetic anomalies was due to an intrusive dolerite dyke. To investigate whether the dyke was associated with groundwater inflow to Pit A, I measured the static water elevations in the two new boreholes 2 weeks after their installation; the groundwater elevations were more than 10 m higher than the pit water elevations and the groundwater elevations in the monitoring boreholes surrounding the pits. This shows that a large hydraulic gradient exists between the groundwater moving along the dyke and the pit water. The dyke therefore appears to extend to remote locations where recharge occurs at a higher elevation than the pit water elevation. These groundwater inflows are the most likely reason for the large difference in the estimated decant rates obtained using the %RF and water balance approach.

Salt and Sulphate Balances for the Colliery

I compiled salt and sulphate balances for the colliery to estimate the rate of salt generation within the pits. These balances were compiled from measured pumping rates, water quality information, and the estimated groundwater inflow to and pit water outflow from the pits. The balances are based on a number of assumptions, namely:

1. The average total dissolved solids (TDS) and sulphate concentrations of the pit water remained constant from January to June 2012.
2. The groundwater flowing into the pits was uncontaminated and had TDS and sulphate concentrations similar to the values recorded in the boreholes intersecting the dolerite dyke (50 and 2 mg/L, respectively).
3. The average TDS and sulphate concentrations of the pit water were 3800 and 2550 mg/L, respectively. These values correspond to the concentrations measured in the boreholes within the pits.
4. The TDS and sulphate concentrations of the offtake were equal to the corresponding concentrations of Dam 2 (4930 and 3430 mg/L, respectively).
5. The TDS and sulphate concentrations of the water reaching the sprayers were equal to the corresponding concentrations of Dam 6 (4150 and 2900 mg/L, respectively).
6. Only 10 % of the salt load pumped to the sprayers was effectively removed from the system. Most of the salt precipitating on the spoils near the sprayers is assumed to be mobilised back to the pit water during rainfall events.

The TDS and sulphate balances for the colliery during years of average rainfall (649 mm) are presented in Tables 4 and 5, respectively. Approximately 10,614 kg/day of salt is removed from the colliery's backfilled pits.

The sulphate balance (Table 5) shows that recharge percolating through the spoils will attain a sulphate concentration of 1961 mg/L. This was calculated by balancing the sulphate loads added to and removed from the system and is a reasonable estimate of the sulphate concentration of the percolating water, considering the sulphate concentration of the pit water (2550 mg/L). The higher sulphate concentration of the pit water may be explained by the continuing oxidation of sulphide minerals at and just below the pit water level where the dissolved oxygen concentration is likely to be high, as well as by the concentrating effect of evaporation from the open water bodies within Pit A.

When the sulphate concentrations of the water from the dams within Pit A were plotted against the TDS concentrations, a linear relationship was observed, with the sulphate concentration being ≈70 % of the TDS concentration (Fig. 8). An interesting observation is that the sulphate and TDS concentrations of the water from Dams 2, 4, 5, and 7 are much greater than in the other dams. The latter three dams do not form part of the water recirculation system (Figs. 2, 3). The lower salt concentrations observed at the other dams within Pit A again indicate that groundwater is entering the system, diluting the pit water recycled in the recirculation system. Although Dam 2 does form part of the water recirculation system, its large surface area and shallow depth have probably led to greater evaporation losses, resulting in higher salt concentrations than the other dams of the recirculation system. Similar observations may be made when considering the concentrations of sodium (a relatively conservative element) measured in the Pit A dams vs. the TDS concentrations (Supplemental Fig. 1).

The linear relationship between the sulphate and TDS concentrations is also observed when comparing the total salt load (10,614 kg/day, Table 4) and the total sulphate load (7,379 kg/day, Table 5). Taking the combined surface area of the pits (1057.4 ha) into account, the total sulphate load equates to 6.98 kg/ha/day (or 7.03 kg/ha/day when estimating the total sulphate load as 70 % of the total salt

Table 4 Estimated salt balance of the colliery during years of average rainfall

	Salt loads added		Salt loads removed		
	Groundwater inflow	Recharge	Pit water outflow	Offtake	Sprayers
Daily volume (ML/day)	2.55	3.76	0.36	0.96	12.28
Concentration (mg/L)	50	2789	3800	4930	4150
Salt load (kg/day)	129	10,485	1368	4150	5096
Total salt loads (kg/day)	10,614		10,614		

Table 5 Estimated sulphate balance of the colliery during years of average rainfall

	Sulphate loads added		Sulphate loads removed		
	Groundwater inflow	Recharge	Pit water outflow	Offtake	Sprayers
Daily volume (ML/day)	2.55	3.76	0.36	0.96	12.28
Concentration (mg/L)	2	1961	2550	3430	2900
Sulphate load (kg/day)	5.14	7374	918	2900	3561
Total sulphate loads (kg/day)	7379		7379		

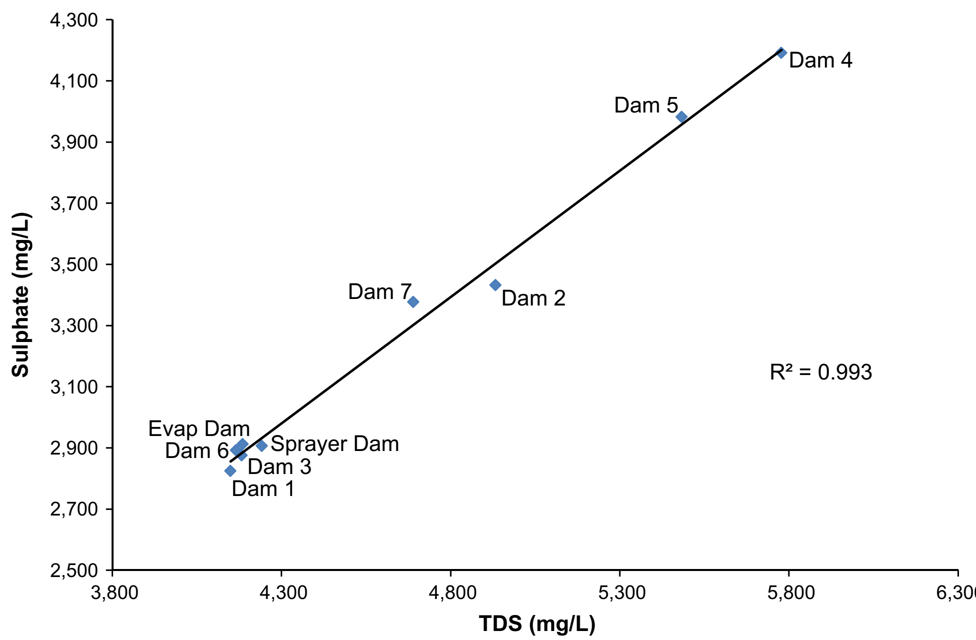

Fig. 8 Sulphate concentrations in the dams of Pit A plotted against TDS concentrations

load). This value is in good agreement with the average sulphate loads generated in the backfilled opencast coal mines in South Africa, as reported by Hodgson and Krantz (1998) (5–10 kg/ha/day) and van Tonder et al. (2003) (7 kg/ha/day).

Limitations

I used the water balance approach to estimate the decant rate at a colliery where daily measurements of rainfall, pumping rates, and dam water levels are taken. The approach is likely to be less successful at other collieries where these quantities are not measured regularly. Furthermore, the approach depends on the accuracy of the measurements. For example, although dam water levels are recorded daily at the colliery of this study, yardsticks (marked every 2.5 cm) embedded in the floors of the dams are used to make visual observations of the water levels. The accuracy of these observations is questionable, particularly on windy days when the water is choppy.

The motivation for using the water balance approach was to avoid the uncertainty associated with assumed recharge rates; however, other uncertainties were introduced. For example, I included estimated evaporation rates in the calculations. Although the estimation was done using a standard method that is widely accepted, the estimates are still associated with inaccuracies that will influence the results.

In constructing the water balance, I used rainfall data from a 6-month period during which unusually low rainfall occurred. This led to an estimate of the decant rate that was not representative of years of average rainfall. Although the water balance approach did allow an estimation of the groundwater inflow to the system, I was still obliged to assume an effective recharge rate to estimate the decant during years of average rainfall.

I assumed that the storage changes in the system were represented by storage changes in the dams. Although I justified this assumption by considering the compartmentalisation of Pit A and the high permeabilities of the spoils, some storage changes may also have occurred in the spoils surrounding the dams. However, the data listed in Table 3 show that the storage changes (ΔS_D) are generally small compared to the volumes pumped (ΔP). The net storage change in all the dams equals only 5.5 % of the net volume displaced through pumping. Inaccuracies in the estimates of the storage changes are therefore unlikely to lead to significant errors in the estimated decant rate (refer to Eq. 6).

Furthermore, I assumed that higher rainfall figures would not significantly increase groundwater inflow along the preferential flow paths associated with the dyke. This assumption may have led to a slight underestimation of the true decant rate. This is illustrated in Supplemental Fig. 2 where 225 pairs of groundwater depth measurements (from 1990 to 2014) in 36 monitoring boreholes of a nearby power station are shown. Each pair of measurements consists of the maximum and the minimum groundwater depths observed in a particular borehole during a particular year. Although the water depths in some boreholes located near surface water bodies may have been buffered against seasonal changes, it is seen that the differences between the maximum and minimum groundwater depths were generally small (0.88 m on average). Considering the large difference (>10 m) between the water levels measured in boreholes on the dyke and the pit water level, the increases in the water levels during and after the rainy season are unlikely to lead to increases in the hydraulic gradient of more than 10 %. According to Darcy's law, the increased groundwater inflow during and after the rainy season is therefore expected to be less than 10 %.

The water balance approach was simple to apply at the colliery of this study because of the very specific conditions that existed there. Due to the compartmentalisation of the pits, the changes in the volumes of water stored in the system could be approximated by the storage changes in the dams. At other collieries, it may not be as straightforward to estimate these changes. Still, despite these limitations, the water balance approach successfully demonstrated that groundwater inflow is contributing substantially to the decant volumes at the colliery. These inflows were not accounted for in the %RF approach, resulting in a considerable underestimation of the long-term average decant rate.

Conclusions

Although *Guideline A5* of the BPGs requires mine management to consider the positions, qualities, and impacts of future decants from rehabilitated opencast pits, no guidance is given regarding the methods to be used in estimating decant rates. Various authors have used the %RF approach to estimate the long-term average decant rates. However, this approach assumes negligible groundwater inflow, which may be invalid when the pits are intersected by geological structures associated with preferential pathways for groundwater migration. In such cases, the decant rate may be significantly underestimated by the %RF approach, leading to flawed mine water management strategies that are unable to cope with the unexpected volumes of decanting pit water. This could result in adverse environmental impacts.

In addition, the effective recharge rates used in the %RF approach are associated with large uncertainties. Many researchers have used the average recharge rates proposed by Hodgson and Krantz (1998) to estimate decant rates. However, while the latter authors considered two separate components of the effective recharge (runoff to the pits and seepage through the spoils), most subsequent studies have not distinguished between these components. It has become common practice simply to assume an effective recharge rate (usually 20 %) and to apply it blindly without taking into account the specific conditions that exist at the particular site.

The value of the %RF approach lies in the fact that a first estimate of the decant rate may be obtained quickly with a very simple calculation. However, this estimate should be viewed with circumspection and should be verified with other methods, such as the construction of water and salt balances.

The water balance approach uses measured and readily estimable quantities to calculate a decant rate without making assumptions about the effective recharge rate through the spoils. This approach also does not assume negligible groundwater inflows and can be used to estimate the groundwater contribution to the decant volumes.

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