

# Predicting Environmental Risks: Using Water Balances for Sustainable Power at Kusile Power Station (South Africa)

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Predictive water balances play a critical role in mitigating environmental risks in power generation by leveraging historical and real-time data for proactive resource management. At Kusile Power Station, these frameworks were used to identify a major environmental challenge and guide the development of an alternative wastewater management strategy. This study introduces a novel approach by integrating predictive modelling with a diffusion-based blending strategy, offering a cost-effective alternative to conventional chemical treatment methods. Instead of direct blending in pollution control dams, which was impractical due to high wastewater levels, a targeted blending strategy within the Flue Gas Desulphurisation (FGD) system was explored. A diffusion model confirmed that this approach could meet 53% of the FGD system's water demand using wastewater, significantly reducing reliance on raw water. By incorporating these findings into the predictive water model, Kusile Power Station successfully optimized wastewater reuse, demonstrating the potential of data-driven strategies for sustainable industrial water management.

## 1. Introduction

All Eskom power stations must strictly adhere to the Zero Liquid Effluent Discharge (ZLED) policy, which prohibits any liquid waste discharge into the environment (Herbst et al., 2016). To comply with this, customized water balances were developed for each station, and pollution control dams (PCDs) were constructed to facilitate wastewater recycling (Van Zyl and Premiall, 2005). Over time, adherence to the ZLED policy, continuous water balance optimizations, and Eskom's commitment to environmental protection prompted the transition from wet to dry technologies in newly commissioned stations, reducing both environmental contamination risks and raw water usage (Tsotsi and Dames, 2011).

The introduction of the Flue Gas Desulphurisation (FGD) system at Kusile Power Station in 2008 disrupted Eskom's optimised water management system. While the system was welcomed for its potential to address South Africa's growing emissions problem by removing harmful SO<sub>2</sub> gases, concerns arose due to its significant water demand, nearly doubling the station's requirements (Pillay and Moodley, 2018). However, it was soon recognized that the FGD system could mitigate water pollution by utilizing both raw and wastewater, easing concerns about environmental discharge and positively influencing the operational water balance (Chen et al., 2018).

In March 2017, the first unit of Kusile Power Station, along with its Flue Gas Desulphurisation (FGD) system, became operational (Barrada, 2023). The system delivered on its promises, effectively removing over 90% of SO<sub>2</sub> emissions from the flue gas and significantly reducing wastewater levels in the pollution control dams (PCDs) (Ezeh, 2018). However, the full impact on PCD levels was initially unclear due to the absence of a comprehensive water balance to monitor construction and commissioning activities. As a result, these processes proceeded without sufficient environmental oversight, leading to rapid PCD filling and a temporary halt in commissioning due to the risk of overflow (Pillay and Moodley, 2018). This challenge highlighted the need for a hybrid water balance to track operational activities and forecast the effects of future commissioning efforts. Predictive controls, as noted by Putri (2024), offer valuable solutions for managing variables such as weather fluctuations and aging infrastructure in water systems.

Each commissioned unit at Kusile Power Station had its own Flue Gas Desulphurisation (FGD) system, with waste streams intended for treatment by a dedicated Wastewater Treatment Plant (WWTP). However, delays in the construction and commissioning of the WWTP led to the redirection of these waste streams into the pollution control dams (PCDs). This, combined with ash and oil contamination, caused a rapid deterioration in wastewater quality, rendering it unsuitable for reuse in the FGD systems.

To assess the potential impact on the station, a predictive water model was used to evaluate the consequences. The analysis revealed a concerning scenario—if the FGD systems could not utilize wastewater, raw water demand at the station would rise sharply, placing undue pressure on the Usutu Water Scheme. This imbalance would increase the risk of environmental contamination, as the volume of wastewater generated would exceed the station's consumption capacity.

Recognizing the urgency of the issue, Kusile Power Station implemented a novel water management strategy by integrating predictive water balances with an alternative wastewater reuse approach. Unlike conventional methods that rely on costly chemical treatment, this study explores the feasibility of blending raw water with wastewater as a low-cost, scalable alternative for maintaining water quality in pollution control dams (PCDs). By developing a diffusion-based predictive model, the study advances the understanding of how industrial water systems can optimize resource utilization while mitigating environmental risks. This approach contributes to the broader field of sustainable industrial water management by demonstrating how data-driven modeling can inform decision-making in complex operational environments.

## 2. Methods

### 2.1 PCD quality correction via blending

Kusile Power Station operates three interconnected pollution control dams — Holding Recycle Dam (HRD), Station Dirty Dam (SDD), and Ash Dump Dirty Dam (ADDD) (see Figure 1) which maintain consistent water quality due to continuous circulation. However, the HRD is of primary concern, as it supplies water to the Flue Gas Desulphurisation (FGD) system. The HRD consists of two compartments, each with a capacity of 34,000 m<sup>3</sup>. Analysis of multiple water samples from these dams, compared to the original FGD design specifications (as shown in Table 1), revealed that the HRD water quality had deteriorated beyond acceptable levels for FGD consumption. With major system overhauls approaching, the station faced a critical timeframe to implement a feasible solution and prevent a full transition to raw water reliance.

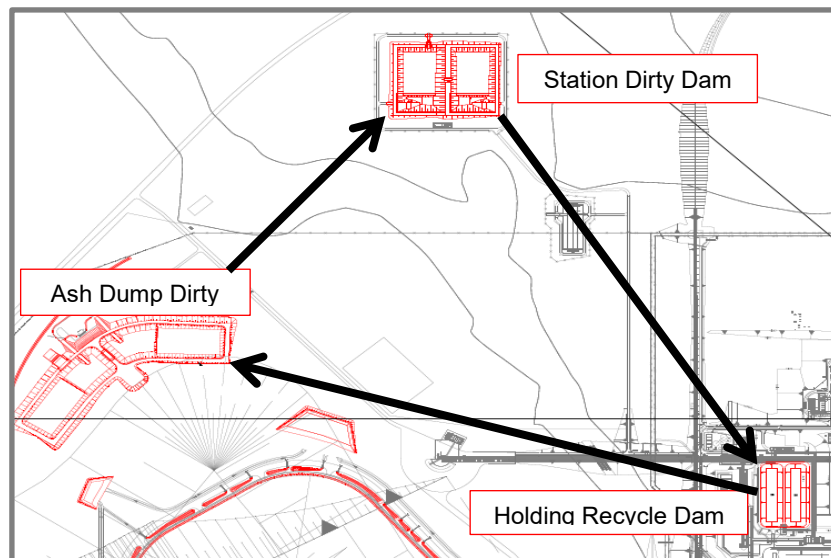


Figure 1: PCDs at Kusile Power Station

Kusile Power Station identified improving the water quality of the Holding Recycle Dam (HRD) as the most viable solution to make it suitable for Flue Gas Desulphurisation (FGD) system consumption. This approach would ensure continued wastewater utilization, thereby minimizing environmental risks. While chemical water treatment was initially considered, it required significant capital investment and extended timelines, which were not feasible for the station. As an alternative, blending raw water with wastewater emerged as a practical solution.

To assess the feasibility of blending, several key data points were required, including the total volume and quality of water stored in the pollution control dams (PCDs), comprehensive flow rate data to facilitate a detailed water balance analysis, raw water quality parameters, and the FGD system's water quality requirements. However, conducting a full-scale experiment to evaluate the impact of raw water blending on the PCDs was impractical due to high water levels. Instead, a theoretical diffusion model was developed to estimate the required raw water volume and the time needed to achieve acceptable water quality at the HRD outlet.

*Table 1: Design and actual water qualities of HRD*

Parameter	Unit	Design	Actual
Conductivity	µS/cm	1110	524
pH		7-10	6.82
TSS	mg/l	<5	13.2
TDS	mg/l	1046	4746
Chlorides as Cl	mg/l	59	83.6
Sulphates	mg/l	283	3485
Calcium as Ca	mg/l	201	681
Magnesium as Mg	mg/l	221	319

## 2.2 Development of a diffusion model to predict spatial and temporal distribution of compound concentrations

Over the years, various diffusion models have been developed using advanced software tools, often resulting in complex solutions that are impractical for daily operational use. To address this challenge, Halil Karahan introduced a more accessible approach by solving a one-dimensional advection-diffusion model using Excel. This Excel-based model provides a simplified yet effective mathematical representation of the diffusion process, making it a practical tool for industrial applications (Karahan, 2006).

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} = D \frac{\partial^2 c}{\partial x^2}, \quad c(x, 0) = f(x), \quad 0 < x \leq L, \quad c(0, t) = g(t), \quad 0 < t \leq T \quad (1)$$

All functions, except for  $c$  are known.  $u$  is the velocity in the  $x$  direction and  $D$  is the dispersion coefficient. Karahan further streamlined the equation, simplifying it to the extent that it became a practical and readily applicable formula, suitable for seamless integration into Excel for efficient processing.

$$c(i, n + 1) = \left\{ \left[ \frac{Cr}{2} + \theta \left( \frac{Cr}{Pe} \right) \right] c(i - 1, n + 1) + \left[ \left( \frac{Cr}{Pe} \right) - \theta \left( \frac{Cr}{Pe} \right) \right] c(i - 1, n) + \left[ 1 + 0.5 \times Cr - 2 \left( \frac{Cr}{Pe} \right) + \theta \left( \frac{Cr}{Pe} \right) \right] c(i, n) + \left[ \left( \frac{Cr}{Pe} \right) - \frac{Cr}{2} \right] c(i + 1, n) \right\} / \left[ 1 + \frac{Cr}{2} + \theta \left( \frac{Cr}{Pe} \right) \right] \quad (2)$$

This is known as the Saul'yev's formula where only  $c(i, n + 1)$  is unknown. The other expressions are known and described as:

$$x_i = i\Delta x \quad \dots \quad i = 0, 1, 2, \dots, M \quad (3)$$

$$t_n = n\Delta t \quad \dots \quad n = 0, 1, 2, \dots, N \quad (4)$$

Where  $x_i$  and  $t_n$  are parallel to the space and time coordinate axis.  $\theta$  is the weighting factor and the constant temporal grid-spacing and constant spatial are  $\Delta t = T/N$  and  $\Delta x = L/M$ . The Peclet number and Courant numbers are described below:

$$Pe = \frac{u\Delta x}{D} \quad (5)$$

$$Cr = \frac{u\Delta t}{\Delta x} \quad (6)$$

The original Saul'yev's formula did not account for an external incoming stream, necessitating a minor adjustment to accommodate water entering the dam after the initial setup. With a functional formula in place, the process of identifying the limiting component could begin. Water quality analysis of the HRD wastewater (Table 2) revealed that sulphates deviated most significantly from the specified requirements, exceeding design standards by over tenfold.

However, due to the complexity of sulphate behavior, a one-dimensional diffusion model could not provide accurate movement predictions. Consequently, the focus shifted to other, less complex components to

determine the feasibility of blending in the HRD. If successful, a more advanced diffusion model would be developed to address the sulphate issue and optimize the required water volume.

Calcium was identified as the next most significant component deviating from design specifications, and calculations were conducted based on its properties. The HRD was divided into 1-meter by 1-meter sections to facilitate initial concentration mapping and establish baseline conditions. Following this, a raw water stream was introduced, and calculations were performed to determine the volume required to achieve the desired water quality in each HRD cell. A simple concentration balance model assuming perfect mixing was applied to the first HRD cell to guide the raw water addition process.

Table 2: Raw water requirement to get HRD quality to acceptable limits (per 34 000 m<sup>3</sup>)

Parameter	Initial concentration in HRD	Raw water concentration	Raw water required
Chlorides as Cl	0.0836 mg/l	0.011 mg/l	13 982 m3
Sulphates	3.485 mg/l	0.034 m/l	390 669 m3
Calcium as Ca	0.569 mg/l	0.05 mg/l	69 909 m3
Magnesium as Mg	0.319 mg/l	0.047 mg/l	14 804 m3

### 3. Results

#### 3.1 HRD and SDD blending results

The one-dimensional diffusion model confirmed that sulphates are the limiting factor, requiring 390,669 m<sup>3</sup> of raw water to bring a single HRD cell within design specifications (see Table 3). However, this represents only the initial mixing conditions. To sustain the required 1:11 dilution ratio, for every cubic meter of wastewater entering the HRD, 11 cubic meters of raw water would be needed. Due to the complexity of this process, the data was integrated into the predictive water model to evaluate its impact on the overall system.

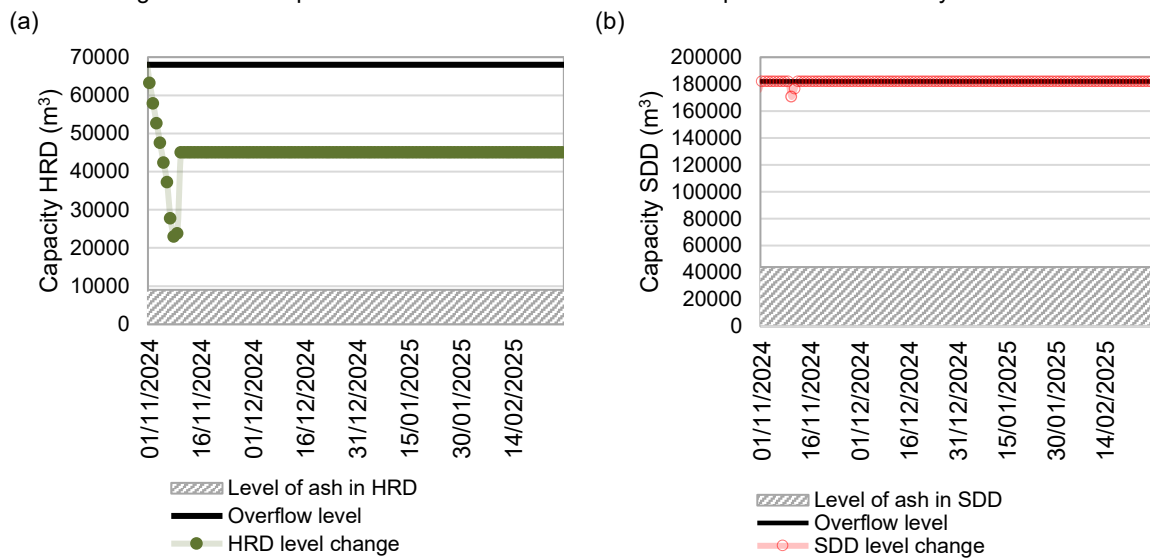


Figure 2(a): Change in wastewater level in the HRD on the predictive water balance, 2(b): Change in wastewater level in the SDD on the predictive water balance

As shown in Figure 2(a), the first step involves emptying the HRD to create space for blending with raw water. During this phase, no water can be transferred from the SDD to the HRD, leading to continued accumulation in the SDD without any means of reducing its levels. Once the HRD reaches an acceptable level, blending can begin with a daily raw water inflow of 28,800 m<sup>3</sup>—the maximum volume that can be supplied. This adjustment reduces the HRD’s operating capacity from 68,000 m<sup>3</sup> to just over 31,000 m<sup>3</sup> to maintain the required dilution ratio. However, this adjustment poses significant risks. The HRD was designed to operate above 90% capacity to ensure a consistent wastewater supply to the station. Lowering its capacity increases the risk of environmental contamination and threatens station operations. Figure 2(b) further demonstrates that blending in the HRD would result in continuous overflow from the SDD into the surrounding environment, confirming that this approach is not a viable solution for wastewater management.

### 3.2 Blending in the FGD

The Flue Gas Desulphurisation (FGD) system at Kusile Power Station was originally designed to operate primarily on wastewater, with raw water serving as a secondary option. The infrastructure was established to accommodate water supply from either source, enabling the potential for blending by simultaneously feeding water from both directions. To evaluate the feasibility of this approach, an assessment of the water-dependent processes within the FGD was conducted to identify areas most affected by degraded water quality.

The FGD system relies on water for several critical functions, including absorber makeup, mist eliminator washing, and reclaim water makeup. Among these, the mist eliminators are particularly crucial as they remove entrained water and slurry droplets produced by the spray nozzles of the recycle pump. Positioned above the scrubbing zone, the mist eliminators ensure efficient gas cleaning and prevent carryover of contaminants, making their proper function essential to the overall performance of the FGD system. The potential impacts of blending raw and wastewater on these components were carefully examined to determine the viability of this approach. The mist eliminator system in the Flue Gas Desulphurisation (FGD) unit consists of both coarse and fine mist eliminator stages, supported by a network of beams. Slurry droplets from the absorber spray zone, entrained in the flue gas, collide and accumulate on the mist eliminator blades. Most of the accumulated slurry drains back into the reaction tank by gravity, but some remains on the blades, leading to scale formation that compromises performance.

To prevent the build-up of suspended solids and scale, the mist eliminator wash system intermittently sprays water onto the blades, flushing accumulated solids back into the reaction tank. Currently, this system relies on wastewater from the Holding Recycle Dam (HRD) as its water source. However, the low pH of HRD water is causing corrosion in the mild steel piping used for water transfer, while its high solids content is leading to blockages and reduced wash flow. Additionally, the HRD water is saturated with gypsum, which poses a significant risk of scaling within the mist eliminator modules.

In contrast, other critical water-dependent processes in the FGD system, such as absorber makeup and reclaim tank makeup, are less sensitive to water quality. The absorber system operates as a slurry with lime dosing, allowing it to tolerate the low pH and high solids content of the HRD water without significant adverse effects. Consequently, addressing water quality challenges for the mist eliminator wash system is crucial to maintaining optimal FGD performance and avoiding operational disruptions. The mist eliminators emerge as the component most vulnerable to variations in water quality. This sensitivity presents an opportunity for an unconventional blending approach. In this approach, the mist eliminator washing system would exclusively utilize 100% raw water, while the absorber makeup and reclaim water makeup would continue to be supplied with wastewater from the HRD.

The Flue Gas Desulphurisation (FGD) system at Kusile Power Station consumes approximately 3,500 m<sup>3</sup>/day per unit, with mist eliminators accounting for around 1,650 m<sup>3</sup>/day. This means that over 50% of the FGD system's water demand can still be met using wastewater from the HRD, reducing the daily raw water requirement to less than 10,000 m<sup>3</sup> for the entire station, which consists of six units.

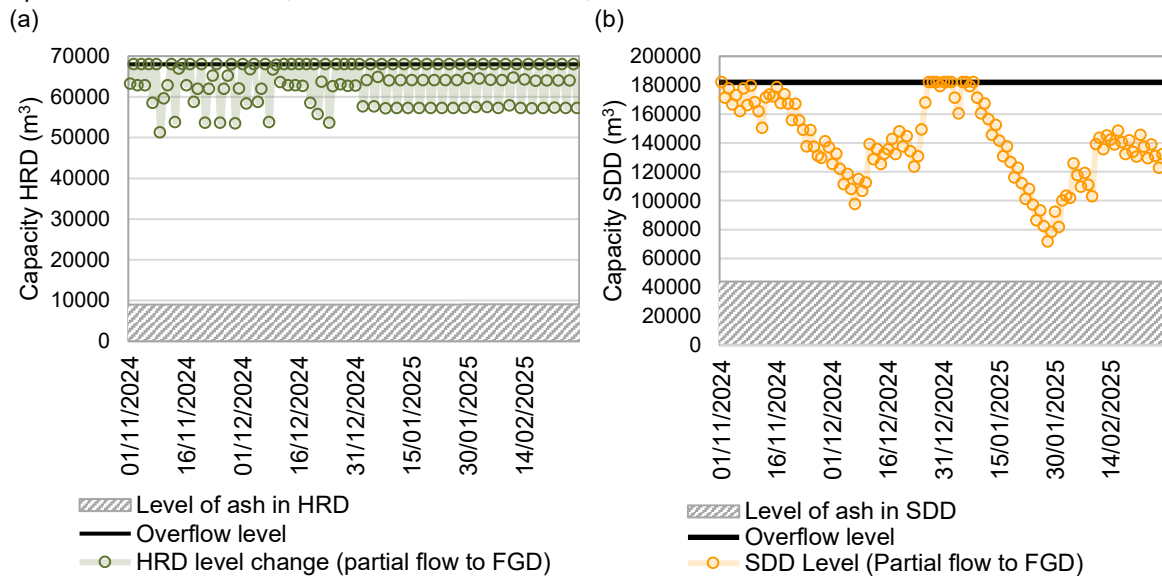


Figure 3(a) : Change in wastewater level in the HRD on the predictive water balance with partial flow to FGD, 3(b): Change in wastewater level in the SDD on the predictive water balance with partial flow to FGD systems

By integrating this data into the predictive water model, significantly better results were achieved compared to direct blending in the HRD. As shown in Figure 3(a), HRD water levels remained within safe operational limits, ensuring continued functionality. An analysis of the SDD levels in Figure 3(b) indicated that they could be effectively managed. While high rainfall in December presented some challenges, they could be mitigated by employing additional wastewater recycling strategies on-site, such as using the excess water for floor washing. In conclusion, blending raw and wastewater in the FGD absorber was determined to be a viable solution, with a maximum raw water demand of under 10,000 m<sup>3</sup>/day for full station operation. This approach not only ensures the reliability of the FGD system but also minimizes reliance on raw water, contributing to sustainable water management at the power station.

#### 4. Conclusions

The implementation of predictive water balances at Kusile Power Station has proven to be an essential tool for managing water resources sustainably and mitigating environmental risks. The study demonstrated that direct blending of wastewater within the Holding Recycle Dam (HRD) posed significant operational challenges and environmental risks, making it an impractical solution. Instead, an alternative approach to blending raw and wastewater within the Flue Gas Desulphurisation (FGD) system was found to be a feasible and effective strategy. This approach ensured that over 50% of the FGD's water demand could still be met using wastewater, significantly reducing reliance on raw water and maintaining compliance with Eskom's Zero Liquid Effluent Discharge (ZLED) policy.

By incorporating these findings into the predictive water model, Kusile Power Station was able to optimize water management strategies, ensuring safe operational levels in both the HRD and Station Dirty Dam (SDD). Although challenges such as high rainfall posed potential risks, they could be effectively managed through additional wastewater recycling measures. The adoption of a targeted blending approach, where mist eliminators exclusively use raw water while other FGD processes rely on wastewater, further enhanced system reliability and minimized scaling and corrosion risks.

Ultimately, the study highlights the value of predictive water modeling as a proactive tool for achieving sustainable power generation while maintaining environmental compliance. The successful implementation of these strategies at Kusile Power Station serves as a model for other power stations seeking to optimize water usage and mitigate environmental risks in line with regulatory requirements.

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