A case study of the importance of hydrogeology to mitigate environmental and technological challenges associated with mine closure options

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Abstract

Kromdraai is a coal operation in South Africa approaching closure. The most substantial closure issues relate to the lack of progressive rehabilitation affected by topsoil shortages, which exacerbate the generation of acidic metalliferous mine water. This is complicated by complex interactions between surface and groundwater associated with historic underground and adjacent open cut mining.

This paper focuses on the phased multi-disciplinary development of an integrated hydrogeological conceptual model, collation and interpretation of historical data, geophysics, hydrogeological data to develop a high confidence numerical flow and transport model to simulate various post-closure water management scenarios. The model provided more accurate discharge volumes and locations, which reduced the uncertainty associated with the initial discharge prediction, resulting in a reduction from 10 to less than 5 ML AMD/day mitigating water related closure costs substantially.

Trade-off studies with cost benefit analysis were completed and considered various improved surface rehabilitation and water treatment options to address long-term closure liabilities.. Critical to closure liability reduction is ingress management in the form of optimised surface rehabilitation as this results in reduced polluted mine water generation and allows for the implementation of more cost-effective passive treatment systems.

Keywords: Hydrogeology, GIS data Collation, Geophysics, Numerical Modelling, Mine Closure, Rehabilitation, Trade-off Studies

Introduction

Kromdraai is a coal operation in South Africa that is approaching closure with mining ceasing at the end of 2018. It was determined in 2014 that water management options needed further study specifically to quantify water discharge volumes, quality of discharge and water discharge locations post closure.

The mine has substantial dispersed AMD across the footprint, which is complicated by the complex interaction between surface water and groundwater associated with historic underground and current open cast mining. The current water management strategy involves the operation of a liming plant, dosing of water with caustic soda, management of water levels in pits, and future extraction of water through bores for potential reverse osmosis (RO) treatment at the eMalahleni Water Reclamation Plant (EWRP). Previous hydrogeological estimates (Hodgson, FDI *et al.*, 2007) indicated a post closure requirement for active treatment of 8 ML/day in perpetuity at a cost of more than ZAR2.5billion (150-year period). There are hence substantial business drivers to reduce or eliminate this requirement for in perpetuity treatment using RO.

Key to understanding the post-closure water management risk is an understanding of the mitigation measures that will reduce rainwater infiltration and the effect it will have on discharge water volumes and quality. Hence, a robust hydrogeological conceptual model, qualifying the groundwater flow regime, recharge rates and areas as well as discharge mechanism and hydrogeological and geochemical controls influencing the groundwater flow and quality over time was developed.

The conceptual flow and transport models were translated into a calibrated numerical groundwater flow and transport model for the site and the model was used to inform possible water management scenarios at closure. The objective of this paper is to highlight how the project identified the most cost-effective long-term scenarios that will ultimately be developed into an executable long-term post-closure water management solution for the site that is cost-effective and delivers an acceptable risk profile.

Methods

The development of a long-term post closure water management solution, included the following steps, outlined in more detail below.

Collation of all existing data into a single GIS database

All existing mine plans, including historic aerial photographs, historical mine plans and the latest aerial images, were obtained from various sources and collated, ensuring all data was in the correct mine coordinate system. Due to the nature of the project, the primary focus was on where mining had taken place, when this had occurred and what rehabilitation had been done. As the information was collated, care was taken to ensure that all data was in the correct mine coordinate system; specifically, LO29, and using the Cape Datum. Once all the readily available data had been collated, it was noted that the exact location of the key historical shafts and declines was missing, and the old Blackstone Colliery, right next to Kromdraai. The above missing information and understanding the locality of discharge points were a key component in formulating a closure strategy. The corporate office aerial photography archives were accessed, and three iterations of photography were found over Kromdraai Colliery from 1971, 1972 and 1986. All the collated historical data overlays were consolidated into an ArcView data base and used to plan the geophysical surveys and subsequent hydrogeological intrusive programme. Historical mine rehabilitation data, showing the temporal, spatial and quality of mine rehabilitation are included.

Geophysical delineation of structures and intrusions

The hydrogeology of the Mpumalanga Coalfields is dominated by a sedimentary sequence of sandstones, siltstones, shales, mudstones and intercalated coal seams, intruded by dolerite sills and dykes. The dolerite intrusions influence the groundwater flow directions and water strikes and often compartmentalise groundwater flow. Understanding the location of dolerite intrusions in relation to historical mining activities are key components of the hydrogeological conceptual model.

Airborne electromagnetic (AEM) and magnetic data were collected in October 2015 over the mine site to characterise the hydrogeology and map geological structures (dykes, faults and sills) believed to act as pathways and/or barriers to water flow and contaminant pathways. Interpretation of the data mapped several dykes and faults (Figure 1), while possible pollution plumes were mapped and digitised from the processed conductivity-maps (Spectrem Air Report, 2017).

Drilling and sampling of additional monitoring boreholes

Based on the results and interpretation of the high-resolution AEM and magnetic data, 21 boreholes were drilled to characterise the water level, aquifer parameters and groundwater quality as well as to map the depth extent of possible pollution plumes. Additional geochemistry test work (Barr, J, 2017) undertaken included static Acid-base accounting (ABA) and Net Acid Generation

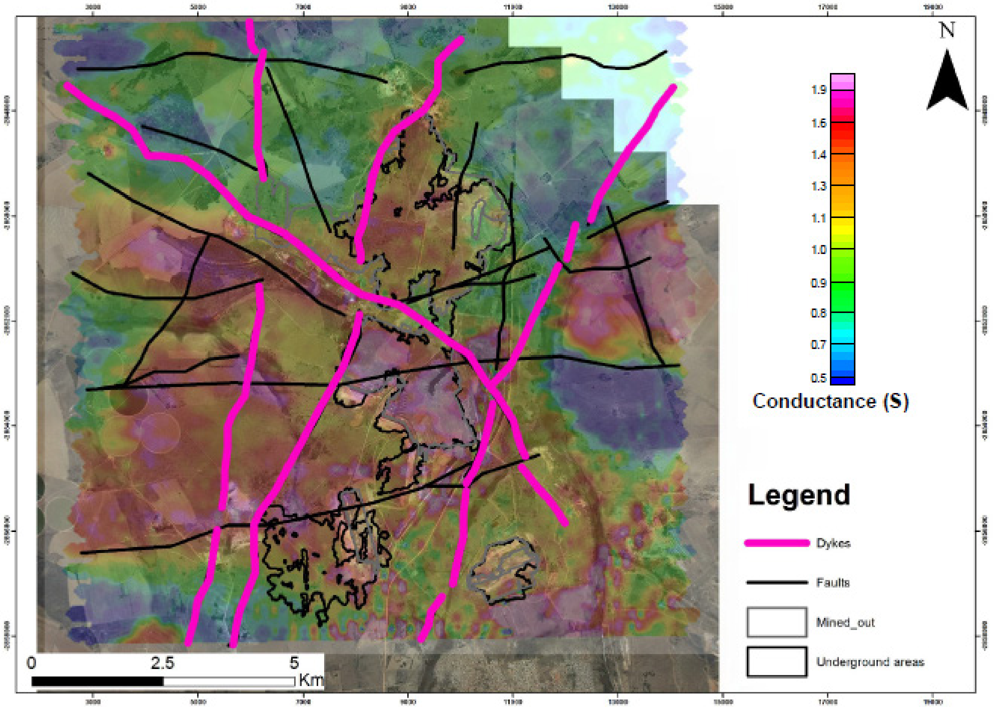

Figure 1 Location and layouts of dykes, faults/structures from geophysics

(NAG) tests, as well as kinetic test work on the coal seam and inter-seam lithologies. A substantial feature of the ABA dataset is the prevalence of negative neutralisation potential (NP) values. These characteristics are further reinforced by NAG test data which indicated an equilibrium pH following spontaneous oxidation of sulphide and consumption of reactive carbonate of the order of 2.4, with a residual acidity release of around 50 mg/L. Kinetic testing produced particularly poor-quality leachate, with a pH of less than 2 and extremely high concentrations of sulphate, iron, manganese and aluminium (WSP Parsons Brinkerhoff, 2017). It is hence unlikely that discharge water will improve in quality to a point which would permit direct environmental release in the short term.

The hydrogeological intrusive program successfully confirms the roles of dolerite intrusion in the groundwater flow and migration pathways. The additional aquifer parameter and water level data was used to calibrate the numerical groundwater flow model.

Building the numerical flow and transport model

All hydrogeological, geochemical, geophysical and groundwater quality data were collated to formulate a hydrogeological conceptual model, describing the dynamics of groundwater flow, infiltration, storage and contaminant movement underground. Aquifer parameters (Huisamen, 2016) and infiltration rates as well as initial concentrations for sulphate were assigned to each source area to determine the effect of different rehabilitation scenarios. The conceptual model was translated into a numerical flow and transport model, using the polygons generated with the ArcView shape files, assigning aquifer parameters in the SPRING software (Witthueser, 2017), as reflected in Figure 2 below.

Rehabilitation scenario modelling

As the geochemical work and simulations in the groundwater model indicated that little can be done to change the quality of the water in the long term, the focus was to identify possible rehabilitation scenarios, which would

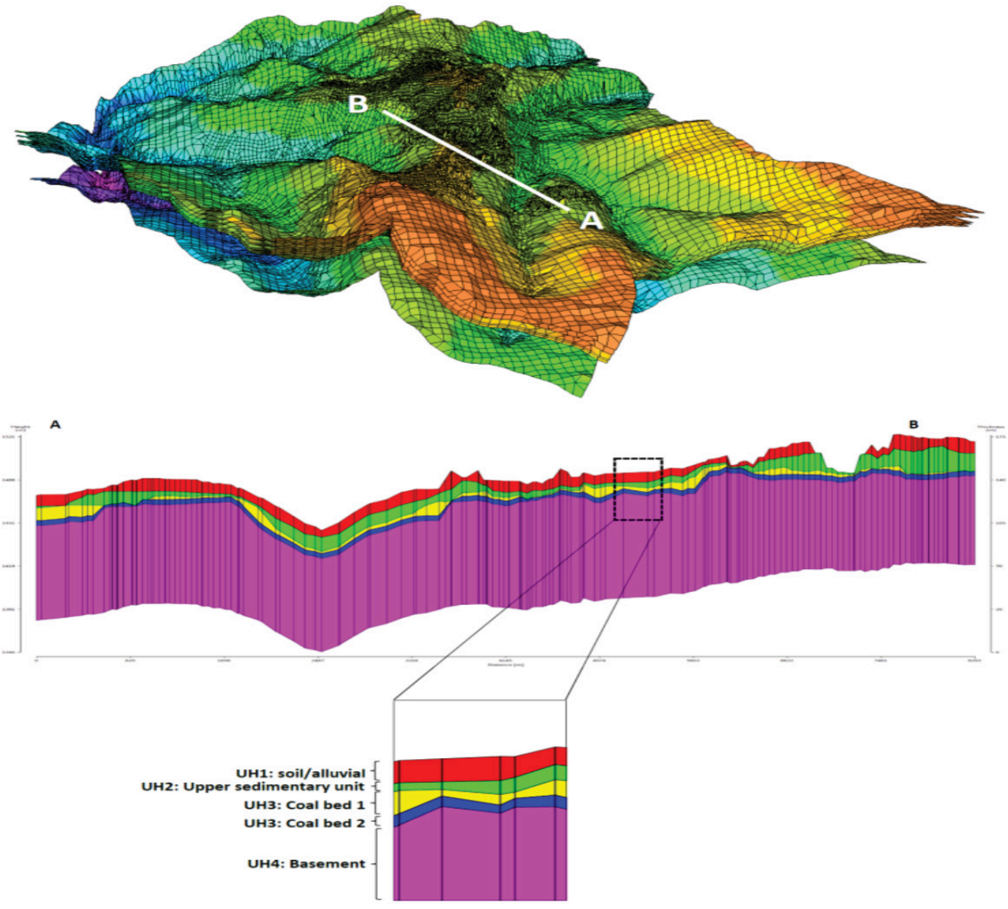

***Figure 2** Vertical discretisation of the groundwater model*

***Table 1** Rehabilitation scenarios*

Scenario	Explanation
Base case	The current closure plan for Kromdraai is to pump water 28 km to the EWRP and to treat through RO and sell a portion of the water to the municipality.
As Is	With no further interventions, large tracts of land will have limited land use and substantial water ingress and higher post closure discharge volumes can be expected.
3BS	Aims only to use all the available topsoil to cover the surface area at the best possible depth, but at least achieving a wilderness land capability.
EMPR	Post closure land use in compliance with existing legal commitments. Due to substantial topsoil shortage, this scenario will require import of growth material.
Upside	Improves on the EMPR scenario by increasing topsoil depths with specific focus on upscaling post closure wilderness land use to grazing.
4BS	Aims to achieve the best possible outcome in terms of soil thickness. Soil thickness is believed to be the best preventative measure for water ingress in addition to vigorous vegetation cover. Import of large amounts of growth medium to achieve a minimum soil thickness of 650mm is required (all arable land).

result in the reduction of infiltration and hence the ultimate volume of water that would require post closure treatment (Table 1).

The four rehabilitation scenarios (3BS, EMPR, Upside and 4BS) consisted of different percentages of arable, grazing and wilderness land, based on different growth medium depths (650mm for arable vs. 350mm for grazing vs. 250mm wilderness cover respectively), which resulted in different seepage rates and different levels of legal compliance, as demonstrated in Figure 3 and Table 2.

Furthermore, closure calculations included rehabilitation requirements as reflected in Table 3, which were added to the capex component in the closure calculation and were spread over four to five years in line with the rehabilitation process. Each scenario was costed for import of topsoil as well as for scavenging of topsoil on site to address the shortfall of topsoil.

Simulation of variable management scenarios

Two phases of scenario modelling were completed (Muhlbauer, 2017). The first phase included modelling of 22 different combinations whilst the second phase included modelling of only five scenarios based on the outcomes of the first phase. During phase 1, the 22 post-closure modelled scenario combinations considered the effect of various rehabilitation strategies on the

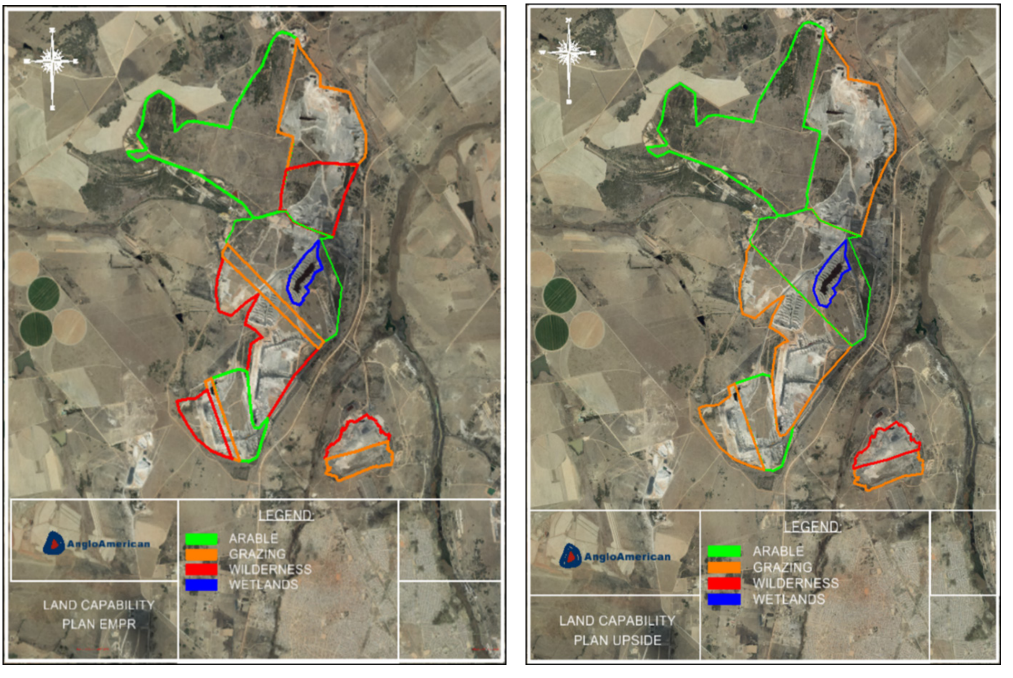

Figure 3 *Environmental Management Plan Report rehabilitation scenario (left) and Upside scenario (right)*

Table 2 *Closure costs for rehabilitation scenarios*

Scenarios	Legal Compliance (Yes / No)	Growth Medium Volume required (m^3)	Rehabilitation Cost (ZAR)*
Scenario 3BS	No	-	84,776,554
EMPR Compliance	Yes	2,249,606	226,661,763
Upside	Yes	2,455,712	233,993,748
Scenario 4BS	Yes	5,265,044	419,469,506

*One USD is approximately 14.50 ZAR

predicted post-closure recharge, leakage from dams containing ferrihydrite ($FeOH_3$ also known as Yellow Boy) and discharge volumes. Model predictions provided discharge locations and discharge rates based on certain assumptions. Therefore, only approximate percentages of discharge rates for the different discharge areas were provided as reflected in Figure 4.

Actual volumes were assigned to each discharge area to enable preliminary comparative water treatment cost calculations to be completed for the identification of scenarios which could then be further refined. In Phase 2, five scenarios (Table 3) were refined using the existing numerical hydrogeological water transport model (Witthueser, 2017). To enable water treatment cost calculations, the estimated discharge volume for each area as reflected in Table 3 was derived from the percentage apportionment of discharge rates in each area using the total estimated closure discharge volume for each scenario.

Selection of the preferred post closure groundwater solution

The post-closure modelled volumes were used to assess the most appropriate treatment scenario. The following criteria for treatment of affected water were applied: (1) Reactive barriers, phytoremediation and expanded wetlands would be used for flow rates of less than 0.2 ML/day. These flow rates are generally dispersed over an area resulting in diffuse seepage; (2) Biological passive treatment systems would be applicable for flow rates between 0.2 and 1.4 ML/day. These flows can be collected in dedicated ponds and gravity-fed into passive biological systems; or (3) RO treatment at the EWRP for flows of 1.4 ML/day or above.

Capital estimates and operational costs

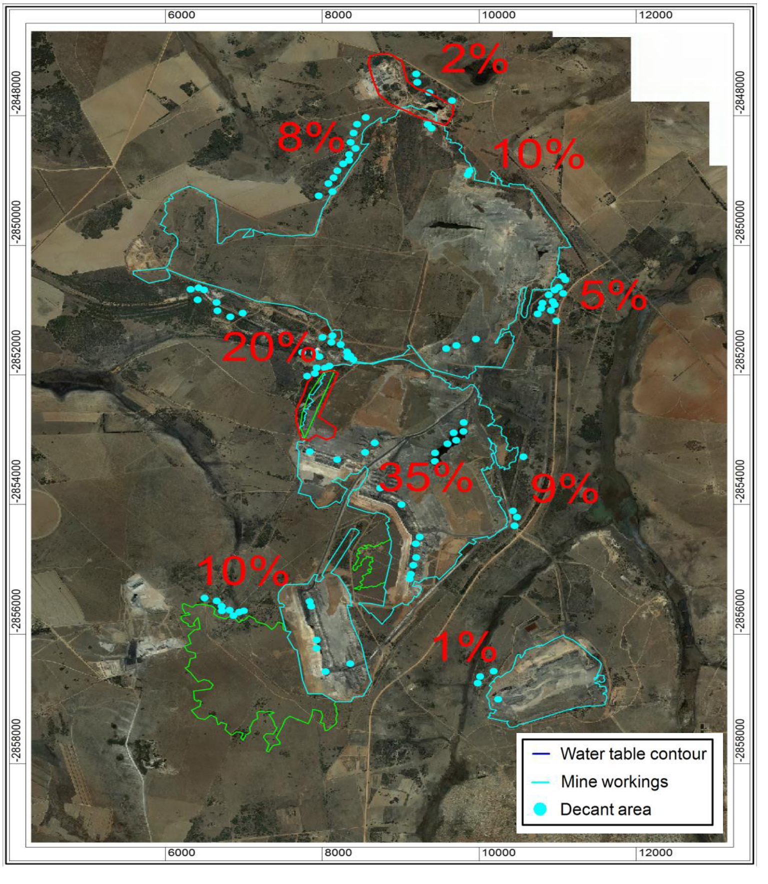

Figure 4 *Apportionment of discharge rates (red) within the mining areas (simulated discharge location)*

Table 3 Post-closure mine water balance for the rehabilitation scenarios

Scenario	Recharge backfilled and undermined areas (ML/d)	Predicted discharge rate (ML/d)
Base case	10.5	7.4
As Is	7.0	4.6
3BS	6.4	4.0
EMPR	5.7	3.5
Upside	5.2	3.1
4BS	4.4	2.5

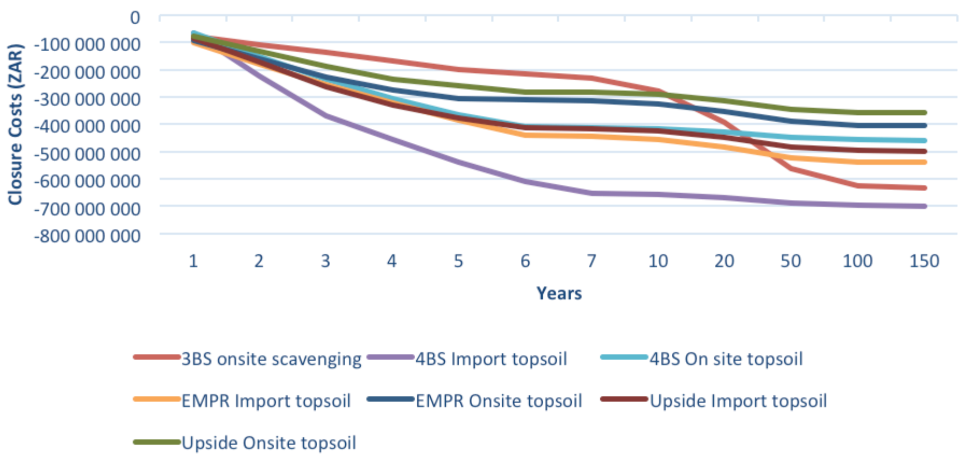

Figure 5 Closure costs for different rehabilitation scenarios (net present cost)

were derived from the closure models used for water liability calculations for both the EWRP and passive treatment calculations. Phytoremediation information was based on planting trees at a certain density to achieve evapotranspiration based on water uptake rates for certain rainfall averages. This enabled the development of detailed cost benefit analysis for each of the various scenarios, comparing increased rehabilitation costs against the benefits of a reduction in long-term groundwater treatment. This ultimately resulted in the selection of the preferred long-term solution.

The effect of improved rehabilitation on water liability costs is evident in Figure 5.

Based on the results from the financial modelling, the "Upside" scenario with on-site scavenging of topsoil aimed at upgrading the wilderness land use to grazing is the most beneficial solution in terms of long-term liabilities, and hence the selected solution.

Conclusions

The development of a defensible hydrogeological conceptual model and calibrated numerical flow and transport model, collating historical information was used to address substantial hydrogeological gaps. This allowed for the simulation of the post closure water volumes and quality applying various rehabilitation scenarios. Improved rehabilitation practices are key to ingress management and as a result discharge volumes that need to be managed. A reduction in discharge volumes allows for the implementation of more cost-effective sustainable treatment options which ultimately reduce long term water liability costs, however this cannot be at the expense of importing topsoil.

Current closure practices tend to defer rehabilitation and mine closure to reduce costs in the short-term, however this increases our long-term financial water liabilities. These typically need to be managed in perpetuity which precludes sites from obtaining closure certificates. The project clearly demonstrates that the timeous implementing of appropriate surface rehabilitation will have a substantial effect on the long-term groundwater and surface water liabilities.

The Upside scenario as the preferred long-term solution, will reduce the original estimated closure liabilities (pre-project) of more than ZAR 2.5 billion to less than ZAR 0.5 billion over a 150-year period. Even though the business case for improved and timeous surface rehabilitation has been demonstrated clearly through this project, the need for sustainable long-term use of the "post passive treatment" water is required to make the solution self-funding and truly sustainable. These requirements can be addressed by initiatives, such as the "The Green Engine" concept that is currently being developed for the Kromdraai area. The Green Engine will provide a self-funding agri-businesses opportunity that will contribute to the management of water ingress and ultimate reduction in discharge of polluted water, by deploying solar PV farms that can capture water run-off, vertical greenhouses and other infrastructure where storm water is captured and used as part of the agri-businesses. The benefits are that water becomes an asset to the community and the agri-businesses and results in a reduction of closure liability costs related to import of top-soil and active water treatment. Changing a perpetuity liability into a sustainable post closure opportunity.

Acknowledgements

The authors wish to thank and acknowledge the Kromdraai team, the Coal Head Office team and the team from Technical & Sustainability for working together over more than two years to complete this project and in doing so adding substantial value to the business.

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