Modelling and optimisation of a hydrocyclone classifier as a pre-treatment stage in fine coal beneficiation

Mpho Ramudzwagi[1,*], *Nkumeleni* Tshiongo[1], *Willie* Nheta[1]

[1]University of Johannesburg, P.O. Box 17011, Doornfontein 2028, Johannesburg, South Africa

Abstract. Coal goes through several types of beneficiation processes that seek to retrieve nearly as much coal as possible in all size fractions. When approaching the finest size of extraction, clean coal extraction becomes limited, hence, there is an increase in fine coal dumps across the top 10 coal-producing countries. Since several extraction processes depend on size, the separation becomes size-limited, i.e., being able to work optimally in a certain size range, be it fines or ultra-fines. The application of hydraulic classifiers and mechanical sieve screens becomes limited when approaching the finest size of extraction. The hydrocyclone classifier has been widely employed to pre-treat the feed in terms of size before fine coal cleaning using other advanced technologies due to its higher centrifugal force. While hydrocyclones serve a crucial function, several factors contribute to the complexity of hydrocyclones in mineral processing plants. In this study, the pre-treatment of coal with an ash of 34.0% was investigated. Several factors of the hydrocyclone classifier were considered, i.e., particle size, spigot size, inlet pressure and the % solids. The modelling and optimisation were achieved using the Taguchi design of experiments, which was an L25 orthogonal array that was developed using Minitab statistical software. The optimal operating parameters for the hydrocyclone were 10% solids w/w, a 20 mm spigot, 770 µm F80, and an inlet pressure of 50 kPa. The best outcomes demonstrated a notable improvement in the quality of the coal, with a 30.3% reduction in the underflow ash. The coal yield was evaluated to be 79.2%. The study demonstrated the capability of the hydrocyclone to pre-concentrate fines.

KEYWORDS: Fine coal processing, Taguchi, hydrocyclone classifier, Optimisation

1 Introduction and background

During the mining and beneficiation process of coal, different size fractions are generated because of the friable nature of coal when conducting blasting and crushing. A typical coal preparation plant crushes coal down to a top size of 50 mm and deslimes at 1 mm. The -50 +1 mm is described as coarse coal size fraction and is treated using gravity concentration technologies such as jigs and dense medium separation. The -1 mm is sent to the hydrocyclone classifier, producing two products, i.e. a -150 um overflow and a -1 +150 um underflow that can be sent for further upgrade using other forms of fines gravity concentrating methods, namely spirals and hindered bed separators [1–3].

It is necessary to separate the fines and ultra-fines for the following reasons: processing inefficiencies occur as gravity-based separation methods are less effective in processing particles less than 150 µm [4]. Finer coal tends to have high ash due to coal being fully liberated from mineral matter, which tends to reduce energy efficiencies during coal combustion. Ultra-fines complicate handling and dewatering, as the finer particles tend to retain more moisture, making subsequent processing stages more challenging and less efficient [5–7]. For more than three decades, the hydrocyclone classifier has been used for sizing applications and is favourable because of its desirable characteristics, such as being very compact and attaining high processing capacity [8–10].The hydrocyclone is not regarded as sizing equipment in coal beneficiation; rather, it is considered as a washing equipment. Consequently, the removal of the -150 µm size fraction has the potential to enhance the quality of the coal in terms of size throughput, ash , and calorific value.

The performance of the hydrocyclone is primarily ascribed to feed-dependence and geometric factors. These factors have significant importance in the selection of the correct cyclone for the desliming of coal fines [8]. Factors such as solids feed rate, particle density, feed slurry volumetric flow rate, required cut point, and estimated solids mass split to underflow are crucial for efficient cyclone operation [11]. Proper cyclone selection and operation can lead to improved separation efficiency and better performance in downstream processes like spiral concentrators. Very small cone-angle hydrocyclones have been investigated for pre-desliming high-ash fine coal [12]. The study found that these hydrocyclones effectively reduced the ash in the fine fraction, leading to improved overall coal quality. This approach is particularly beneficial for coal slimes characterised by a high ash fine coal fraction. Turkish lignite tailings were evaluated to study the effects of different process variables on hydrocyclone performance for beneficiation[13]. The study demonstrated that hydrocyclones could effectively reduce ash and improve the calorific value of the clean coal product, highlighting their applicability in processing lignite tailings

To maximise separation efficiency, decrease ultrafine contaminants, and improve process performance and product quality, this study explores the modelling and optimisation of a hydrocyclone classifier as a pretreatment step in fine coal beneficiation.

2 Methodology

2.1 Materials and Characterisation

South African run-of-mine (RoM) coal from Wonderfontein seam 3 with a -600 +1 mm size range was used to conduct the study. The material characterisation includes particle size distribution (PSD) and chemical analysis, which includes XRF, XRD and proximate analysis (ISO 174246:2001). ISO 1928:2009 using e2k combustion was used to determine the calorific value (MJ/kg). To separate the coal into fines and ultra-fines, a VV165 hydrocyclone classifier with a fixed vortex finder and a diameter of 40 mm and 165 mm, respectively, was used (Fig. 1).

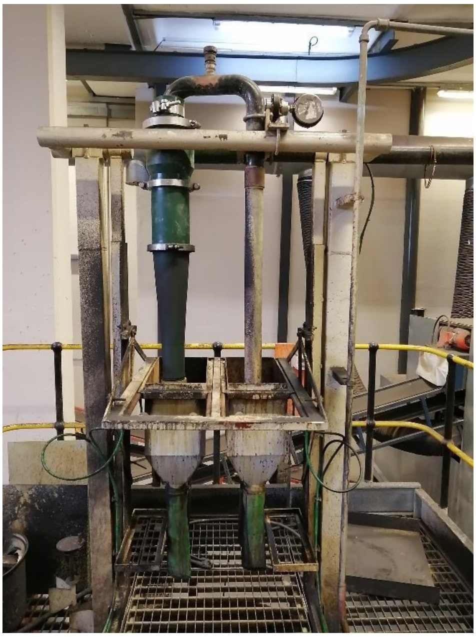

Fig. 1. Experimental hydrocyclone classifier rig

2.2 Modelling

To better optimise the hydrocyclone as per the study objective, a Taguchi design of experimentation was utilised. An L25 orthogonal array was developed as shown in Table 1 to maximise the performance of the hydrocyclone classifier by manipulating the parameters such as % solids (A), spigot size (B), F80 (C) and inlet pressure (D). The hydrocyclone classifier was optimised based on the following output variables: % ash value and % yield. The L25 orthogonal array is summarised below. The mathematical regression model is in the form of Equation 1, which incorporate the main parameters and two-way interactions in line with Taguchi methodology.

$$y = M + A + B + C + D + AB + AC + AD + BC + BD + CD \qquad (1)$$

Table 1: L25 orthogonal array

Experiment number	solids (wt.%)	Spigot size (mm)	F80 (μm)	Inlet pressure (Kpa)
1	5	15	770	20
2	5	18	650	40
3	5	20	530	50
4	5	23	310	60
5	5	25	220	80
6	7	15	650	50
7	7	18	530	60
8	7	20	310	80
9	7	23	220	20
10	7	25	770	40
11	10	15	530	80
12	10	18	310	20
13	10	20	220	40
14	10	23	770	50
15	10	25	650	60
16	13	15	310	40
17	13	18	220	50
18	13	20	770	60
19	13	23	650	80
20	13	25	530	20
21	15	15	220	60
22	15	18	770	80
23	15	20	650	20
24	15	23	530	40
25	15	25	310	50

3 Results and discussion

3.1 Particle size distribution of the coal sample after crushing and milling

Fig.2 shows the different F80 size distribution of the hydrocyclone classifier generated from crushing and milling.

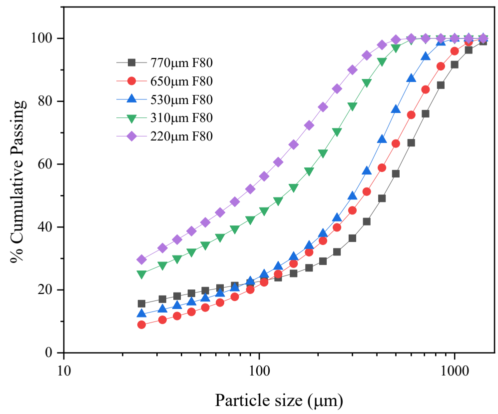

Fig. 2. RoM particle size distribution after crushing and milling

3.2 Proximate and chemical analysis

3.2.1 Proximate analysis

34.03% ash was attributed on to the RoM using proximate analysis which also contained 1.37% moisture content, 24.02% volatile matter content, 40.88% fixed carbon content and a calorific value of 19.66MJ/kg.

Fig. 3 depicts the ash profile of the various hydrocylone feeds demonstrating that, for the various size fractions that, the ash value rises as the feed's top size decreases.

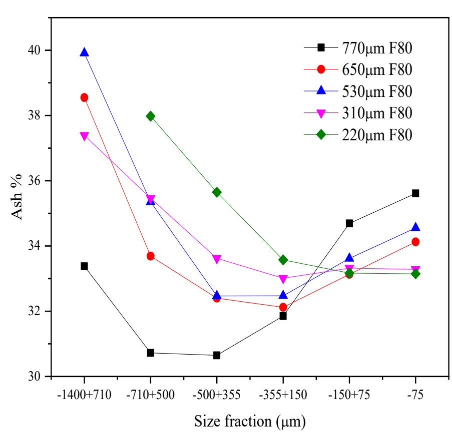

Fig. 3. Ash profile of the various feeds of RoM

3.2.2 Chemical analysis using XRF and XRD

The coal has a high concentration of Si (23.3%) and Al (13.7%). Kaolinite, quartz, and ilmenite material—three of the most dominant minerals in Southern African coal—are primarily linked to this elemental composition[14]

3.3 Modelling

3.3.1 Signal-to-noise ratio analysis

Signal-to-noise ratio was used to determine optimum operating conditions, and again to determine the level of significance of parameters based on the stability of variation between mean effect and response variables of the hydrocyclone classifier. The Signal-to-Noise ratio analysis confirmed that spigot size was the most influential factor for ash reduction, as it produced the largest delta in the smaller-the-better formulation which signifies a goal to obtain low ash as shown in Table 2. A less negative (i.e., higher) S/N for ash indicates lower ash with less variability. When comparing factor levels, the level that maximizes the S/N (because it penalizes large ash values and variability) was nominated. For yield, the larger-the-better formulation which signifies a goal to obtain high yield showed inlet pressure and spigot size as the most significant contributors as displayed in Table 3. A higher S/N for yield indicates higher yield with less variability. Overall a higher S/N ratio indicates not only improved performance (lower ash or higher yield) but also more consistent results with reduced variability. This highlights that optimising spigot size and inlet pressure is critical to achieving stable and efficient hydrocyclone performance.

Table 2: Signal-to-noise ratio for % Ash value

Level	Solids (Wt.%)	Spigot size (mm)	F80 (µm)	Inlet Pressure (kPpa)
1	-27,9	-27,26	-28,29	-27,63
2	-27,86	-27,66	-27,78	-27,69
3	-27,53	-27,7	-27,69	-27,69
4	-27,66	-28,02	-27,27	-27,72
5	-27,99	-28,29	-27,91	-28,21
Delta	0,46	1,03	1,02	0,58
Rank	4	1	2	3

Table 3: Signal-to-noise ratio for % yield

Level	Solids (Wt.%)	Spigot size (mm)	F80 (µm)	Inlet Pressure (kPa)
	37,43	36,47	36,86	37,57
2	37,57	36,95	36,77	37,28
3	37,33	37,1	37,82	37,12
4	37,21	38,19	37,9	37,48
5	37,88	38,7	38,06	37,97
Delta	0,67	2,23	1,29	0,85
Rank	4	1	2	3

3.3.2 Regression model for % ash and % yield

Analysis of variance for the % ash and % yield is displayed in Tables 4 and 5, respectively. R^2 values above 80% demonstrate that the regression models explain most of the variability in the data, confirming good predictive accuracy[15]. Durbin Watson test statistics number for both response models i.e. % ash and % yield was closer to two; this suggested that the developed models are adequate and reliable. Durbin Watson number being close to two is important in understanding the reliability of regression model[16]. The significance of each parameter was confirmed using both the F- and p-values. For example, spigot size showed the highest effect on ash content (**F = 15.46, p = 0.002**), while inlet pressure had the strongest effect on yield (**F = 6.90, p = 0.020**). A two-sided confidence interval of 90% ($p < 0.10$) was adopted, and statistically significant values have been highlighted in bold in the ANOVA Tables 4 and 5. By making use fissure test (F-value), the order of significance in terms of parameter effect on the % ash and % yield was observed to be as follows.

- % Ash: B > AB > BC > C > BD > D > A > CD > AD > AC
- % Yield: D > BD > CD > B > C > AD > AB > BC > A > AC

Table 4: ANOVA for % ash

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	59,3812	5,9381	7,61	0
A	1	1,7128	1,7128	2,2	0,161
B	1	12,059	12,059	15,46	**0,002**
C	1	3,7127	3,7127	4,76	**0,047**
D	1	1,9264	1,9264	2,47	0,138
AB	1	7,5704	7,5704	9,7	**0,008**
AC	1	0,0003	0,0003	0	0,986
AD	1	1,3526	1,3526	1,73	0,209
BC	1	4,5913	4,5913	5,89	**0,029**
BD	1	2,4315	2,4315	3,12	**0,099**
CD	1	1,352	1,352	1,73	0,209
Error	14	10,9209	0,7801		
Total	24	70,3021			
Note R^2 = 84,47%; R^2 (adj.) = 73.37%					

$$Ash\,\% = 24{,}565 + 0{,}0835A + 0{,}3165B - 0{,}00150C + + 0.0102D - 0{,}0761AB - 0{,}000010AC + 0{,}00625AD - 0{,}001156BC - 0{,}00503BD - 0{,}000114CD \quad (2)$$

Table 5: ANOVA for % yield

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	2019,62	201,962	12,51	0
A	1	19,01	19,014	1,18	0,296
B	1	40,72	40,72	2,52	0,135
C	1	34,93	34,927	2,16	0,163
D	1	111,4	111,403	6,9	**0,02**
AB	1	20,19	20,187	1,25	0,282
AC	1	8,41	8,415	0,52	**0,482**
AD	1	30,24	30,244	1,87	0,193
BC	1	19,32	19,323	1,2	0,292
BD	1	97,03	97,029	6,01	**0,028**
CD	1	69,65	69,647	4,31	**0,057**
Error	14	226,07	16,148		
Total	24	2245,69			
Note R^2 = 89,93%; R^2 (adj.) = 82,74%					

$$\%Yield = 75{,}479 + 0{,}511A + 1.973B + 0{,}01418C + 0{,}0526D + 0{,}124AB + 0{,}00181AC + 0{,}0295AD - 0{,}00237BC - 0{,}0318BD - 0{,}000816CD \quad (3)$$

3.3.3 Parameter effects on the % ash.

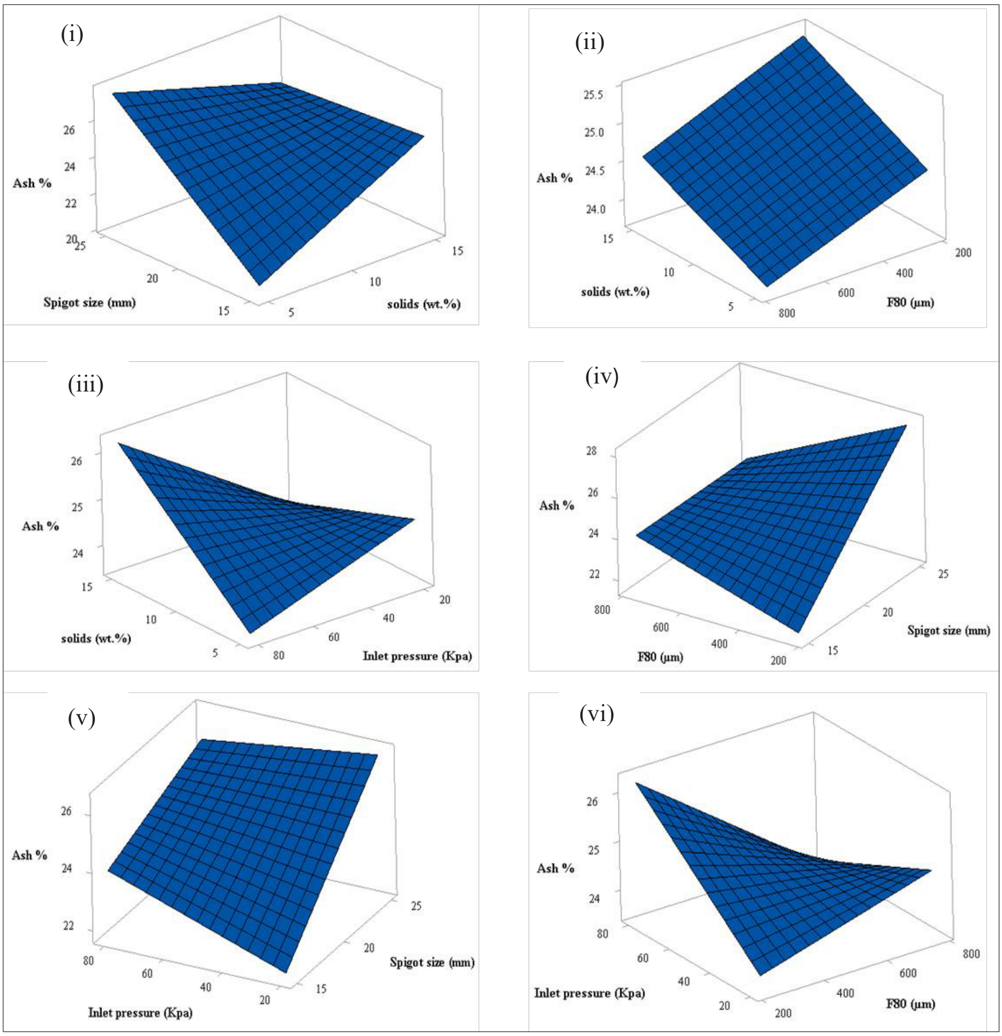

Fig 4. Parameter interaction on the ash % (i) A*B, (ii) A*C, (iii) A*D, (iv) B*C, (v) B*D and (iv) C*D

Fig 4(i) to (vi) display the effects and their interaction effect on the % ash parameter interaction was observed according to Fig 4(ii) was observed between % solids and F80. Figures(i), (iii), (iv), (v) and (vi) observed an interaction that exists between parameters that are in participation. From equation 2 to it was observed that an increase in % solids, spigot size and inlet increases the % ash. It has been observed [17–19] that an increase in inlet pressure and % solids have an increasing effect on the % ash of the underflow. An increase in spigot size has been reported [20] to lower the d50, which causes an increase in pressure drop, hence an increase in the underflow ash %. Regarding Fig 4 (ii), observation was made [21–24] that increasing the % solids increase the d50, which overall reduces the fines associated with high ash in the underflow.

3.2.4 Parameter effects on the % yield

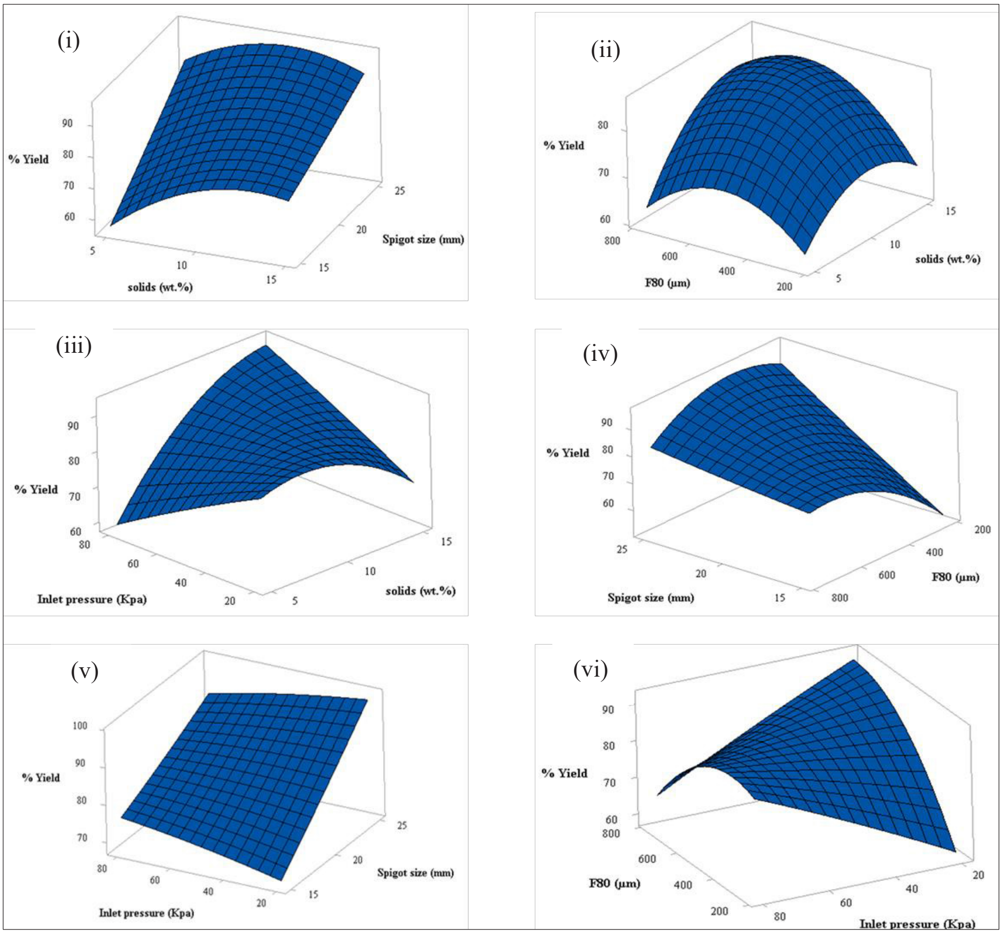

Fig 5: Parameter interaction on the % yield (i) A*B, (ii) A*C, (iii) A*D, (iv) B*C, (v) B*D and (iv) C*D

Fig 5 (i) – (iv) displays the parameter effect and interaction that exist on the % yield of the product underflow of the hydrocyclone classifier. The effect of parameters differs depending on the level set point, which results in a potential interaction existing between the two parameters in question. With the assistance of equation 3, positive 1st order coefficients were observed, which suggest that increasing the effect of % solids, spigot size, F80 and inlet pressure results in an increase in % yield. [25] concluded that particles reporting in the underflow product increases with increasing particle size. [26] also concluded that increased spigot size is associated with reduced resistance of flow of material to underflow, which eventually increases the % yield. Regarding Figure 5 (i), a small spigot size results in increased solids concentration within the hydrocyclone classifier, this results in reduced air-core, which leads to roping increase in by-pass, which produces high yield underflow [27] .Increasing the % solids increase pressure drop within hydrocyclone system which increases fines to report to underflow thereby increasing % yield [28] .

4 Conclusions

The hydrocyclone was able to reduce the % ash in the feed by obtaining an underflow with 22.7% ash and 79.2% yield. The feed before beneficiation had a 30.9% ash reduction, indicating that the hydrocyclone classifier can be used as a pre-treatment stage to reduce the ash percentage in coal fines feed. The operating parameters established were 10% solids w/w, 20 mm spigot size, F80 of 710µm and inlet pressure of 50 kPa.

The statistical significance of parameters was established for both % ash and % yield. The spigot size is the most sensitive factor when operating the hydrocyclone classifier. The level of significance was established to be as follows:

- spigot size > F80 of feed > Inlet pressure > % solids.

R^2 for both established models were greater than 80%, which showed good fit and correlation with actual response and predicted response on the effect of each input parameter under investigation. The Durbin-Watson value for both models was close to 2, which illustrates that the models developed are adequate and reliable. The models could be used to explain the parameter effects on the response variable. The errors of the model obtained were less than 10%. It was also observed that the effect of parameters on response variables differs depending on the level of parameters that the hydrocyclone is being operated at, hence parameter interactions were observed in both % ash and % yield.

5 Recommendations

Additional design parameters, such as vortex finder, cyclone length, and cyclone diameter, should be investigated in terms of how they affect the studied response variables. Parameter interaction among operational and response variables was noticed. Parameter interaction can be examined and how they affect the overall hydrocyclone performance. The study should also investigate the validity of the optimal conditions obtained to higher ash feeds.

The authors gratefully acknowledge the support of the University of Johannesburg Mineral Processing and Technology Research Centre (MPTRC) and Gravitas Minerals. This work was funded by the National Research Foundation (NRF), South Africa Coal Processing Society (SACPS) and Multotec Mineral Processing SA. Data supporting this study are available from the corresponding author upon reasonable request. M. Ramudzwagi: conceptualisation,

methodology, writing, statistical modelling and data validation. N. Tshiongo-Makgwe and W. Nheta: supervision, review and editing.

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