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Condition and Performance Assessment of Irrigation Infrastructure at Agri-Parks in Gauteng Province, South Africa

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Abstract: South African agriculture accounts for 62% of the national water demand. Almost 45% of the water is wasted. Therefore, irrigation systems need to improve their water-use efficiency (WUE). However, the WUE of smallholder irrigation schemes in the country, including Agri-Parks, is not precisely known. A study was performed at four Agri-Parks (Rooiwal, Soshanguve, Tarlton, and Westonaria) in Gauteng province to assess the condition and performance of the irrigation systems, as part of a project that aimed to develop a WUE model for smallholder irrigation systems. The Agri-Parks were equipped with efficient irrigation systems in forms of drip and microjets. The assessments were performed at the system component level in February–March 2021. A Condition Assessment Model (CAM), developed by ARC-NRE/AE, was used for the condition assessment. Enumerators observed the system components visually and assigned conditions, which they uploaded into the model to generate condition indices (CIs). Water conveyance efficiency (*CE*) and distribution uniformity (*DU*) were assessed on delivery and infield systems, respectively. The CI values ranged 4–6, implying significant deterioration had occurred. The *CE* was 61–78%, while the *DU* was 60–95%. The infield system CI correlated positively with the *DU*, suggesting the CI could predict the *DU* in drip systems, which was encouraging for the proposed WUE model. However, further research covering a longer period and more Agri-Parks is recommended.

Keywords: Agri-Parks; condition index; performance evaluation; irrigation water management

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1. Introduction

Water is a limited resource in many countries where agriculture is the cornerstone for food security, economic development, and poverty reduction. In general, agriculture is the biggest user of water worldwide accounting for 70–90% of water utilization [1,2]. Most of the agricultural water use is for irrigation because its contribution to food security is very significant [3,4]. While only 20% of the global agricultural land is irrigated, about 39% of the food supply across the world is produced under irrigation. Irrigation also improves the efficiency of production inputs, such as fertilizers, improved seeds, and agrichemicals [5]. However, water losses in agriculture, in particular irrigation schemes, are generally high [6]. In South Africa, where agriculture accounts for 62% of the national demand [7], the water losses from agriculture are estimated at about 45% of the water supplied [8]. Irrigation schemes are reported to account for about 27% of the water losses, with about 12% of the losses occurring in conveyance networks [8]. However, the challenge of water scarcity in South Africa goes beyond the losses in agriculture and the inefficiency of irrigation systems. In a review of challenges and opportunities for water conservation in South African irrigated agriculture, ref. [9] cited the impact of climate change as the major driver of water scarcity.

South African irrigation schemes are under pressure to improve their water-use efficiency [10]. Efficient use of irrigation water is crucial for regions where water resources are diminishing [11]. Efficient water-dispensing irrigation systems and good water management are important for high water-use efficiency (WUE) in irrigation schemes. All types of irrigation systems can potentially be managed to achieve high WUE, but pressurised piped systems offer better prospects than surface flood irrigation methods. The main advantage of the piped systems is their adaptability to almost all crop types, variable topographic conditions, and soil types. However, the pressurized systems are more costly to install and manage than the flood irrigation methods.

Modern low-pressure-requiring systems, such as drip, microjet, and micro-sprayer, systems are more efficient than traditional systems, such as impact sprinklers and pivots, in terms of water application [12]. For instance, the drip system, which applies water slowly but steadily at frequent rates, can save large amounts of water because evaporative losses are very low as the water is applied close to plants. A properly designed, installed, and managed drip system can achieve high water application efficiency in the range of 90–95% [10,11] compared against other systems, such sprinkler systems, whose efficiency is around 70% [13]. High water-application efficiency results in water savings [14] and improves water productivity [15]. Another important aspect of drip irrigation is its ability to combine water and chemical applications, which saves time and labour, and improves the uniformity of chemical applications. The drip system is also compatible with almost all crop types due to its flexibility on row spacing. However, the adoption rate of the drip irrigation system is generally low [16] due to several challenges that include a high capital cost to install the system and the proneness of the emitter to clogging by accumulated salts and suspended materials in the water, which expose farmers to frequent cleaning and replacement schedules. Farmers also perceive irrigation to be synonymous with the wetting of the soil surface, which a drip system does not do appreciably.

The application efficiency of irrigation systems is evaluated during design and operation of the systems [17]. System performance changes over time due to deterioration of equipment. Hence, it is important to assess performance [18,19] to understand current levels and factors of influence [6,20], which is crucial when trying to solve problems of irrigation development and management [1]. Nevertheless, system performance also varies across farms due to differences in management choices and practices. Smallholder irrigators generally lack the means and incentives to know the amount of water they use, their water application rates, and the responses of their crops to different water management practices [10]. In addition, they also lack information on the condition and water delivery performance of their irrigation infrastructure. A study was carried out at selected Agri-Parks in Gauteng Province, South Africa. The aim was to evaluate the correlation between condition of irrigation infrastructure and its performance in terms of water delivery.

2. Materials and Methods

2.1. Study Sites

The study was performed at four selected Agri-Parks in Gauteng province of South Africa, namely Rooiwal, Soshanguve, Tarlton, and Westonaria (Figure 1). An Agri-Park is a market-driven integration of agricultural activities to form a networked innovation system of agro-production, processing, logistics, marketing, training, and extension services. Agri-Parks contribute immensely to food security, economic development, and poverty reduction, especially among women and youth. There are 44 Agri-Parks dotted across South Africa, some of which have collapsed [21]. The four selected Agri-Parks in Gauteng province were active at the time of the study and were easy to access.

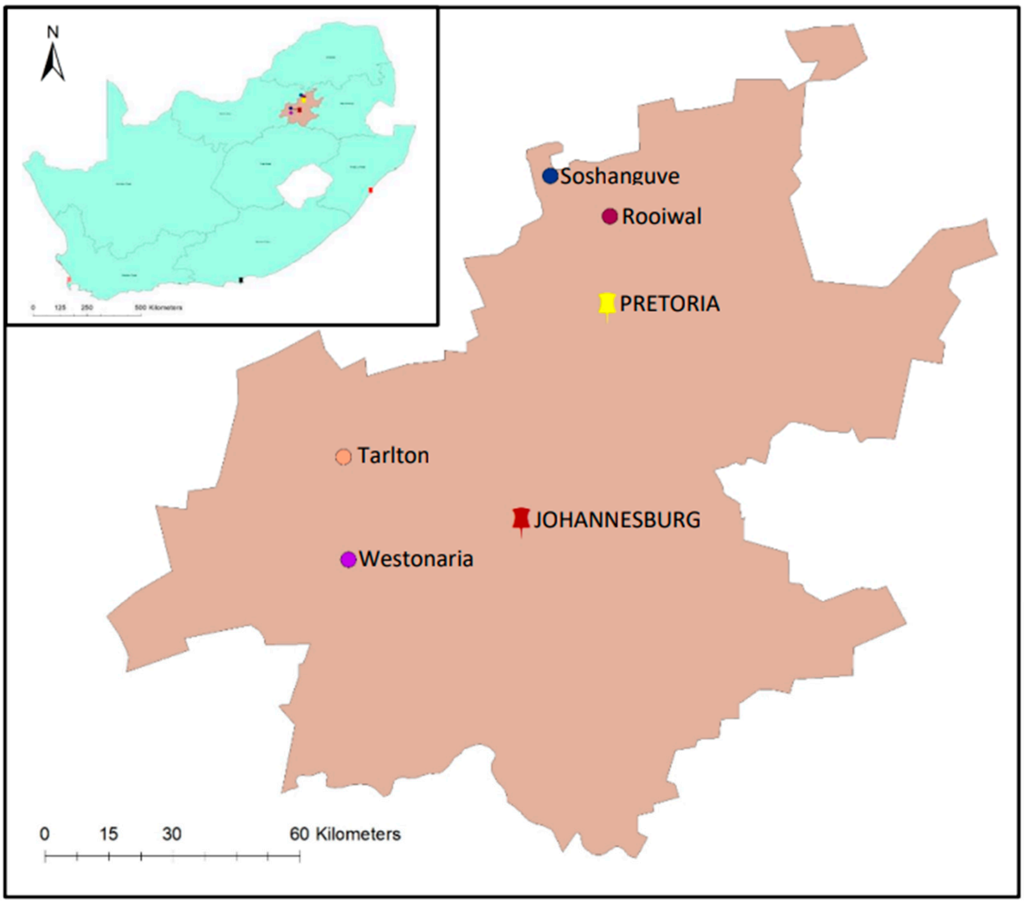

Figure 1. Map of Gauteng province showing locations of Soshanguve, Rooiwal, Tarlton, and Westonaria relative to the cities of Pretoria and Johannesburg. Insert is a map of South Africa showing the location of Gateng Province.

According to the Weather Atlas (www.weather-atlas.com, accessed on 16 November 2022), the climatic characteristics for the four study sites differed significantly. The average precipitation for Soshanguve and Rooiwal, which are in the northern zone of Gauteng, are 583 and 516 mm year^{-1}, respectively. The average precipitation for Westonaria is 541 mm year^{-1}. Tarlton is the driest site with average precipitation of 441 mm year^{-1}. Long-term average temperature also varies greatly with Soshanguve and Rooiwal averaging 18.5 and 18.8 °C, respectively. The respective average temperatures for Tarlton and Westonaria are 23.8 and 15.9 °C, respectively. Soil properties also show great variability with Rooiwal and Tarlton exhibiting loamy soils, while Soshanguve has gravelly soil and Westonaria sandy soil.

The drip irrigation system was the irrigation technology used at the selected sites. It is the most efficient irrigation water application system with a capacity to deliver water and chemicals precisely and uniformly at a higher frequency of application than other systems [5]. It offers many advantages over other irrigation methods, such as reduced hazard of runoff and erosion on steep slopes; leaching of excessive salts and phytotoxins from the root zone; adaptability to remote areas without pressurized water systems; conservation of water where it is costly or scarce; and promotion of deep root growth and better plant development [22]. Conventional methods of irrigation have not been efficient in the use of water, thus, resulting in excessive wastage of water and creation of environmental problems, such as waterlogging and salinity [4]. Tomato and green pepper were the dominant crops at the selected Agri-Parks. However, coriander was also an important crop at Rooiwal.

2.2. Experimental Layout

Agri-Parks consist of several irrigation blocks that share water from boreholes at the sites. A typical irrigation block layout consists of a borehole, mainline pipe, storage tank or nest of storage tanks, booster pump, and several greenhouse/shade net tunnels serviced by a sub mainline from the booster pump (Figure 2). The tunnels constitute the irrigation units where water is applied through the drip systems. One irrigation unit at each of the selected sites was randomly chosen for the current study. Figure 2 show a schematic layout of an irrigation block as used in the study.

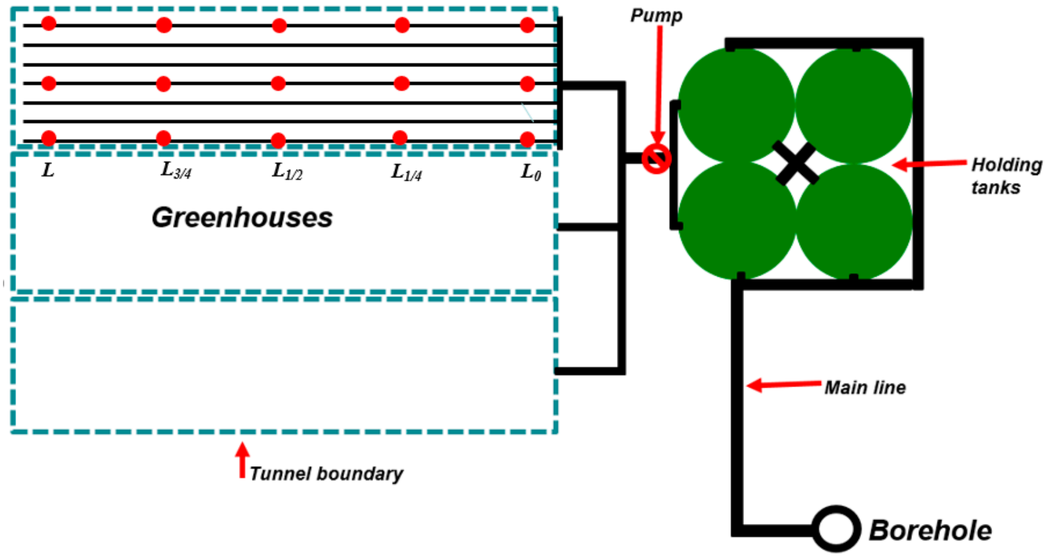

Figure 2. Schematic layout of an irrigation block at each Agri-Park. Dots on the drip lines are the emitter positions along the lateral lines.

2.3. Data Collection

Data collection was performed during the period February to March 2021. The irrigation block selected at each site was divided into five components to facilitate data collection and analysis, namely Pump–Tank, Tank–Booster pump, Booster pump–Filter unit, Filter unit–Manifold, and Infield system. Analysis was performed at the level of these components because remedial actions (maintenance, repair, and/or replacement) were targeted at the level of system components. Nevertheless, each component had its own subcomponents.

2.3.1. Condition Assessment

Data on the condition of the irrigation infrastructure at the selected Agri-Parks were captured and processed using a Condition Assessment Model developed by ARC-NRE/AE (funded by the Gauteng Department of Agriculture, Rural Development and Environment). Data collection involved visual observations and scoring of the visual indicators. The data collection was performed by ARC-NRE/AE engineers. Data collection involved scoring of visual observations of the subcomponents; however, the analysis outcomes generated automatically by the model were at the component level. The model was developed following an Analytical Hierarchical Approach, where irrigators, irrigation equipment suppliers, and experts from the irrigation field were interviewed to help with weighting of factors and subfactors that affect the condition of the irrigation infrastructure. Therefore, the resultant condition index for each component factored in the relative contribution of each subfactor and factor to the condition of a subcomponent. The resultant condition indices for the components were interpreted following Table 1, which was adopted from [23].

Table 1. Condition scores used to rate the irrigation infrastructure at the Agri-Parks, Gauteng province (adopted from [23]).

Scale	Linguistic Scale	Criteria	Action Needed
9–10	Excellent	Newly/recently installed.	No action required.
8–9	Very good	Like new with no signs of corrosion or deterioration.	Reassess in 15 years.
6–8	Good	Coatings, linings still intact. Remaining wall thickness more than 90% of original.	Reassess in 10 years. Schedule for cathodic protection within next 5–10 years.
4–6	Moderate	Some damage to coatings and/or linings noted. Remaining wall thickness 75% or more of original.	Reassess in 3–5 years. Schedule for lining and rehabilitation within next 5–10 years.
3–4	Poor	Significant signs of internal/external corrosion. Collapse inevitable. No lining or coatings. Leaking. Remaining wall thickness 50–75% of original.	Schedule for rehabilitation or replacement within next 3–5 years.
<3	Critical	Severe internal or external corrosion. Collapse evident. Large cracks/holes. Remaining wall thickness less than 50% of original. Breakage rate > 3.	Immediate repair or replacement required.

2.3.2. Performance Assessment

- Conveyance efficiency

Performance assessment was also for both the off-field and infield components. When water passes through the system, every component of the system causes a head loss, which in turn influences efficiency of delivery. In addition, water loss through leakages also affects water delivery efficiency. The off-field components were assessed for water delivery. Therefore, water flow (Q, m^3/s) in pipes constituting the delivery systems between main pumps at boreholes and manifolds at edges of the irrigated lands was measured using an ultrasonic flow transducer (FLEXIM GmbH, Berlin, Germany). The measurements were performed during normal irrigation operating periods when water was running in the pipes. The transducer was calibrated for pipe size, material, fluid type, and temperature before measurements could be performed. Flow measurement was performed at the inlet (inflow) and outlet (outflow) of each component, and the difference between the inflow and outflow constituted a water loss. Conveyance efficiency (CE_i) was the preferred flow performance index and was computed using the equation:

$$CE_i = 100\frac{Q_{in} - Q_{out}}{Q_{in}} \tag{1}$$

where CE_i = conveyance efficiency (%) for the ith component; Q_{in} and Q_{out} = inflow and outflow rates (m^3/s), respectively. The overall conveyance efficiency (CE) at each Agri-Park was computed as the product of the conveyance efficiencies for the system components.

- Distribution uniformity

In addition to head losses, energy loss in the water flowing through pipes also influences the variation of discharge, for example, from the first to the last emitter of a system [3]. Head loss was not investigated in the current study. Drip emitter discharge (q_e, L h^{-1}) was measured at five positions on each of three selected drip lines (Figure 2). The q_e values were subsequently used to compute the Distribution Uniformities (*DU*s, %) for each system using the following equation:

$$DU = \frac{q_{e-1/4}}{q_e} \quad (2)$$

where DU = distribution uniformity (%); $q_{e-1/4}$ = average emitter discharge rates for the lower quarter of the discharge data set in terms of discharge rate, and q_e = average emitter discharge rate for all the measured values.

2.4. Statistical Analyses

Simple statistics were used to analyse and compare the condition and performance of the system components at the selected Agri-Parks. Significancy of differences were tested using the *t*-test at $p < 0.05$.

3. Results

3.1. State of Infrastructural Condition

Table 2 shows the condition indices (CIs) for different irrigation system components as generated using the Condition Assessment Model. The CI values varied greatly among the components at a selected Agri-Park and across the Agri-Parks. The CI values at Rooiwal, varied from 4.71 for the Tank–Booster pump to 5.99 for the Pump–Tank. Therefore, the irrigation infrastructural condition at this Agri-Park was interpreted to be in moderately good condition. The Booster pump–Filter unit at Soshanguve was in the worst condition (CI = 2.73), while the Pump–Tank was in the best condition (6.29). The other components at this Agri-Park were in moderately good condition with CI values varying from 4.10 (Booster pump–Filter unit) to 5.48 (Filter unit–Manifold). Similar to the situation at Soshanguve, the Pump–Tank component at Tarlton was also in the best condition (6.25) amongst all the system components at this Agri-Park. The other components were in moderately good condition (4.90–5.65). Amongst the four Agri-Parks assessed, Westonaria had the worst Pump–Tank (5.61) and Booster pump–Filter unit (2.12) conditions. Overall, the Pump–Tank was in the best condition (5.61–6.29) at all Agri-Parks. The infield systems exhibited surprisingly similar conditions with CI values varying marginally between 5.00 and 5.05. Nevertheless, the infield CIs decreased in the order Rooiwal > Tarlton > Westonaria > Soshanguve.

Table 2. Condition indices (CIs) for irrigation infrastructure components at the Agri-Parks, Gauteng province (February–March 2021).

Irrigation System Component	**CI**			
	Rooiwal	**Soshanguve**	**Tarlton**	**Westonaria**
Pump–Tank	5.99	6.29	6.25	5.61
Tank–Booster pump	4.71	4.10	4.90	4.43
Booster pump–Filter unit	4.90	2.73	5.54	2.12
Filter unit–Manifold	5.52	5.48	5.65	5.60
Infield	5.04	5.00	5.05	5.02

3.2. Water Conveyance Efficiency

Water conveyance efficiency (*CE*) varied greatly across the Agri-Parks with *CE* values hovering between 81 and 99% (Table 3). Rooiwal had *CE* values varying between 92 and 97% for the Filter unit–Manifold and Main pump–Tank, respectively. Soshanguve values ranged from 81% for the Filter unit–Manifold to 99% for the Tank–Booster pump. Tarlton Agri-Park exhibited the lowest *CE* value of 83% for the Main pump–Tank and the highest value of 94% for the Booster pump–Filter unit. The Booster pump–Filter unit performed the poorest at Westonaria with a *CE* value of 73%. However, its Tank–Booster pump component performed impressively at 98% *CE*. Overall, the performance of the Agri-Parks in terms of water conveyance efficiency declined in the order Rooiwal > Soshanguve > Tarlton > Westonaria (Table 3).

Table 3. Conveyance efficiency (*CE*) for irrigation infrastructure components at the Agri-Parks, Gauteng province (February–March 2021).

Section	*CE* (%)			
	Rooiwal	Soshanguve	Tarlton	Westonaria
Main pump–Tank	94	86	83	89
Tank–Booster pump	97	99	91	98
Booster pump–Filter unit	93	99	94	73
Filter unit–Manifold	92	81	93	96
Overall *CE* (%)	78	68	66	61

3.3. Emitter Discharges

Emitter discharge (q_e) varied greatly across the Agri-Parks with Soshanguve showing much lower values in comparison to the others (Figure 3). Performance in terms of the overall average q_e decreased in the order Tarlton > Westonaria > Rooiwal > Soshanguve with respective q_e values of 1.42 ± 0.02, 1.12 ± 0.07, 1.10 ± 0.01 and 0.51 ± 0.01 L h^{-1}. Therefore, the average q_e for Tarlton was the most significant, while that for Soshanguve was the least significant. There was no significant difference in the average q_e between Rooiwal and Westonaria.

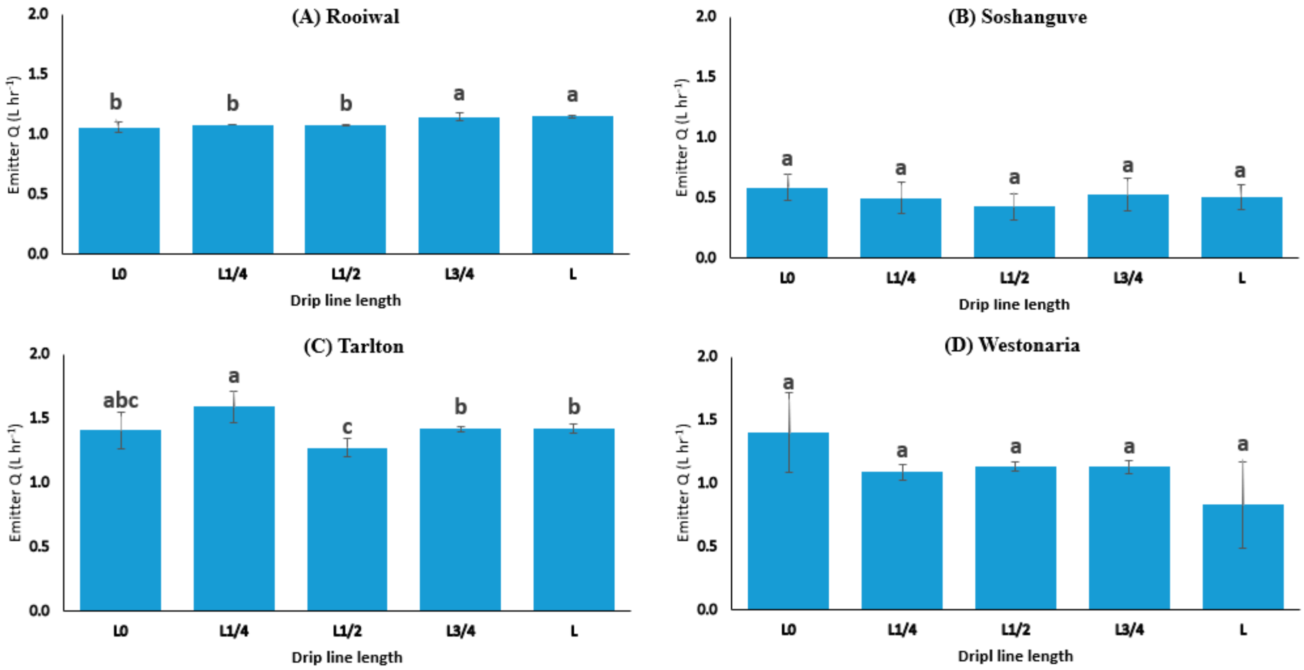

Figure 3. Mean emitter discharges for the different areas of drip lines at (**A**) Rooiwal, (**B**) Soshanguve, (**C**) Tarlton, and (**D**) Westonaria. Bars accompanied by similar letter in each subfigure were not significantly different at $p < 0.05$.

The q_e also varied along the drip lines at each Agri-Park; however, the differences were not always significant. The trend of q_e along the drip lines varied from one Agri-Park to the other. Rooiwal exhibited a general increase in q_e along the drip lines culminating in the highest q_e at $L_{3/4}$ (1.15 ± 0.03 L h^{-1}) and L (1.15 ± 0.01 L h^{-1}), which were not significantly different (Figure 3A). The lowest q_e occurred at L_0 (1.06 ± 0.04 L h^{-1}); however, it was not significantly different from $L_{1/4}$ (1.08 ± 0.00 L h^{-1}) and $L_{1/2}$ (1.08 ± 0.01 L h^{-1}). Soshanguve showed a general decrease in q_e from the inlet to the middle of the drip lines followed by an increase in the downstream direction (Figure 3B). However, the differences of q_e were not significant with values varying from 0.43 ± 0.11 L h^{-1}for $L_{1/2}$ to 0.59 ± 0.11 L h^{-1} for L_0.

In contrast, Tarlton's q_e increased from L_0 to $L_{1/4}$ and then decreased to $L_{1/2}$ followed by an increase (Figure 3C). The highest q_e (1.59 ± 0.12 L h^{-1}) occurred at $L_{1/4}$ and the lowest at $L_{1/2}$ (1.27 ± 0.07 L h^{-1}), which were significantly different. The q_e for the other measurement positions on the drip lines were not significantly different. Westonaria exhibited a general decrease in q_e in the downstream direction (Figure 3D); however, there was no significant differences among the q_e. Therefore, the highest q_e (1.40 ± 0.31 L h^{-1}) occurred at L_0 and the lowest at L (0.83 ± 0.34 L h^{-1}).

3.4. Distribution Uniformity

The computed distribution uniformities (*DU*s) also showed big variations among the Agri-Parks (Figure 4). Nevertheless, all the *DU*s were greater than 50%. The Agri-Park-level *DU* performance decreased in the order Rooiwal > Tarlton > Westonaria > Soshanguve with *DU* values of 95, 86, 67, and 60%, respectively. Nevertheless, these values were generally lower than expected for pressure-compensated drip irrigation systems. Comparing these values with the standard *DU* for drip irrigation of 85% [24], indicates that only Rooiwal and Tarlton were performing at the acceptable level, while Westonaria and Soshanguve performed poorly. Noteworthy is that the value of 86% for Tarlton can be a cause for concern as it is just above the acceptable limit.

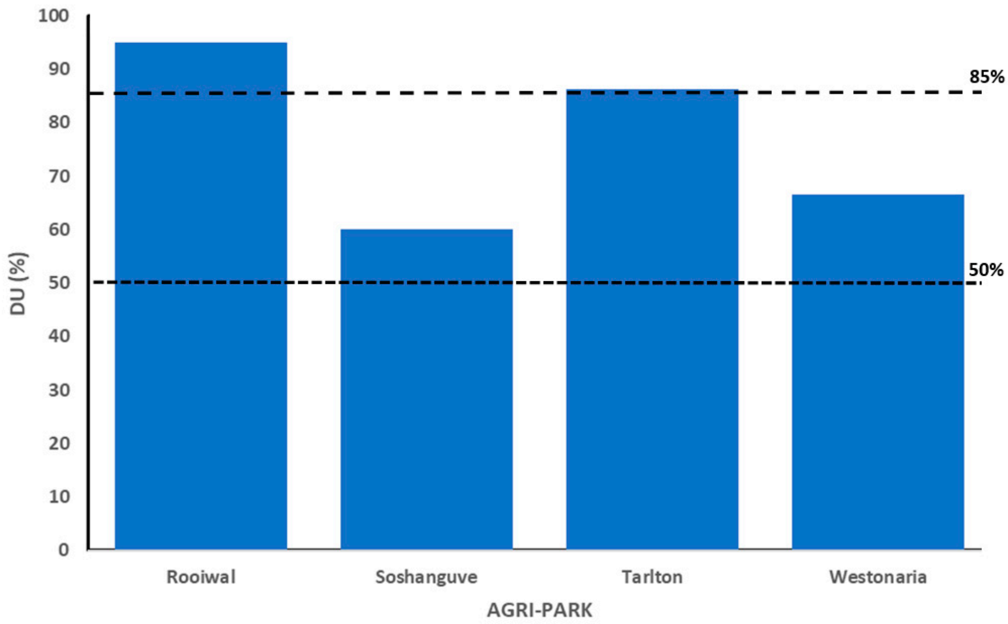

Figure 4. Comparison of distribution uniformities for four Agri-parks in Gauteng province, namely Rooiwal, Soshanguve, Tarlton, and Westonaria.

4. Discussion

Evaluating the condition of irrigation infrastructure is essential because the condition reflects on the level of management and maintenance on the systems. Moreover, the condition often correlates with the performance of the systems. Irrigation system performance is generally evaluated using several parameters and/or indicators at a time [5,17,24,25] because none of the performance parameters are individually conclusive. The authors [5] used distribution uniformity (*DU*), coefficient of uniformity (*CU*), emission uniformity (*EU*), application efficiency (*AE*), and potential application efficiency of the lower quarter. The authors [24] used *CU*, delivery performance ratio, irrigation productivity, labour requirement, and water quality. The authors [25] used *CU*, *EU*, and *DU*. The authors of [17] used a mix of indicators from [5,24]. The choice of parameters depends on whether the assessment is focusing on technical or physical characteristics of the system, aim of assessment, components to be assessed, taste and experience of the evaluator(s), and many other considerations.

Despite no access to baseline data for all the four study sites, the condition assessment results suggest the systems had deteriorated significantly [23]. The condition indices (CIs) varied from 2.12 to 6.29 (Table 2). According to [23], the CIs of <3 for the Booster pump–Manifold at Soshanguve and Westonaria (Table 1) implied a need for immediate replacement because the components had deteriorated beyond meaningful repair. Most of the irrigation system components at the Agri-Parks had CIs between 4 and 6, which implied their use could only be allowed for the next 3–5 years with a reassessment to be performed within the same period. In addition, there is need for the Agri-Parks to plan for repairing the components in 5–10 years' time from the date of the current assessment. The components with CIs > 6, such as the Main pump–Tank components at Soshanguve and Tarlton, were in good condition at the time of the current assessment with clear signs of recent repair works. The recommendations on continued use with contingent plans for repairs are only valid in the absence of a sudden and drastic deterioration during the intervening period. For instance, thefts and vandalism of the system components can invalidate the recommendations. It is, therefore, important to note that the recommendations presented [23] depend on component material responses to the vagaries of the natural operating environments.

It was surprising to observe that some components performed well despite their very poor condition as depicted by their CI values, and some performed not so well despite their good condition (compare Tables 2 and 3). For example, the Booster pump–Filter units at Soshanguve and Westonaria performed well with conveyance efficiencies (CEs) of 99 and 73%, respectively, despite the very low respective CIs of 2.73 and 2.12. This was indicative of the fact that sometimes patchwork repairs can be effective, especially in the smallholder systems where resources are limited. Rubber and plastic were evidently used to reduce water leaks from broken subcomponents at the Agri-Parks. However, the success of patchworks cannot be guaranteed as evidenced by the poor performance of the Booster pump–Filter unit at Westonaria. In contrast, the good condition of the Pump–Tank components at Soshanguve and Tarlton did not result in impressive water *CE*s, where the respective values were 86 and 83%. Nevertheless, Soshanguve still performed better in terms of water conveyance than Tarlton despite the poorer condition, which brings to fore the impact of good management skills and experience. Soshanguve is managed by an individual farmer who has hired a skilled labour force to operate the system daily, while the co-operative of more than five individuals at Tarlton is less-skilled.

Drip irrigation is one of the most efficient irrigation systems when it is managed and maintained properly [26]. The distribution uniformity results show pristine performance at Rooiwal, acceptable performance at Tarlton, and below-acceptable standard at Westonaria and Soshanguve (Figure 4). The results of the study show a close link between the infield infrastructural conditions and distribution uniformity, with both parameters decreasing in the order Rooiwal > Tarlton > Westonaria > Soshanguve. This close relationship suggests that the condition indices could be used as predictors of distribution uniformities in drip irrigation systems at the Agri-Parks. However, there was no clear relationship between the condition indices, on one hand, and conveyance efficiency and emitter discharge, on the other. These Agri-Parks were characterised by rampant water leaks at pipe joints, broken drip lines, suspended drip lines resulting in water drops migrating down the line before they coalesce and fall to the ground, and poor sealing at end of the drip lines.

The current study did not have access to the design documents for the Agri-Parks, which hampered the interpretation of the results because there was no background information to compare against the study observations. The other limitation is that nonphysical parameters that may have a significant influence on the performance of the Agri-Parks (such as the type of land tenure in place and quality of training imparted on the farmers) were not considered. There was also a lack of variety in the study as all the studied Agri-Parks exhibited a close similarity in terms of the irrigation infrastructure and layout. Therefore, there was no opportunity to test the Condition Assessment Model on different setups. It is on the bases of these limitations that a longer-term study covering more and diverse smallholder irrigation systems is recommended. Testing the Condition Assessment Model on a wider scale would help in improving its robustness and predictive capacity. The other recommendation is for proper training of the extension officials responsible for Agri-Parks and similar enterprisers and the farmers' irrigation scheduling under drip systems for better benefits. There is also a need for clear guidelines on cleaning and maintenance of the drip systems and to ensure that the systems are operated within the design limits. Broken drip lines causing leakages need to be replaced immediately.

5. Conclusions

The main conclusion from the study is that the condition of the infield drip irrigation infrastructure has a positive correlation with its distribution uniformity. Therefore, it is possible to use the Condition Assessment Model (developed by ARC-NRE/AE)-generated condition indices to predict the distribution uniformity of a drip irrigation system. This sets a firm foundation for developing a simple model/tool for motoring and evaluating smallholder drip irrigation systems. The tool can be used by extension advisors and local decision makers to guide necessary corrective strategies in the smallholder irrigation sector. It is also clear from the study results that patchwork repairs affected the possible relationships between condition indices and conveyance efficiency of the pipe networks at the Agri-Parks.

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