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Spatial Accessibility to Livestock Sanitary Infrastructure in the Kaniama-Kasese Site in Haut-Lomami Province, Democratic Republic of Congo: A GIS-Based Assessment of Veterinary Vulnerability

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ABSTRACT

Livestock production in rural and peri-rural areas depends not only on herd size and grazing resources but also on access to essential sanitary infrastructure such as dipping facilities, veterinary clinics, watering points, and transport routes. This study analyzes the spatial accessibility of livestock sanitary infrastructure in the Kaniama-Kasese site in Haut-Lomami Province, Democratic Republic of Congo, using Geographic Information Systems (GIS), distance-based indicators, spatial autocorrelation, and multicriteria analysis.

The analysis was based on georeferenced data for 23 kraals, 38 route segments, 24 points associated with watering infrastructure, one veterinary clinic, one existing dipping facility, and one visited kraal. Spatial analyses were conducted in a projected metric coordinate system (UTM Zone 35S). Indicators included kraal density, Euclidean distance to the nearest watering point, veterinary clinic, and dip, as well as proximity to the road network. Global and local spatial autocorrelation were used to examine the spatial structure of sanitary accessibility. A multicriteria sanitary vulnerability index was also developed by combining normalized distances to dips, watering points, and routes.

The results show a low overall kraal density of 0.091 kraals/km² over a convex-hull area of 253.40 km². Mean distance from kraals to the nearest watering point was 1.70 km, whereas the mean distance to the veterinary clinic reached 8.99 km. Kraals were generally well connected to routes, with an average distance of only 0.04 km. In contrast, access to the existing dip was markedly unequal, with a mean kraal-to-dip distance of 8.70 km and strong positive spatial autocorrelation (Moran's $I = 0.584$, $z = 5.09$, $p < 0.001$), indicating significant spatial clustering of sanitary disadvantage.

A simulated second dip located in the most disadvantaged area reduced mean distance to dipping services to 6.22 km, corresponding to a reduction of 28.57%. Spatial clustering also decreased substantially, with Moran's I falling from 0.584 to 0.352. This improvement was statistically significant according to both the paired t-test ($p = 0.0017$) and the Wilcoxon signed-rank test ($p = 0.0039$).

These findings demonstrate the usefulness of GIS-based spatial analysis for identifying veterinary service gaps and supporting evidence-based planning of livestock sanitary infrastructure. The study provides a practical framework for improving spatial equity in animal health service provision in the Kaniama-Kasese site in Haut-Lomami Province.

Keywords: livestock health, veterinary accessibility, sanitary infrastructure, GIS, spatial autocorrelation, multicriteria analysis, Democratic Republic of Congo

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1. INTRODUCTION

Livestock production systems depend heavily on the availability and accessibility of essential sanitary infrastructure. Veterinary clinics, dipping facilities, watering points, and transport routes play a major role in maintaining herd health, reducing disease transmission, and supporting the productivity of pastoral and agro-pastoral systems. In territories where such infrastructure is unevenly distributed, livestock keepers may face important spatial constraints that reduce access to preventive and curative services.

From the perspective of health geography, the spatial organization of service infrastructure strongly influences effective access and territorial equity. Spatial inequalities in service distribution may generate clusters of advantage and disadvantage, particularly where transport conditions, settlement dispersion, and resource location vary significantly across space (Cromley & McLafferty, 2012; Guagliardo, 2004). In livestock systems, such inequalities may translate into longer distances to dips, reduced access to watering points, and heavier logistical burdens for herd management.

Geographic Information Systems (GIS) provide powerful tools for analyzing the spatial structure of service accessibility. Through the integration of georeferenced infrastructure data, distance measures, and spatial statistics, GIS-based approaches make it possible to identify underserved areas, detect clustering patterns, and support infrastructure planning (Longley et al., 2015; Malczewski, 1999). In this regard, spatial autocorrelation techniques such as Moran's I and Local Indicators of Spatial Association (LISA) are particularly useful for determining whether accessibility problems are randomly distributed or territorially concentrated (Anselin, 1995; Moran, 1950).

Despite the growing use of GIS in public health and territorial planning, empirical applications to livestock sanitary infrastructure remain comparatively limited in many African settings. In the Kaniama-Kasese site in Haut-Lomami Province, access to veterinary facilities appears to be uneven, but this inequality has not yet been assessed through a coherent spatial framework combining accessibility indicators, spatial autocorrelation, and scenario-based infrastructure planning.

The objective of this study is therefore to assess the spatial accessibility of livestock sanitary infrastructure in the Kaniama-Kasese site in Haut-Lomami Province using GIS-based methods. Specifically, the study aims to: (i) map the spatial distribution of kraals and key sanitary infrastructure; (ii) measure kraal accessibility to watering points, veterinary services, and the dipping facility; (iii) identify spatial clustering patterns of sanitary disadvantage; and (iv) evaluate the potential effect of introducing a second dip in the most disadvantaged zone.

2. STUDY AREA

The study was conducted in the Kaniama-Kasese site in Haut-Lomami Province, located in the southern part of the Democratic Republic of Congo. According to the spatial extent of the georeferenced data, the study area lies approximately between 23.94°E and 24.09°E longitude and 7.81°S and 7.60°S latitude. The mapped landscape consists of kraals, route segments, watering points, a veterinary clinic, and a dipping facility.

The area presents characteristics typical of livestock production territories where herd management depends on both mobility and access to basic sanitary services. Spatial organization is structured by the location of kraals, the distribution of watering points, and the configuration of the local route network. In such contexts, the relative distance between animal enclosures and sanitary infrastructure becomes a key determinant of veterinary accessibility.

The study area includes a dispersed set of kraals distributed over a relatively broad space. This spatial dispersion makes it especially relevant for examining territorial inequalities in access to animal health services and for testing infrastructure planning scenarios based on GIS.

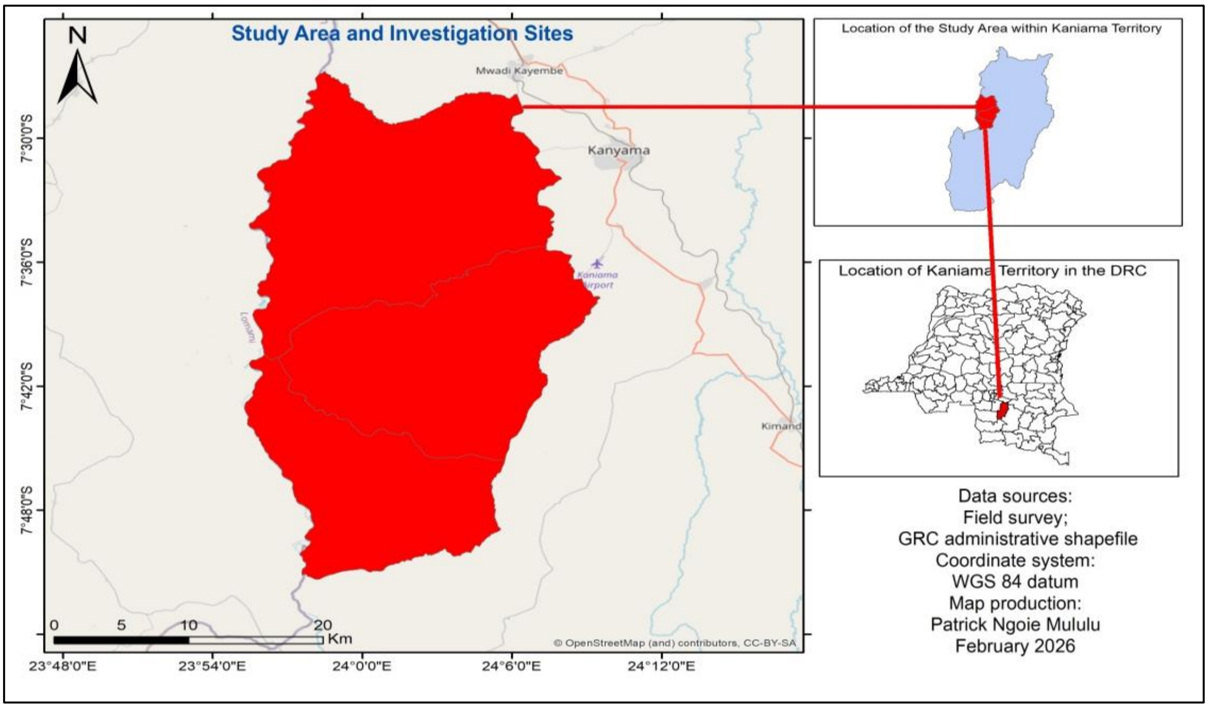

Figure 1. Location of the Study Area in Kaniama Territory, Haut-Lomami Province, DRC

3. MATERIALS AND METHODS

3.1 Data Sources

The analysis was based on six georeferenced spatial datasets describing livestock infrastructure and kraal locations within the Kaniama-Kasese site in Haut-Lomami Province, Democratic Republic of Congo. These datasets were compiled from field observations and spatial digitization and organized into the following shapefiles:

- All_kraal_bien: 23 kraal locations representing livestock enclosures
- All_Rivers: 24 points representing watering infrastructure and associated service locations
- All_Routes: 38 route segments representing the local road network
- Clinique: location of the veterinary clinic
- Dip: location of the existing dipping facility
- Visitekraal: one reference kraal used for field validation

All spatial data were initially recorded in geographic coordinates using the World Geodetic System 1984 (WGS 84). For spatial analysis and metric distance computation, the datasets were projected into UTM Zone 35S (EPSG:32735). Projection to a metric coordinate system is necessary to ensure accurate distance measurements and spatial statistical analysis (Longley et al., 2015).

3.2 Spatial Data Processing

Spatial analyses were conducted using the R statistical environment (R Core Team, 2023) and several specialized spatial packages, including sf, dplyr, tmap, and spdep. The *sf* package was used for handling vector spatial data and coordinate transformations (Pebesma, 2018), while *spdep* enabled the implementation of spatial autocorrelation statistics (Bivand et al., 2013).

All geometries were projected into the UTM coordinate system prior to analysis, and Z-dimension values were removed to ensure two-dimensional spatial consistency. A preliminary cartographic representation was produced to visualize the spatial arrangement of kraals, watering points, routes, the veterinary clinic, and the existing dipping facility.

Kraal density was estimated by dividing the number of kraals by the area of the convex hull enclosing all kraal locations. The convex-hull method is commonly used to estimate the spatial extent of dispersed point datasets and to approximate settlement density in pastoral landscapes.

3.3 Distance-Based Accessibility Indicators

Spatial accessibility to livestock sanitary infrastructure was evaluated using Euclidean distance measures between kraals and key service points. Distance-based accessibility indicators are widely used in health geography to assess spatial proximity to services (Guagliardo, 2004).

For each kraal, three primary accessibility indicators were calculated:

1. Distance to the nearest watering point
2. Distance to the veterinary clinic
3. Distance to the nearest route segment

In addition, the Euclidean distance to the existing dipping facility was computed for each kraal to evaluate accessibility to preventive veterinary services.

All distances were expressed in kilometers and summarized using descriptive statistics including minimum, first quartile, median, mean, third quartile, and maximum values. These indicators provide a quantitative description of spatial disparities in livestock sanitary accessibility.

3.4 Zootechnical Flow Analysis

To better understand the spatial dynamics of livestock management, weekly zootechnical flows between kraals and sanitary infrastructures were reconstructed using spatial connectivity networks. These flows represent the potential movement paths between kraals, watering points, and the dipping facility.

Network visualization allowed the identification of spatial interaction patterns and the estimation of cumulative weekly travel distances associated with routine livestock management activities. The total weekly travel distance for each kraal (distance_totale_hebdo) was calculated and represented through proportional node symbols, enabling the identification of kraals experiencing higher logistical burdens in accessing sanitary services.

This approach provides insights into the territorial organization of livestock management systems and complements classical accessibility indicators.

3.5 Spatial Autocorrelation Analysis

To evaluate whether accessibility to sanitary infrastructure was spatially structured or randomly distributed, spatial autocorrelation analysis was conducted using Global Moran's I (Moran, 1950). Moran's I measures the degree to which similar values occur near one another in geographic space.

Spatial weights were constructed using a k-nearest neighbor structure ($k = 4$) in order to define spatial relationships between kraals. This approach is widely used in spatial statistics when analyzing point datasets with irregular spatial distribution (Anselin, 1995).

An exploratory Moran test was first performed for the distance to watering points. Subsequently, a more robust spatial weight structure was applied to analyze clustering patterns in distance to the dipping facility, which represents the most critical sanitary infrastructure.

Local spatial autocorrelation was also evaluated using Local Indicators of Spatial Association (LISA), allowing the classification of kraals into local spatial clusters such as:

- high–high clusters

• low–low clusters
• high–low spatial outliers
• low–high spatial outliers
• non-significant patterns

This analysis enabled the identification of spatial clusters of sanitary disadvantage.

3.6 Multicriteria Sanitary Vulnerability Analysis

To capture the combined effects of multiple accessibility constraints, a multicriteria sanitary vulnerability index was developed. Multicriteria spatial analysis is commonly used in geographic information science for evaluating complex spatial decision problems (Malczewski, 1999).

Three accessibility indicators were included in the vulnerability index:
• distance to the dipping facility
• distance to the nearest watering point
• distance to the nearest route

Each indicator was normalized to a comparable scale, and the final index was calculated as a weighted linear combination:

Vulnerability Index =
0.5 × normalized dip distance
- 0.3 × normalized water distance
- 0.2 × normalized route distance

Greater weight was assigned to the dipping facility because of its critical role in livestock disease prevention.

The resulting index values were classified into five categories:
• very low vulnerability
• low vulnerability
• moderate vulnerability
• high vulnerability
• very high vulnerability

This classification enabled the spatial identification of kraals experiencing the greatest sanitary accessibility constraints.

3.7 Scenario Analysis: Installation of a Second Dipping Facility

To explore potential improvements in veterinary service accessibility, a scenario analysis was conducted by simulating the installation of a second dipping facility. Scenario-based spatial planning is frequently used to evaluate alternative infrastructure configurations in territorial planning studies.

The candidate location for the new dip was identified based on two criteria:
• the kraal farthest from the existing dip
• the upper range of the kraal-to-dip distance distribution

Once the new dip location was defined, distances from each kraal to the nearest dipping facility were recalculated by assigning each kraal to the closest of the two facilities.

The impact of this intervention was assessed using four indicators:
• mean kraal-to-dip distance
• Global Moran's I for dip accessibility
• paired t-test comparing distances before and after the intervention
• Wilcoxon signed-rank test as a non-parametric robustness check

These statistical tests allowed evaluation of whether the simulated infrastructure improvement produced a statistically significant reduction in spatial accessibility constraints.

4. RESULTS

4.1 Spatial Distribution of Livestock Sanitary Infrastructure

The spatial distribution map shows a dispersed pattern of kraals across the study area, connected by a network of 38 route segments and associated with watering points distributed across the landscape. The veterinary clinic, the dip, and the visited kraal occupy distinct positions within this territorial system.

The map suggests that kraals are not evenly distributed. Some areas present local concentrations of kraals, whereas others are more sparsely occupied. Water-related points are also spatially scattered, while the main sanitary infrastructure particularly the veterinary clinic and the dip appears centralized relative to several kraals.

Figure 2 presents the spatial distribution of kraals, watering points, routes, the veterinary clinic, and the existing dipping facility across the Kaniama-Kasese site.

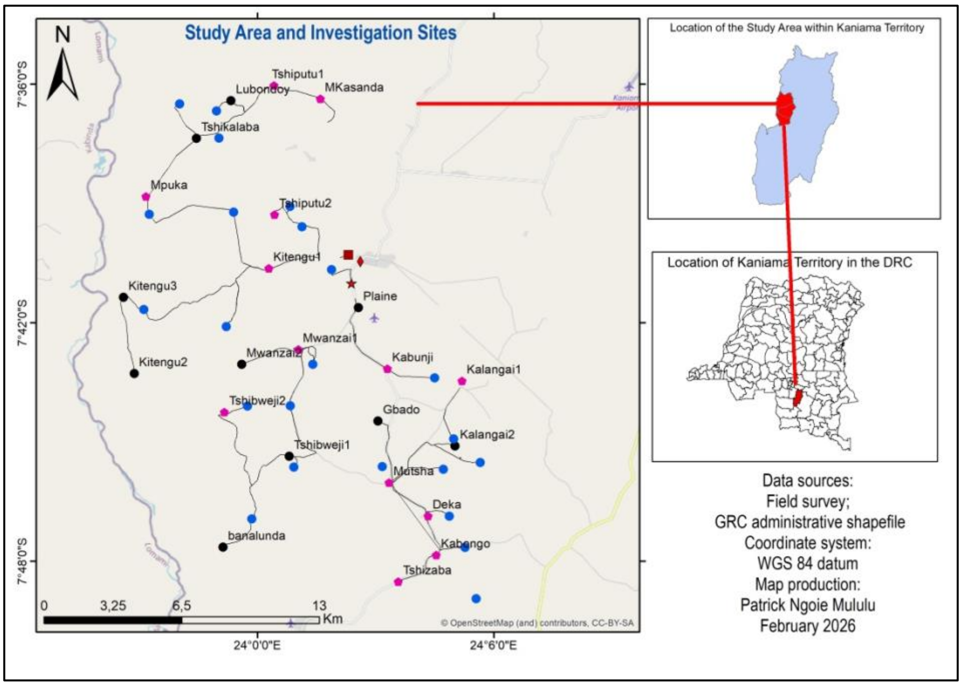

Figure 2. Spatial distribution of livestock sanitary infrastructure in the Kaniama-Kasese site, Haut-Lomami Province, DRC

The mapped features reveal a dispersed pattern of kraals and livestock-related infrastructure across the study area, structured in part by the local route network. While watering points and kraals are distributed throughout the territory, the veterinary clinic and dipping facility appear more spatially concentrated. This spatial configuration suggests unequal access to sanitary infrastructure among livestock keepers and provides the territorial basis for subsequent analyses of accessibility, spatial clustering, and veterinary vulnerability.

4.2 Density of Kraals

The convex-hull area covering all kraals was estimated at 253.40 km². Based on 23 kraals within this area, overall kraal density was 0.091 kraals/km², indicating a low-density livestock settlement pattern. The grid-based exploration further confirmed that kraals are unevenly distributed, with many grid cells showing absence and only a few containing kraals.

4.3. Zootechnical flows to watering points and dip

Figure 3 illustrates the weekly zootechnical flows connecting kraals to key livestock sanitary infrastructures, particularly watering points and the dipping facility. The network of lines represents the movement or interaction pathways between kraals and these infrastructures, highlighting the spatial organization of routine livestock management activities within the study area.

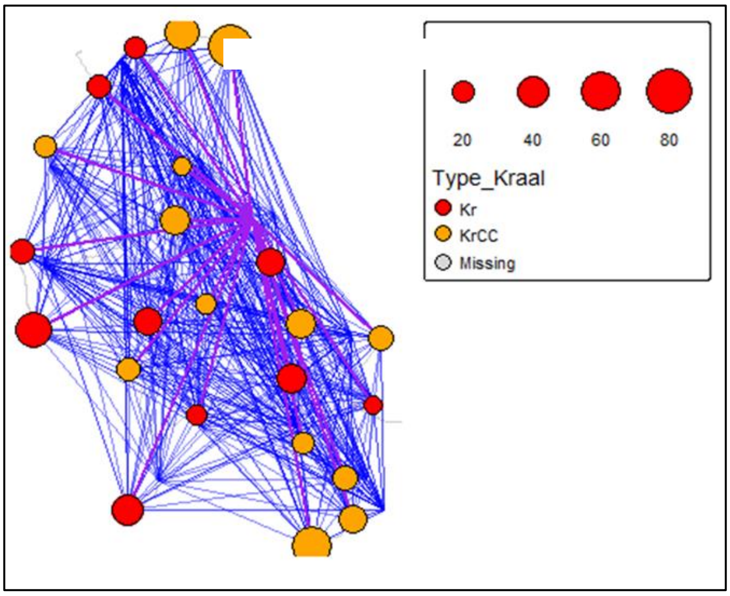

Figure 3. Weekly zootechnical flows to watering points and dip

The size of the nodes reflects the total weekly travel distance associated with livestock movements (distance_totale_hebdo), indicating the relative intensity of sanitary and watering-related movements for each kraal. Larger circles correspond to kraals with greater cumulative travel distances, suggesting a higher logistical burden in accessing essential livestock services. The color classification differentiates between two types of kraals (Kr and KrCC)**,** allowing the visualization of possible structural differences in mobility patterns between livestock management units.

The dense network of connections reveals a high level of spatial interaction within the livestock production system, with multiple kraals depending on a limited number of sanitary infrastructures. Several kraals appear to concentrate flows toward the central dip and major watering points, illustrating the role of these infrastructures as territorial hubs of zootechnical activity**.**

However, the unequal distribution of node sizes also indicates that some kraals must travel considerably longer cumulative distances to access these services. This spatial imbalance reinforces the findings from the accessibility and vulnerability analyses, which highlighted significant disparities in sanitary infrastructure access across the territory.

Overall, the figure demonstrates that livestock sanitary management in the Kaniama-Kasese site relies on a highly interconnected but spatially uneven mobility network, where certain kraals bear a disproportionate share of the movement burden. These patterns support the need for improved territorial planning of veterinary infrastructure, particularly through the strategic placement of additional dipping facilities to reduce travel distances and optimize livestock sanitary flows.

4.4 Accessibility to Water, Clinic, and Routes

Distance analysis reveals contrasting accessibility patterns depending on the type of infrastructure.

4.4.1 Distance to Watering Points

The average distance from kraals to the nearest watering point was 1.70 km, with a median of 1.28 km. Minimum distance was 0.34 km, whereas the maximum reached 4.89 km. These results suggest that access to watering points is generally moderate, although some kraals remain comparatively distant from water infrastructure.

4.4.2 Distance to the Veterinary Clinic

The veterinary clinic was substantially less accessible than watering points. Mean distance from kraals to the clinic was 8.99 km, with a minimum of 2.49 km and a maximum of 15.35 km. This indicates that veterinary clinical services are spatially remote for a large share of kraals.

4.4.3 Distance to Routes

By contrast, kraals were generally located very close to the route network. The average distance to the nearest route was only 0.042 km, with a median of 0.020 km and a maximum of 0.328 km. This suggests that physical road access is relatively favorable and does not constitute the main spatial bottleneck for sanitary access.

4.5 Accessibility to the Existing Dip

The dip represented the most spatially constraining component of the sanitary system. The mean distance from kraals to the existing dip was 8.70 km, with a median of 8.91 km. Distances ranged from 2.16 km to 14.96 km, showing strong territorial disparities in access to dipping services.

These results indicate that dipping services are highly centralized relative to the distribution of kraals, imposing substantial travel burdens on many livestock keepers.

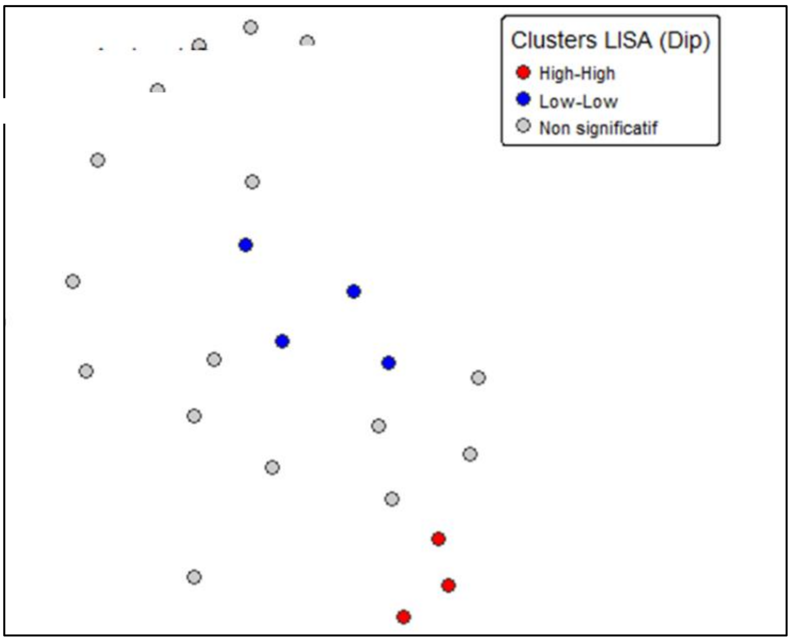

Figure 4. LISA clusters of dip accessibility

4.6 Spatial Autocorrelation of Dip Accessibility

4.6.1 Water Accessibility

The Moran test applied to kraal distance to watering points produced a non-significant negative autocorrelation:

- Moran's I = -0.080
- z = -0.539
- p = 0.705

This result indicates that kraal distance to watering points does not follow a clear clustered spatial structure.

4.6.2 Dip Accessibility

By contrast, distance to the dip exhibited strong and statistically significant positive spatial autocorrelation:

- Moran's I = 0.584
- z = 5.09
- $p = 1.76 \times 10^{-7}$

This confirms that sanitary disadvantage in access to dipping services is not randomly distributed but spatially clustered. In other words, kraals that are far from the dip tend to be located near other similarly disadvantaged kraals.

Local Moran results further highlighted the existence of meaningful spatial grouping patterns, although the dominant message of the local analysis was the territorial concentration of dip inaccessibility rather than a uniformly random configuration.

4.7 Multicriteria Sanitary Vulnerability

The multicriteria sanitary vulnerability index combined distance to dip, water, and route infrastructure. The resulting index ranged from 0.099 to 0.714, with a mean of 0.371.

This distribution indicates notable heterogeneity in sanitary vulnerability among kraals. The highest vulnerability scores were associated with kraals combining long distances to the dip and relatively poor access to watering points, even where route proximity remained favorable. The vulnerability map revealed a clear territorial hierarchy between less constrained and more constrained kraals.

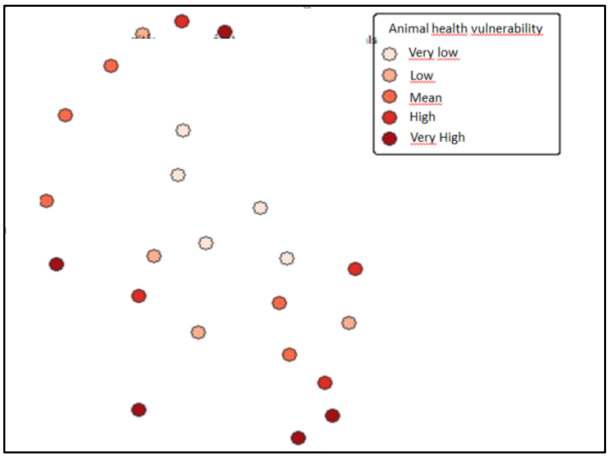

Figure 5. Multicriteria sanitary vulnerability of kraals

Figure 5 illustrates the multicriteria sanitary vulnerability of kraals based on the combined accessibility to the dipping facility, watering points, and the road network. The vulnerability index reveals a heterogeneous spatial pattern across the study area. Several kraals fall into the moderate to high vulnerability categories, indicating relatively unfavorable sanitary accessibility conditions.

Kraals classified as very high or high vulnerability are generally those located at greater distances from the existing dipping facility and, in some cases, relatively distant from watering points. These locations experience a cumulative spatial disadvantage despite their generally good proximity to the road network.

Conversely, kraals categorized as low or very low vulnerability tend to be situated closer to key sanitary infrastructure, particularly the dipping facility or major watering points. Their more favorable spatial position reduces the logistical burden associated with routine livestock sanitary management.

Overall, the map highlights a clear spatial differentiation in veterinary sanitary accessibility, confirming that sanitary vulnerability is not uniformly distributed across the territory. Instead, it reflects the combined effects of infrastructure location and the dispersed settlement pattern of kraals. This spatial heterogeneity provides a strong basis for identifying priority zones for improving livestock sanitary infrastructure, particularly through the strategic placement of additional dipping facilities.

4.8 Simulation of a Second Dip

A second dip was simulated in the most disadvantaged part of the study area.

4.8.1 Change in Mean Accessibility

After simulation, the mean kraal-to-dip distance decreased from 8.70 km to 6.22 km, representing an average gain of 2.49 km per kraal. This corresponds to a 28.57% reduction in mean distance to dipping services.

4.8.2 Change in Spatial Autocorrelation

The simulated infrastructure also reduced spatial inequality in access:

- Before: Moran's I = 0.584, $z = 5.09$, $p = 1.76 \times 10^{-7}$
- After: Moran's I = 0.352, $z = 3.18$, $p = 7.36 \times 10^{-4}$

Thus, spatial clustering of sanitary disadvantage decreased by 39.68% after installation of the second dip, although some clustering remained.

Table 1: Comparison of Spatial Indicators Before and After the Installation of the Second Dipping Facility

Indicator	Before	After
Mean distance (km)	8.7	6.22
Moran's I	0.584	0.352
Z-score	5.09	3.18
p-value	1.761652e-07	7.364108e-04

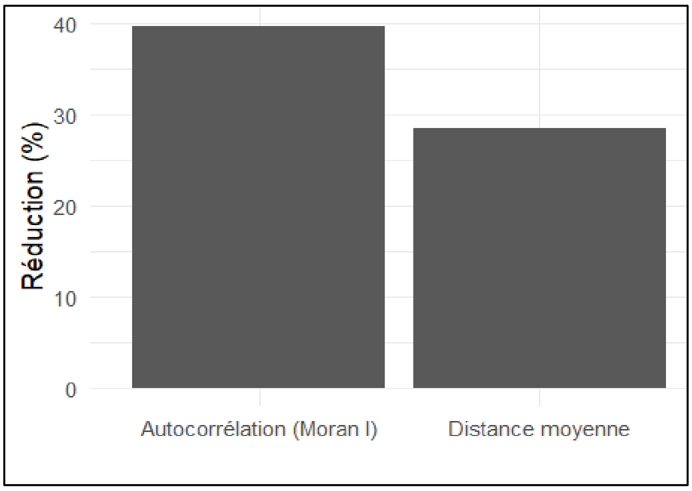

Figure 6. Percentage Reduction in Spatial Inequality and Average Distance After the Installation of a Second Dipping Facility

Figure 6 illustrates the relative reduction in two key spatial indicators following the simulated installation of a second dipping facility in the study area. The results show that the intervention significantly improved both overall accessibility and spatial equity in livestock sanitary infrastructure.

The average distance between kraals and the nearest dipping facility decreased by approximately 28.6%, indicating a substantial improvement in physical accessibility for livestock keepers. This reduction reflects the effect of introducing an additional service point closer to previously underserved areas.

At the same time, the level of spatial autocorrelation (Moran's I) decreased by nearly 40%, revealing a marked reduction in the spatial clustering of sanitary disadvantage. Prior to the intervention, kraals located far from the dipping facility tended to be grouped together, creating territorially concentrated accessibility deficits. The installation of a second dip reduces this clustering effect and promotes a more balanced spatial distribution of sanitary access.

Overall, the results demonstrate that the strategic placement of additional veterinary infrastructure can simultaneously improve average accessibility and reduce territorial inequalities in livestock sanitary services. This highlights the importance of GIS-based spatial planning for optimizing the location of veterinary facilities in dispersed livestock production systems.

The comparison of spatial indicators before and after the simulated installation of a second dipping facility reveals a substantial improvement in sanitary accessibility across the study area. The mean distance between kraals and the nearest dipping facility decreased from 8.70 km to 6.22 km, representing a reduction of approximately 28.6% in average travel distance. This change indicates a significant improvement in the spatial availability of dipping services for livestock keepers.

The spatial structure of accessibility also changed markedly. Prior to the intervention, the distribution of kraal-to-dip distances exhibited strong spatial clustering, as indicated by a Global Moran's I of 0.584, with a high z-score of 5.09 and an extremely small p-value (1.76×10^{-7}). These values confirm that sanitary disadvantage was highly clustered, meaning that kraals located far from the dipping facility tended to be spatially grouped.

After the installation of the second dipping facility, the degree of spatial clustering decreased significantly. Moran's I dropped to 0.352, while the z-score declined to 3.18, indicating a reduction in spatial inequality in access to dipping services. Although spatial clustering remained statistically significant ($p = 7.36 \times 10^{-4}$), its intensity was substantially lower than in the initial configuration.

Overall, these results demonstrate that the strategic placement of a second dipping facility would not only improve average accessibility but also reduce the spatial concentration of sanitary disadvantage. The intervention therefore contributes both to improving overall service coverage and to enhancing territorial equity in livestock sanitary infrastructure.

4.8.3 Statistical Significance of the Improvement

The improvement in kraal accessibility after simulation was statistically significant:

- Paired t-test: $t = 3.58$, $df = 22$, $p = 0.00168$
- Wilcoxon signed-rank test: $V = 66$, $p = 0.00386$

These results confirm that the proposed location of a second dip would produce a meaningful and measurable improvement in veterinary sanitary accessibility.

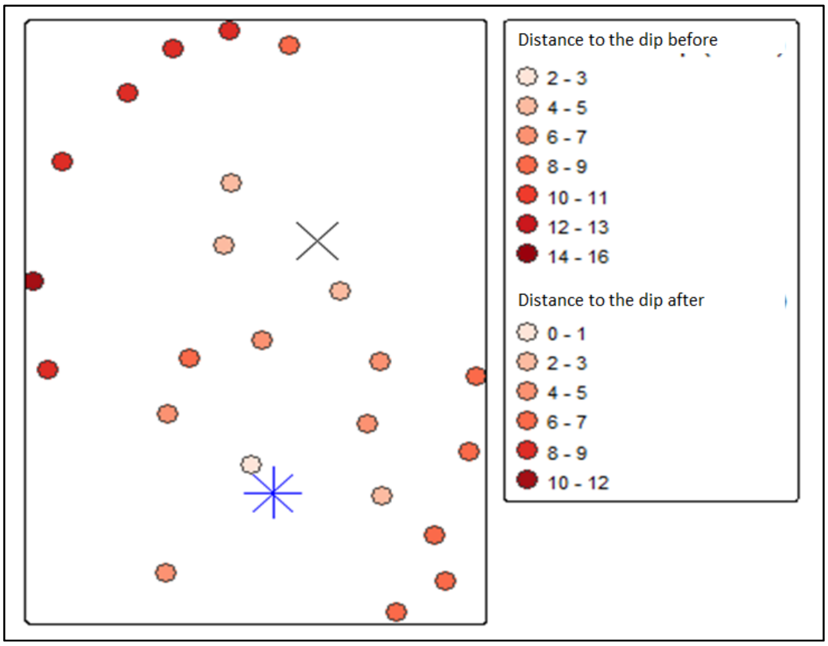

Figure 7. Accessibility to the nearest dip after simulation of a second dip

The figure illustrates the spatial distribution of kraal distances to the dipping facility before and after the installation of a second dip. In the initial configuration, accessibility to the existing dip shows a clear spatial imbalance. Several kraals are located at relatively large distances from the facility, particularly in the peripheral zones where distances reach 12 to 16 km. Only a limited number of kraals are situated within short distances of the dip, indicating a highly centralized sanitary infrastructure.

After the simulated installation of the second dipping facility, the spatial accessibility pattern improves considerably. The presence of the additional dip reduces the distance between many kraals and the nearest dipping facility, particularly in the southern sector of the study area. Several kraals that were previously located more than 10 km from the existing dip become positioned within shorter accessibility ranges, generally between 4 and 7 km, and in some cases even closer.

This redistribution of sanitary infrastructure produces a more balanced spatial configuration of dipping services across the territory. The intervention reduces extreme distances and limits the concentration of kraals in highly disadvantaged locations. Consequently, the installation of a second dip contributes to improving territorial equity in livestock sanitary services and supports more efficient access for livestock keepers within the Kaniama-Kasese site.

5. DISCUSSION

The results of this study reveal significant spatial inequalities in access to livestock sanitary infrastructure in the Kaniama-Kasese site in Haut-Lomami Province. The spatial analysis shows that kraals are dispersed across a relatively large territory, while key veterinary infrastructures such as the dipping facility and the veterinary clinic remain spatially concentrated. This type of spatial configuration often generates unequal accessibility conditions in pastoral and agro-pastoral systems where service infrastructure is limited (Catley et al., 2013; Perry & Grace, 2009).

The low kraal density observed in the study area (0.091 kraals/km²) reflects a dispersed livestock settlement pattern, which is typical of many pastoral production systems in sub-Saharan Africa. In such contexts, sanitary infrastructure located at a single fixed point must serve livestock populations distributed across large territories, which can create substantial spatial constraints for livestock keepers (Scoones, 1995). The results confirm that while kraals are generally located close to the road network, access to veterinary services remains uneven due to the spatial concentration of sanitary facilities.

Accessibility analysis highlights clear contrasts between different types of infrastructure. Watering points appear relatively accessible, with an average distance of 1.70 km, whereas veterinary clinical services are considerably more distant, with a mean kraal-to-clinic distance approaching 9 km. Similar accessibility gradients have been documented in livestock systems where watering infrastructure tends to be spatially distributed across grazing areas, while veterinary facilities remain centralized in administrative or settlement centers (Perry et al., 2002). These spatial differences illustrate how livestock management activities depend on multiple infrastructures with varying levels of accessibility.

The analysis also reveals that dipping services represent the most spatially constraining component of the sanitary system, with an average distance of 8.70 km between kraals and the existing dip. Such distances can significantly affect the frequency with which livestock keepers are able to access preventive veterinary services. Previous studies have shown that long travel distances can reduce the regular use of veterinary services, thereby increasing vulnerability to livestock diseases and reducing herd productivity (Grace et al., 2015).

Spatial autocorrelation analysis provides additional insight into the territorial organization of these accessibility constraints. The strong positive Moran's I value (0.584) indicates that kraals experiencing poor access to the dipping facility are not randomly distributed but spatially clustered. In other words, certain areas accumulate sanitary disadvantage, forming territorial clusters of limited accessibility. According to Anselin (1995), such clustering patterns are characteristic of spatial inequalities where infrastructure distribution does not match settlement patterns.

By contrast, the absence of significant spatial autocorrelation in kraal distance to watering points suggests that water accessibility is more spatially diffuse. This difference highlights the role of infrastructure distribution in shaping spatial accessibility patterns. While watering points are relatively scattered across the landscape, veterinary infrastructure remains centralized, producing stronger territorial disparities in access.

The multicriteria sanitary vulnerability analysis further reinforces this interpretation. By integrating distances to the dip, watering points, and routes, the vulnerability index reveals a clear spatial hierarchy among kraals. Some kraals face significantly greater sanitary constraints due to their combined distance from multiple infrastructures. Multicriteria spatial approaches have been widely used in geographic information science to identify areas of cumulative disadvantage and support infrastructure planning (Malczewski, 1999).

One of the most important contributions of this study is the scenario analysis evaluating the potential installation of a second dipping facility. The simulation demonstrates that a strategically placed second dip could substantially improve accessibility. The average distance to dipping services decreased by approximately 28.6%, while the spatial clustering of sanitary disadvantage declined by nearly 40%. This reduction in Moran's I indicates that the intervention would not only improve average accessibility but also reduce territorial inequalities.

Infrastructure scenario analysis has become an increasingly important tool in spatial planning because it allows decision-makers to evaluate the potential impact of alternative infrastructure configurations before implementation (Longley et al., 2015). In the present case, the results clearly show that adding a second dipping facility in the most disadvantaged zone would produce a statistically significant improvement in veterinary accessibility, as confirmed by both the paired t-test and the Wilcoxon signed-rank test.

These findings demonstrate the usefulness of Geographic Information Systems (GIS) as a decision-support tool for veterinary infrastructure planning. By integrating spatial accessibility analysis, spatial statistics, and multicriteria evaluation, GIS allows researchers and policymakers to identify priority intervention areas and optimize the location of veterinary services. Similar GIS-based approaches have been successfully applied in public health and livestock systems to improve service accessibility and reduce territorial inequalities (Guagliardo, 2004; Longley et al., 2015).

Despite these contributions, the study presents several limitations. First, accessibility was evaluated using Euclidean distances rather than travel times along the road network. Although kraals were generally located close to routes, actual travel conditions may vary depending on terrain, seasonality, or transportation means. Second, the analysis was based on a relatively small number of kraals, which may limit the generalization of the results to larger livestock territories. Finally, the analysis focused on spatial accessibility and did not incorporate herd size, disease incidence, or service utilization patterns, which could further refine vulnerability assessments.

Future research could therefore integrate network-based travel models, livestock epidemiological data, and socio-economic factors affecting veterinary service utilization. Such approaches would provide a more comprehensive understanding of livestock sanitary systems and further support evidence-based planning of veterinary infrastructure.

Overall, the results highlight the importance of considering spatial accessibility when planning livestock sanitary services. In dispersed pastoral territories such as the Kaniama-Kasese site, strategic placement of veterinary infrastructure can significantly improve sanitary coverage and reduce territorial inequalities in access to animal health services.

6. CONCLUSION

This study assessed the spatial accessibility of livestock sanitary infrastructure in the Kaniama-Kasese site in Haut-Lomami Province using GIS-based analysis of kraals, watering points, routes, a veterinary clinic, and a dipping facility. The results show that kraals are dispersed across a large territory and that access to veterinary sanitary services is spatially unequal.

While access to routes is generally favorable and access to watering points is moderate, access to the existing dip is markedly constrained, with a mean distance of 8.70 km and strong positive spatial autocorrelation. This indicates that sanitary disadvantage is territorially concentrated rather than randomly distributed.

The multicriteria vulnerability index confirms that kraals do not face the same level of sanitary exposure. Some are clearly more disadvantaged because they combine long distances to the dip and weaker access to complementary infrastructure. The simulation of a second dip demonstrates that a targeted territorial intervention could substantially improve sanitary equity, reducing mean distance to dipping services by 28.57% and reducing spatial clustering of disadvantage by nearly 40%.

Overall, the study shows that GIS-based accessibility analysis can provide a rigorous basis for veterinary infrastructure planning. In contexts of dispersed livestock settlement and limited sanitary resources, spatial decision-support tools can help identify priority intervention areas and improve the territorial efficiency of animal health systems.

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