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Geospatial Mapping of Malaria Commodity Mismatches for Targeted Redistribution Hotspot Identification in Uganda

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Abstract

Malaria remains a critical public health challenge in Uganda, marked by significant subnational transmission heterogeneity. This study analyzed 260 weekly surveillance reports (January 2020-December 2024) to quantify geographic imbalances in artemisinin-based combination therapies (ACTs) and rapid diagnostic tests (RDTs). Emerging Hot Spot Analysis (EHSA) revealed a "mismatch contradiction": while ACT understocking trended downward by late 2024, RDT deficits remained tenfold higher. Longitudinal analysis identified 31 districts (23%) as Sporadic Cold Spots of chronic oversupply, while Persistent Hot Spots of understocking were concentrated in the Central region. These findings indicate that manual logistics are insufficient to rectify geographic maldistribution. We recommend an integrated AI-GIS redistribution framework to facilitate real-time, demand-driven commodity transfers. These findings indicate that traditional manual logistics frameworks are insufficient to rectify geographic maldistribution. This study advocates for a digital transformation of the supply chain, proposing an integrated AI-GIS redistribution framework to facilitate real-time, demand-driven commodity transfers.

Keywords

Malaria, Supply Chain Resilience, Spatio-Temporal Analysis, Emerging Hot Spot Analysis, Artificial Intelligence, Commodity Redistribution, Uganda, Geospatial Intelligence, Inventory Mismatch, Public Health Logistics

1. Introduction

Uganda's malaria control program depends on the consistent availability of three core commodities: artemisinin-based combination therapies (ACTs) for treatment, and rapid diagnostic tests (RDTs) and microscopy for diagnosis [1] [2]. Maintaining optimal stock levels is vital; shortages lead to untreated cases and presumptive treatment, while oversupply results in wastage and resource inefficiency [1] [3]. This paper analyzes national surveillance data from 2020 to 2024 to identify spatio-temporal trends and regional imbalances in ACT and RDT distribution [4] [5].

Problem Statement: Despite the necessity of uninterrupted access to diagnostics and treatment, persistent supply chain gaps continue to undermine service delivery in Uganda. Frequent stock-outs in public health facilities delay diagnosis and treatment, directly increasing morbidity and mortality [2] [6]. Comparative studies from Kenya and India indicate that nearly half of the variability in medicine availability stems from weak ICT systems, inadequate training, fragmented supply chain design, and limited oversight [7] [8].

1.1. Literature Review

Significant gaps remain in linking national diagnostic and treatment data to inventory levels, limiting the ability of programs to anticipate shortages [9]. Current insights are often constrained by the recall bias of household surveys or the lack of real-time consumption data from facility-level assessments. Geographic access also remains a primary barrier; spatial analysis indicates that while high concentrations of health centers improve access to ACTs and mosquito nets, clusters of high malaria incidence persist in underserved regions [10].

Financial sustainability further complicates the supply chain. The Ugandan government allocates only 10% of the total malaria budget, leaving households to bear 67% of the cost [11]. Consequently, poorer regions with higher incidence rates frequently experience alarming shortages at lower-level healthcare facilities, perpetuating a cycle of poverty and disease. Currently, 20% of public facilities in Uganda experience stock-outs, leaving approximately 33% of essential medicines unavailable [1]. These shortages force vulnerable populations to seek alternatives in informal markets, where substandard or falsified antimalarials are prevalent [12]. Improving inventory management is therefore essential not only for clinical outcomes but also for reducing the economic burden on low-income households [1] [13].

1.2. Technology-Based Solutions

Geographic Information Systems (GIS) have emerged as a critical tool for improving stock visibility across Uganda's diverse regions [14]. By mapping medicine availability in real-time, health authorities can identify regional shortages and facilitate emergency redistributions, particularly in remote areas [14]. Complementing GIS, AI-powered forecasting tools enable data-driven decision-making by analyzing consumption trends, weather patterns, and outbreak alerts to predict future demand. Unlike manual forecasting, machine learning can detect complex patterns and trigger proactive countermeasures—such as automated resupply alerts or reallocations—before a stock-out occurs [3] [15]. Integrating these technologies makes the supply chain more agile, reducing health inequities and upholding the right to health for at-risk populations [16]. However, a fully operational, digitized surveillance and evaluation (SME) system that incorporates climate and seasonality models into inventory management is still lacking [9].

2. Research Methods

This study utilized a dual-phase quantitative framework to evaluate malaria supply chain resilience through a spatio-temporal analysis of secondary longitudinal records.

2.1. Analytic Dataset and Sample Frame

Phase I established a historical baseline utilizing 260 weekly malaria surveillance reports spanning January 2020 through December 2024, sourced from the Uganda Ministry of Health (MOH) Knowledge Management Portal [4] [5] [17] [18]. To ensure the structural integrity of the Space-Time Cube required for Phase II, 133 of Uganda's 146 districts were included based on a a ≥ 90% reporting completeness threshold. To mitigate potential Selection Bias, a comparative analysis confirmed that the 13 excluded districts demonstrated no statistically significant differences in baseline Test Positivity Rates (TPR) compared to adjacent included districts ($p > 0.05$). Geographic Bias was minimized as exclusions were distributed across the West Nile, Karamoja, and Central regions, suggesting data was Missing at Random (MAR). Missing entries (<5% total volume) were addressed via linear interpolation; sensitivity analysis confirmed this method preserved seasonal peaks, with variance remaining within a +2% margin of error compared to five-year historical means [19] [20].

2.2. Computational Environment and Geospatial Analysis

Quantitative processing was performed using Python (Pandas/NumPy), with longitudinal trends visualized via Matplotlib to identify systemic "mismatch" patterns. This workflow provided the validated foundation for Phase II, which utilized ArcGIS Pro to conduct an Emerging Hot Spot Analysis (EHSA). The primary outcome variable was defined as Weeks of Stock on Hand (SOH). Understock (<8 weeks) and overstock (>52 weeks) thresholds were operationalized according to the MOH Health Sector Strategic and Investment Plan (HSSIP) [21].

The EHSA utilized a neighborhood of eight nearest neighbors to reflect the average administrative adjacency of Ugandan districts, ensuring identified hotspots represent regional clusters rather than isolated anomalies [2] [6]. A two-month temporal window was selected to align with the MOH bimonthly emergency resupply cycles, allowing the model to distinguish between transient logistical delays and sustained trends [16] [22]. Statistical significance was determined using the Mann-Kendall trend test to evaluate Z-score trajectories across 15 monthly time steps ($p < 0.05$) [10] [16] [23].

2.3. Integration of Malaria Burden

For the Emerging Hot Spot Analysis (EHSA), a neighborhood of eight nearest neighbors was selected to reflect the average administrative adjacency of Ugandan districts, ensuring that identified hotspots represent regional clusters rather than isolated outliers [6]. A two-month temporal window was utilized to align with the bimonthly emergency resupply cycles of the Ministry of Health, allowing the model to distinguish between transient logistical delays and sustained trends. Within this framework, the Mann-Kendall trend test evaluated the statistical significance of Z-score trajectories across 15 time steps to categorize spots as "persistent" or "emerging" at $p < 0.05$ [10] [16]. Malaria burden was incorporated using TPR data sourced from official MOH weekly reports [4] [5]. Districts were classified as "High-Burden" if TPR consistently exceeded 50%. This measure was linked to inventory data to calculate a Demand-Weighted Mismatch (DWM) score for each district (i), operationalized as:

$$\text{DWM}_i = \left(\text{TPR}_i - \overline{\text{TPR}}\right) \times \left(\text{SOH}_{threshold} - \text{SOH}_i\right)$$

A positive DWM score identifies critical priority zones where transmission pressure outpaces available inventory [10] [20].

3. Results Section

Analysis of the MOH weekly surveillance bulletins [24]-[26] reveals a volatile landscape characterized by systemic "mismatching" of commodities. The analysis identifies a recurring "Pendulum Effect" within the supply chain. During the initial phase (2020-2021), an "Inverse Supply Gap" was observed; by January 2021, overstocking of ACTs reached 31.6%, while 25.7% of districts experienced a "Diagnostic Deficit" of RDT scarcity. This was followed by the 2022 resurgence, where stockouts increased exponentially from five districts in 2017 to 85 by 2022 [27] [28].

Recent data suggests that aggressive resupply efforts resulted in a peak ACT overstock of 79.0% by August 2024. Spatial analysis indicates persistent regional disparities where Northern regions consistently exhibited supply strain [29], whereas Southwestern districts maintained a "Treatment Surplus" exceeding 17 - 20 months of ACT supply [21].

Regional Patterns of Malaria Commodity Stock Imbalances

This chart directly quantifies the north-south divide. The deep red bars represent "Chronic Understock" (the story of strain), and the green bars represent "Chronic Overstock" (the story of inefficiency). Northern & Eastern Uganda (The Hotspots): The red bars are dominant, capturing the status of districts like Maracha, Napak, and Kaberamaido, which struggle to diagnose and treat patients due to recurring shortages, especially during surges in late 2024. Western Uganda (The Inefficiency): The green bar dominates, highlighting regions with lower malaria burden, including Kabale, Kisoro, and Rubirizi, which frequently end up with months' worth of unused ACT stock, posing risks of expiry and waste in Figure 1.

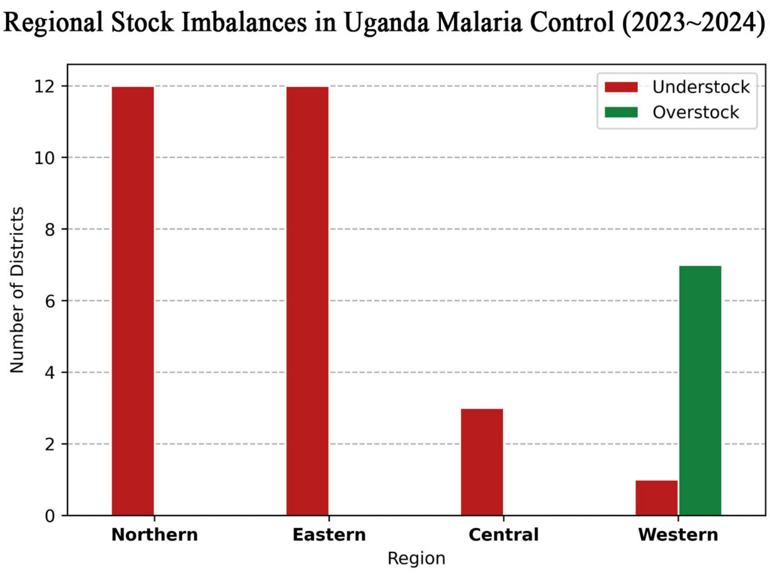

Figure 1. Regional patterns of malaria commodity stock imbalances.

This grouped bar chart effectively maps the "north-south divide", moving beyond national aggregate estimates.

Percentage Breakdown of Districts Affected by ACT vs. RDT Imbalances

This stacked bar chart provides a granular view of which commodity type is driving the supply chain mismatch in each region, supporting a more nuanced analysis of local logistics.

Northern & Eastern (Diagnostic Deficit): In these high-burden regions, RDT imbalances—specifically critical understocking—are the overwhelmingly predominant issue, represented by the blue portion of the bars. This data aligns with field reports indicating that hotspots like Napak often hold less than two weeks of diagnostic supply, leaving health workers unable to confirm cases before treatment. Western (Treatment Surplus): Conversely, ACT imbalances, shown in the orange portion, are the primary concern in the Southwest. These districts often hold over 20 months of ACT supply. This surplus is frequently driven by reactive bulk resupply policies that fail to account for the region's lower malaria incidence, leading to significant risks of pharmaceutical expiry. Central (The Intersection): The central region presents a unique intersection of these challenges. While it shows significant RDT stress (blue)—suggesting logistical planning gaps that exist independently of disease burden (as seen in Kiboga)—it also displays a notable ACT overstock (orange). This dual imbalance highlights the complexity of managing urban and peri-urban supply chains where low transmission and high population density overlap Figure 2.

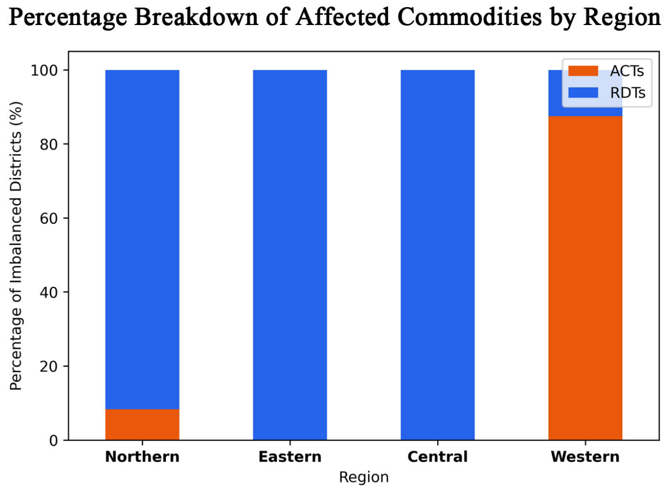

Figure 2. Percentage breakdown of districts affected by ACT vs. RDT imbalances.

The 2022 Distribution Paradox

This bar chart visualizes the simultaneous over- and understocking trends that occurred during the 2022 malaria resurgence.

The Inefficiency: In the same year, while 39% of districts were critically short of RDTs, nearly half of the country (49%) held an overstock of ACTs. **Insight:** This visual effectively proves your point that the 2022 crisis wasn't just a national shortage, but a failure of the "pull" system to redistribute existing stock to where demand was surging Figure 3.

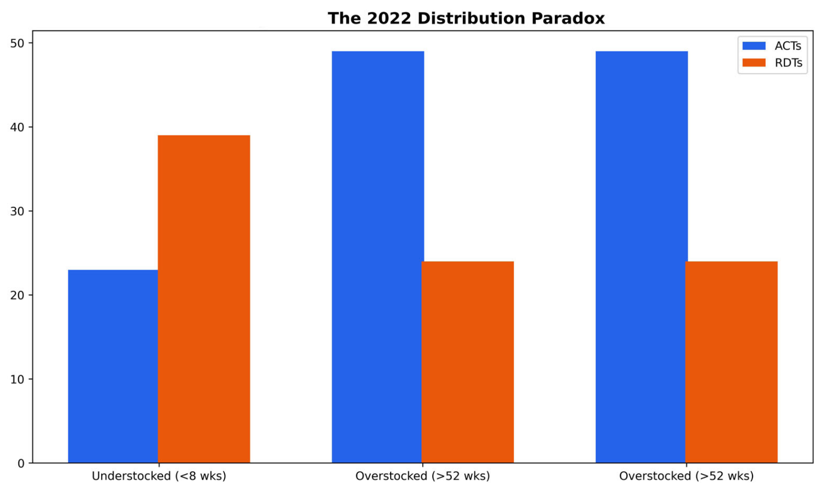

Figure 3. The 2022 distribution paradox.

The Inverse Supply Gap (2020-2021)

This line graph tracks the "ACT Abundance vs. RDT Scarcity" trend mentioned in your early study period. **The Mismatch:** You can see the steady rise in ACT overstocking (reaching 31.6% by Jan 2021) directly contrasted with persistent RDT understocking (~26%). **Insight:** This illustrates the "bundle-based" logistics failure you noted—districts were flush with medicine but lacked the diagnostics to use them accurately in Figure 4.

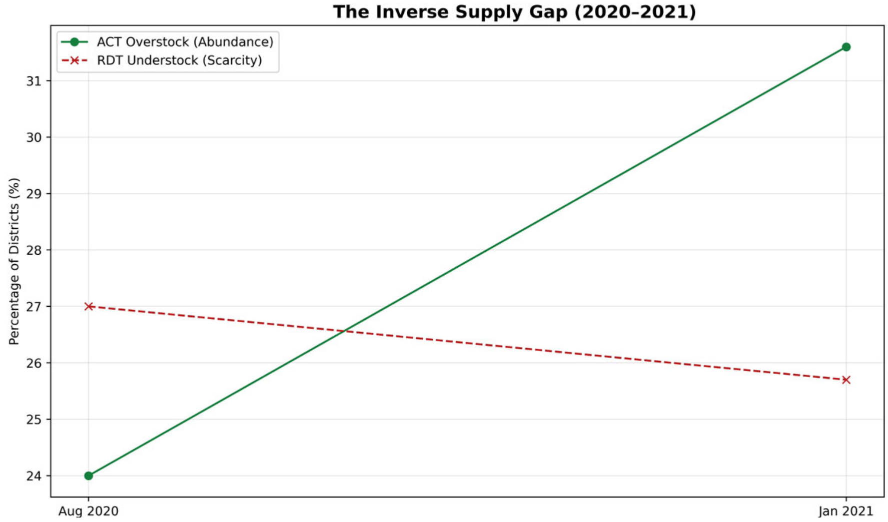

Figure 4. The inverse supply gap (2020-2021).

Analysis of the Ministry of Health (MOH) weekly surveillance bulletins from 2020 to 2024 reveals a volatile landscape characterized by systemic "mismatching" of commodities. The data indicate that supply chain resilience was severely tested by the transition from the COVID-19 pandemic into the 2022 malaria resurgence.

This visualization highlights the "Pendulum Effect"—the dramatic swings between extreme understocking during health crises and extreme overstocking following bulk resupply events.

National Trends: The "Pendulum Effect" (2020-2024)

The analysis identifies a recurring "Pendulum Effect" within the malaria commodity supply chain in Uganda, characterized by systemic oscillations between acute scarcity and resource-intensive surpluses. During the initial phase of the study (2020-2021), an "Inverse Supply Gap" was observed; specifically, by January 2021, overstocking of artemisinin-based combination therapies (ACTs) reached 31.6%, while 25.7% of districts simultaneously experienced a "Diagnostic Deficit" characterized by rapid diagnostic test (RDT) scarcity. This logistical misalignment was closely followed by the 2022 nationwide malaria resurgence. During this period, the supply chain "pendulum" shifted toward critical shortages, with the number of districts experiencing ACT stockouts increasing from five in 2017 to 85 by 2022 [28].

Following a stabilization period in early 2024 associated with the R21 vaccine rollout, a large-scale bulk resupply initiative resulted in a peak ACT overstock of 79.0% by August 2024. Spatial analysis indicates persistent regional disparities: high-burden zones in the Northern and Eastern regions (e.g., Napak and Maracha) consistently exhibited supply strain, whereas Southwestern districts (e.g., Kabale and Kisoro) maintained a "Treatment Surplus," with inventory levels reaching 17 - 20 months of ACT supply in Figure 5 [30].

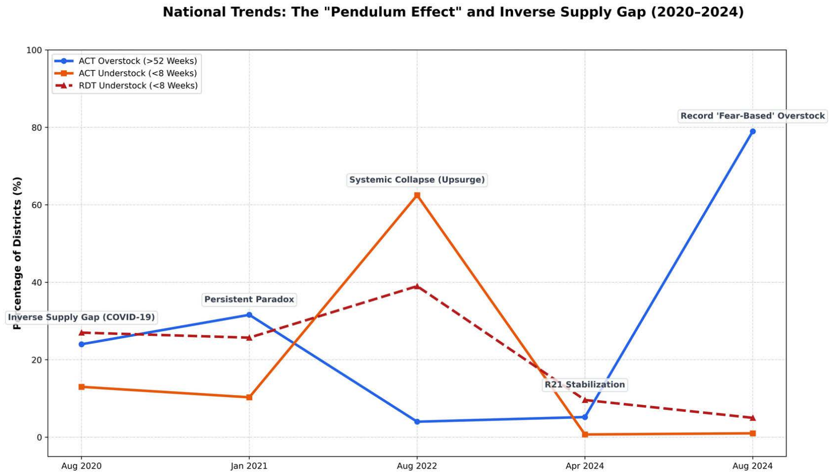

Figure 5. National trends in stock imbalance (2020-2024).

3.1. The Mismatch Contradiction (2020-2021)

To evaluate the long-term stability of the supply chain, a continuous time-series analysis was performed across the 260-week study period (2020-2024). As illustrated in **Figure 5**, the national stock levels exhibit a cyclical 'Pendulum Effect.' Rather than a stable equilibrium, the data show high-frequency oscillations where acute understocking during transmission peaks is followed by sharp, aggregate over-corrections. By plotting the full weekly dataset, we confirm that the 79% overstock observed in late 2024 was not an isolated event but the culmination of a multi-year pattern of systemic volatility.

The early study period was defined by a paradoxical surplus of treatment and a deficit of diagnostics. In August 2020, 24% of districts were overstocked with ACTs (holding > 52 weeks of supply), yet 27% of these same districts faced critical understocking of RDTs (<8 weeks). This indicates a failure in "bundle-based" logistics, where patients could be treated but not accurately diagnosed. By January 2021, ACT overstocking peaked at 31.6% of districts, signaling a significant risk of pharmaceutical expiry and resource tie-up in low-burden areas.

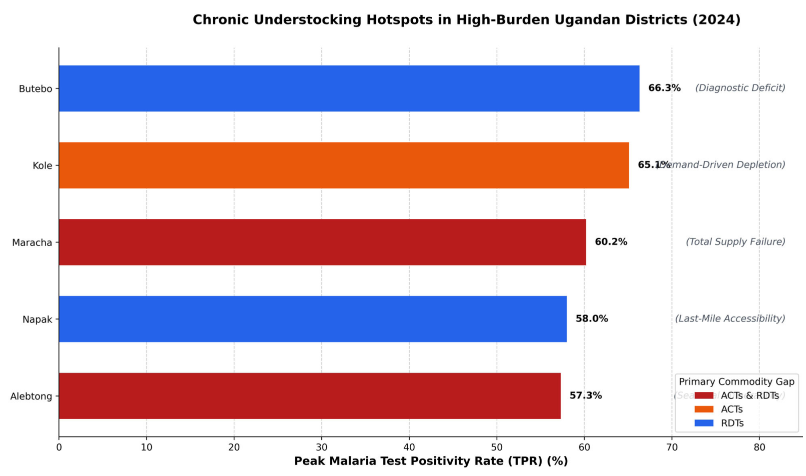

Figure 6. Chronic understocking hotspots in high burden Ugandan Districts (2024).

The chart is sorted by TPR to emphasize the areas with the highest malaria burden relative to their supply challenges **Figure 6**.

Butebo shows the highest peak TPR at 66.3%, driven primarily by an RDT gap (Diagnostic Deficit).

Kole (Lango) follows with 65.1%, attributed to an ACT gap (Demand-Driven Depletion).

Districts like Maracha and Alebtong face a combined ACTs & RDTs gap, leading to Total Supply Failure and Seasonal Vulnerability, respectively.

3.2. Resurgence and Systemic Collapse (2022)

The 2022 nationwide malaria upsurge exposed the fragility of the "pull" system. During this period, the number of districts experiencing frequent ACT stockouts increased exponentially from 5 in 2017 to 85 in 2022. RDT understocking reached its highest level in the study period, with 39% of districts reporting < 8 weeks of supply. Even during the 2022 crisis, a "distribution ghost" remained: while 23% of districts were understocked, 49% of districts simultaneously held overstocks of ACTs. This proves that the crisis was not a national shortage of medicine, but a geographic maldistribution that manual logistics could not rectify.

3.3. Geographic Clustering of Imbalances (2023-2024)

The use of GIS mapping identified distinct "Hotspots of Inequality." In the Northern and Eastern regions, districts such as Maracha, Kole, and Serere consistently operated in "Emergency Mode." Maracha documented 0 weeks of stock during peak transmission, representing a total service delivery collapse. In contrast, districts in the Southwestern highlands, such as Kabale and Rubirizi, maintained over 20 months of ACT supply **Figure 7**.

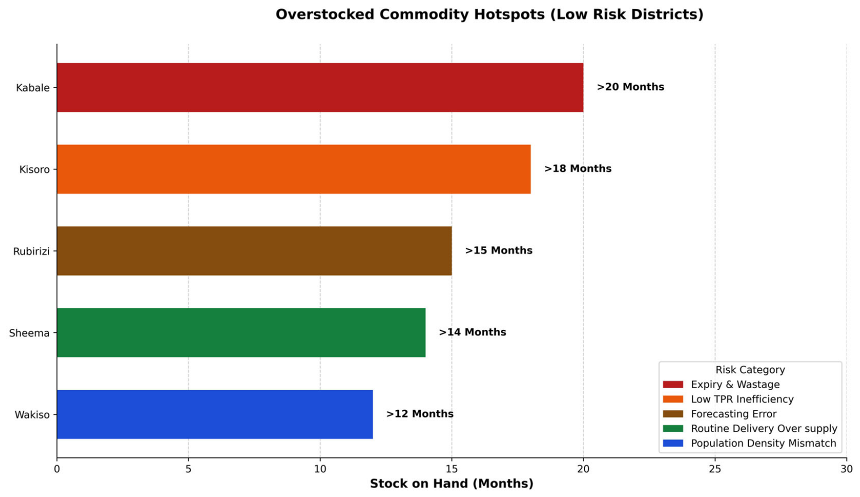

Figure 7. Overstocked commodity hotsports (Low Risk Districts).

Red (Expiry & Wastage): Kabale faces the most critical risk with over 20 months of stock on hand. Orange (Low TPR Inefficiency): Kisoro has a significant surplus

(>18 months) that does not align with its local malaria positivity rates. Green & Blue (Operational Misalignment): Districts like Sheema and Wakiso have surpluses driven by routine supply issues or population density mismatches.

3.4. Space-Time Commodity Imbalances (EHSA)

A critical analytical divergence exists between Acute Severity and Statistical Persistence. While the descriptive data identifies Northern and Eastern districts (e.g., Maracha, Kole, and Napak) as having the highest transmission burden, these areas frequently fall into the "No Pattern Detected" category within the EHSA framework. This classification is indicative of logistical volatility rather than stability. These regions experience "logistical chaos"—extreme oscillations between total service delivery collapse (zero stock) and emergency bulk replenishment. This high-variance signal lacks the linearity required for trend detection, effectively masking the severity of the crisis in a standard temporal model.

In contrast, the Persistent Hot Spots identified in the Central region (e.g., Kamuli, Kayunga, and Mukono) represent a different systemic failure. These locations exhibit a stable, chronic understocking trend that reaches statistical significance ($p < 0.05$). This suggests a structural mismatch in the "pull" system within peri-urban settings; routine allocations consistently fail to account for high patient volumes, yet these steady deficits rarely reach the catastrophic thresholds that trigger the emergency "shock" resupplies observed in the Northern "Red Zones in **Figure 8**.

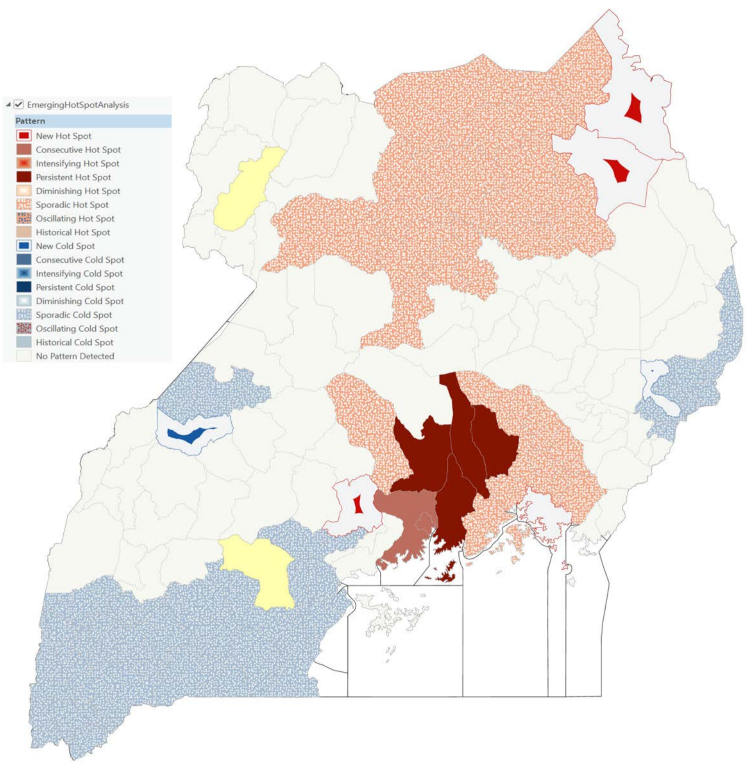

Figure 8. Map of Uganda showing emerging hot spot analysis for untreated cases due to days out of stock.

Technical Analysis Report: Space-Time Commodity Imbalances

The findings confirm a high degree of spatial-temporal volatility within the national supply chain. Of the 133 locations analyzed, 68 (51%) exhibited statistically significant trends. The identification of Persistent Hot Spots combined with a high frequency of Sporadic fluctuations underscores a dual systemic challenge: entrenched understocking in specific high-burden clusters and inconsistent supply reliability across the broader network.

3.5. Spatial-Temporal Framework

The analytical model was constructed using 1-month temporal intervals to provide high-fidelity tracking of stock shifts across 15 distinct time steps, covering the critical transition period through the end of 2025. By evaluating each location against its eight nearest neighbors over a 2-month temporal window, the methodology employed a neighborhood analysis that ensured identified "Hot Spots" reflected significant regional geographic clusters rather than isolated anomalies

4. Interpretation of "Hot Spot" Trends (Understock Risk)

The interpretation of "Hot Spot" trends identifies critical geographic clusters of understock risk, categorized throughout this study as "Red Zones." Within these clusters, Persistent Hot Spots represent the most severe cases, comprising four locations that remained significantly understocked for at least 90% of the study period, indicating a systemic failure of the "Pull" logistics system in high-burden areas. Emerging vulnerabilities are evidenced by four New Hot Spots, which reached statistical significance only in the final time step of December 2025, potentially signaling recent supply chain ruptures or localized transmission spikes. Additionally, two Consecutive Hot Spots reflect districts currently undergoing an uninterrupted run of understocking that, while not yet meeting the persistent threshold, suggests a deepening crisis. Finally, the largest category of imbalance consists of 25 Sporadic Hot Spots, where districts fluctuate in and out of understocking; this pattern validates the "Seasonal Trigger" theory, highlighting a failure of supply levels to synchronize with predictable peaks in malaria transmission.

5. Interpretation of "Cold Spot" Trends (Overstock/Blue Zones)

The interpretation of "Cold Spot" trends identifies geographic clusters characterized by a statistically significant surplus of malaria commodities, formally categorized as "Blue Zones." Within this classification, two New Cold Spots represent districts that have recently transitioned into a state of excessive inventory. These locations provide statistical evidence of the "Safety Swing"—a reactive phenomenon where the supply chain system over-resupplies aggressively in response to a previous shortage. Furthermore, the largest group within this category consists of 31 Sporadic Cold Spots, indicating a high volume of districts that experience intermittent overstocking. This pattern suggests that the current manual logistics framework is highly susceptible to "bullwhip effects," in which the system overcorrects for localized stockouts by pushing excessive commodity volumes into low-burden regions.

The specific spatio-temporal classifications for each district, including the identification of Persistent and Sporadic Hot Spots, are summarized in Table 1.

Table 1. Space-time trend classification of Uganda districts.

Category	District (s)
Persistent Hot Spots	Kamuli, Kayunga, Luwero, Mukono
Consecutive Hot Spots	Kampala, Wakiso
Sporadic Hot Spots	Abim, Agago, Apac, Bugiri, Bugweri, Buikwe, Buvuma, Buyende, Gulu, Iganga, Jinja, Kaliro, Karenga, Kitgum, Kole, Lamwo, Lira, Luuka, Nakaseke, Namutumba, Nwoya, Omoro, Otuke, Oyam, Pader
New Hot Spots	Kaabong, Kotido, Mayuge, Mityana
Sporadic Cold Spots	Amudat, Bududa, Buhweju, Bukomansimbi, Bukwo, Bushenyi, Gomba, Isingiro, Kabale, Kalungu, Kanungu, Kapchorwa, Kikuube, Kiruhura, Kisoro, Kween, Kyotera, Lwengo, Lyantonde, Masaka, Mbarara, Mitooma, Ntungamo, Rakai, Rubanda, Rubirizi, Rukiga, Rukungiri, Rwampara, Sheema, Sironko
New Cold Spots	Bulambuli, Kagadi
No Pattern Detected	Adjumani, Alebtong, Amolatar, Amuria, Amuru, Arua, Budaka, Bukedea, Buliisa, Bundibugyo, Bunyangabu, Busia, Butaleja, Butambala, Butebo, Dokolo, Hoima, Ibanda, Kabarole, Kaberamaido, Kakumiro, Kalaki, Kalangala, Kamwenge, Kasese, Kassanda, Katakwi, Kazo, Kibaale, Kiboga, Kibuku, Kiryandongo, Koboko, Kumi, Kwania, Kyankwanzi, Kyegegwa, Kyenjojo, Manafwa, Maracha, Masindi, Mbale, Moroto, Moyo, Mpigi, Mubende, Nabilatuk, Nakapiripirit, Nakasongola, Namayingo, Namisindwa, Napak, Nebbi, Ngora, Ntoroko, Obongi, Pakwach, Pallisa, Serere, Soroti, Tororo, Yumbe, Zombo

6. Discussion and Strategic Recommendations: Toward a Dynamic Supply Chain

The results of this spatio-temporal analysis provide empirical evidence of a "mismatch contradiction" that extends beyond aggregate national trends, building upon the longitudinal baseline documented by the Uganda National Institute of Public Health (UNIPH) [27] [28]. While prior assessments identified national-level shortages between 2017 and 2022 [28], this study demonstrates that contemporary logistical crises are geographically clustered, with acute deficits in high-burden regions occurring simultaneously with significant surpluses in low-transmission zones [29]. This "Pendulum Effect" suggests systemic friction in the current "pull" logistics model, likely exacerbated by transport infrastructure bottlenecks, workforce shortages at lower-level facilities, and a political economy of allocation that favors larger administrative centers regardless of real-time incidence [11] [30]. Furthermore, the observed "Safety Swing" of August 2024—where aggressive resupply resulted in a 79% ACT overstock—revealed a critical diagnostic-treatment contradiction; while ACT understocking plummeted to 0.7%, RDT scarcity remained ten times higher at 9.6% [21]. This "medication-heavy" but "diagnostic-light" imbalance risks pharmaceutical wastage through presumptive treatment and creates "frozen assets" in Southwestern "Blue Zones" like Kabale and Mbarara, where surpluses often exceed 17 - 20 months [21] [31].

To rectify these maldistributions, this study advocates for a digital transformation of the supply chain centered on a GIS-driven redistribution framework [14] [16]. By identifying 31 Sporadic Cold Spots as donor clusters and 25 Sporadic Hot Spots as recipients, the Ministry of Health could authorize automated lateral transfers to optimize existing inventory [20] [23]. This proactive posture should be supported by AI-driven "Predictive Pushing," which utilizes seasonal triggers to front-load supplies in Northern "Red Zones" before peak transmission in June [12]. Additionally, we propose a mandatory "commodity bundling" policy to ensure ACT dispatches are electronically linked to RDT availability, preventing medication delivery where diagnostic capacity is absent [22]. However, the efficacy of such high-tech interventions is contingent upon resolving the "digital divide" [32]. Persistent Hot Spot districts often lack the power stability and mobile connectivity required for high-fidelity reporting; therefore, technological integration must be coupled with fundamental investments in last-mile digital infrastructure and power resilience to ensure that logistical oversight reflects ground-truth inventory levels [24] [33].

6.1. Policy Recommendations

1) Institutionalize an AI-GIS-Driven National Redistribution Policy

The Ministry of Health should institutionalize a national AI-GIS-enabled redistribution framework that integrates real-time inventory surveillance, malaria burden indicators, and predictive analytics to guide dynamic redistribution of malaria commodities across districts. Such a policy would allow automated identification of understocked "Hot Spots" and overstocked "Cold Spots," enabling rapid lateral transfers before facilities reach critical shortages. By shifting from reactive procurement to predictive redistribution, Uganda can reduce geographic inequities, minimize expiries, and improve supply chain resilience during seasonal malaria surges.

2) Enforce Mandatory Diagnostic-Treatment Commodity Bundling

The Ministry of Health should adopt a mandatory commodity bundling policy requiring synchronized distribution of ACTs and RDTs across all levels of the health system. This policy would address the "diagnostic-treatment contradiction" identified in the study, where treatment commodities remained available while diagnostic supplies were critically understocked. Enforcing electronic linkage between ACT and RDT dispatches would improve rational malaria case management, reduce presumptive treatment, and strengthen accountability within the national malaria supply chain.

6.2. Targeted Infrastructure and Digital Audits

The four Persistent Hot Spots identified in this study represent chronic failures where routine resupply has been ineffective for over 12 months. An immediate multi-disciplinary audit of these zones is required to assess health center storage capacity, power stability for digital reporting, and the accuracy of facility-level data entry. This ensures that underlying barriers to resilience are addressed beyond mere inventory replenishment.

The proposed framework

This framework demonstrates how an integrated AI-GIS system enhances supply chain resilience by transitioning from traditional reactive distribution to a dynamic redistribution model driven by real-time demand.

Phase 1: Diagnostic Baseline. The framework first identifies core systemic vulnerabilities: inventory instability resulting from the bullwhip effect in forecasting, and critical "bundle mismatches" between diagnostic (RDT) and treatment (ACT) commodities. These inefficiencies historically manifest as simultaneous stockouts and overstocking across varied geographic clusters.

Phase 2: Operational Integration. The framework then synthesizes GIS spatial mapping, real-time inventory metrics, and epidemiological trends into a centralized AI-GIS Redistribution Hub. By utilizing Emerging Hot Spot Analysis (EHSA), the system distinguishes between chronic surpluses (Cold Spots) and acute shortages (Hot Spots), facilitating dynamic lateral transfers to optimize commodity alignment without requiring national-level resupply.

The proposed logic for this dynamic redistribution is visualized in the AI-GIS Framework (see Figure 9).

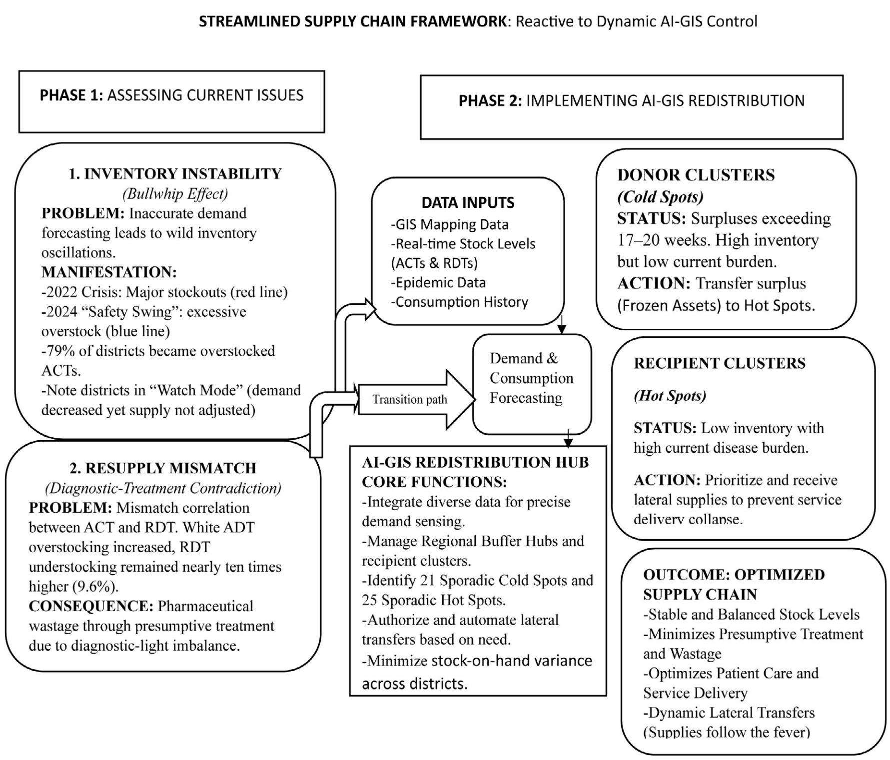

Figure 9. Streamlined supply chain framework: Reactive to dynamic AI-GIS control.

7. Conclusions

The persistent mismatch of malaria commodity supply and demand in Uganda is primarily a geographic and technological challenge rather than a national shortage. The fact that 51% of analyzed locations show active trends proves a state of constant flux. By integrating GIS for spatial visibility and AI for predictive modeling, the Ministry of Health can achieve a resilient, data-driven supply chain that optimizes geographic alignment and upholds the right to health for all at-risk populations.

Study Limitations

While this study provides high-resolution insights, several limitations exist. The analysis relies on secondary surveillance data from the MOH Knowledge Management Portal, subject to district-level reporting accuracy [4] [5]. Second, although the 133 districts met a high reporting threshold, the absence of granular facility-level data and stock buffers from the private health sector means the findings primarily reflect public-sector logistics. Furthermore, EHSA does not account for non-spatial logistical shocks such as infrastructure failure or fuel price volatility [2] [6].

8. Areas for Further Study

Further study is required to evaluate the cost-benefit and operational feasibility of using unmanned aerial vehicles (drones) for last-mile delivery in high-burden districts characterized by infrastructure bottlenecks.

Research should explore the potential for public-private data sharing agreements to create a comprehensive national view of commodity availability across both sectors.

A dedicated health economics analysis is needed to quantify the financial implications of pharmaceutical expiry resulting from the "safety swing" over-corrections observed in low-burden regions.

Data Sharing

Aggregated data is available via the Uganda Ministry of Health Portal.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Lugada, E., Komakech, H., Ochola, I., Mwebaze, S., Olowo Oteba, M. and Okidi Ladwar, D. (2022) Health Supply Chain System in Uganda: Current Issues, Structure, Performance, and Implications for Systems Strengthening. *Journal of Pharmaceutical Policy and Practice*, **15**, Article No. 14. https://doi.org/10.1186/s40545-022-00412-4

[2] Akpan, G.U., Mohammed, H.F., Touray, K., Kipterer, J., Bello, I.M., Ngofa, R., *et al.* (2022) Conclusions of the African Regional GIS Summit (2019): Using Geographic

Information Systems for Public Health Decision-Making. *BMC Proceedings*, **16**, Article No. 3. https://doi.org/10.1186/s12919-022-00233-y

[3] Zuma, S.M. (2022) Assessment of Medicine Stock-Outs Challenges in Public Health Services. *Africa's Public Service Delivery & Performance Review*, **10**, Article No. 578. https://doi.org/10.4102/apsdpr.v10i1.578

[4] MOH Uganda (2021) Malaria Weekly Status Report—Week 4, 2021. https://library.health.go.ug/communicable-disease/malaria/malaria-weekly-status-report-week-4-2021-week-25th-31st-january-2021

[5] MOH Uganda (2020) Malaria Weekly Status Week 31, 2020. https://library.health.go.ug/communicable-disease/malaria/malaria-weekly-status-week-31-2020

[6] ESRI (n.d.) How Emerging Hot Spot Analysis Works. ArcGIS Pro Documentation. https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern-mining/learnmoreemerging.htm

[7] Epstein, A., Namuganga, J.F., Nabende, I., Kamya, E.V., Kamya, M.R., Dorsey, G., *et al*. (2023) Mapping Malaria Incidence Using Routine Health Facility Surveillance Data in Uganda. *BMJ Global Health*, **8**, e011137. https://doi.org/10.1136/bmjgh-2022-011137

[8] Evans, D.R., Higgins, C.R., Laing, S.K., Awor, P. and Ozawa, S. (2019) Poor-Quality Antimalarials Further Health Inequities in Uganda. *Health Policy and Planning*, **34**, iii36-iii47. https://doi.org/10.1093/heapol/czz012

[9] Fitzpatrick, A. (2022) The Impact of Public Health Sector Stockouts on Private Sector Prices and Access to Healthcare: Evidence from the Anti-Malarial Drug Market. *Journal of Health Economics*, **81**, Article ID: 102544. https://doi.org/10.1016/j.jhealeco.2021.102544

[10] Monitor. (2023) Govt Looks to Technology to Stop Drug Theft, Stock-Outs. https://www.monitor.co.ug/uganda/news/national/govt-looks-to-technology-to-stop-drug-theft-stock-outs-4153206

[11] Okungu, V. and Mans, J. (2019) Efficiency, Equity, and Effectiveness of Malaria Funding in Uganda: Making the Case for Reforming Public Financing for Health. *International Journal of Health Services Research and Policy*, **4**, 131-144. https://doi.org/10.23884/ijhsrp.2019.4.2.07

[12] Kamba, P.F., Ireeta, M.E., Balikuna, S. and Kaggwa, B. (2017) Threats Posed by Stockpiles of Expired Pharmaceuticals in Low- and Middle-Income Countries: A Ugandan Perspective. *Bulletin of the World Health Organization*, **95**, 594-598. https://doi.org/10.2471/blt.16.186650

[13] Talisuna, A.O., Daumerie, P.G., Balyeku, A., Egan, T., Piot, B., Coghlan, R., *et al*. (2012) Closing the Access Barrier for Effective Anti-Malarials in the Private Sector in Rural Uganda: Consortium for ACT Private Sector Subsidy (CAPSS) Pilot Study. *Malaria Journal*, **11**, Article No. 356. https://doi.org/10.1186/1475-2875-11-356

[14] Intelligent Health.tech (2023) How AI Is Transforming the Fight against Malaria in Africa. https://www.intelligenthealth.tech/2023/09/07/how-ai-is-transforming-the-fight-against-malaria-in-africa/

[15] Chain Drug Review (2024) AI Will Allow Pharmacies to Stay Ahead of Demand. https://chaindrugreview.com/ai-will-allow-pharmacies-to-stay-ahead-of-demand/

[16] Komugabe, M.A., Caballero, R., Shabtai, I. and Musinguzi, S.P. (2024) Advancing Malaria Prediction in Uganda through AI and Geospatial Analysis Models. *Journal*

of Geographic Information System, **16**, 115-135.
https://doi.org/10.4236/jgis.2024.162008

[17] ResearchGate (2024) Artificial Intelligence in Healthcare Supply Chains: Enhancing Resilience and Reducing Waste.
https://www.researchgate.net/publication/381728757_Artificial_Intelligence_in_Healthcare_Supply_Chains_Enhancing_Resilience_and_Reducing_Waste

[18] MOH Uganda (2023) Weekly Malaria Report—Epi Week 52, 2023.
https://library.health.go.ug/communicable-disease/malaria/weekly-malaria-report-epi-week-52-2023

[19] MOH Uganda (2024) Weekly Malaria Report-Epi Week 46, 2024.
https://library.health.go.ug/communicable-disease/malaria/weekly-malaria-report-epi-week-46-2024

[20] Ankwatsa, I., Aguma, H., Atwiine, F. and Kalidi, R. (2025) Factors Affecting Data Quality and Reporting Rates for Real-Time ARV Stock Status (RASS) in the West Acholi Sub-Region, Uganda: A Mixed Methods Cross-Sectional Study. *Integrated Pharmacy Research and Practice*, **14**, 45-57. https://doi.org/10.2147/iprp.s514648

[21] Hevner, A. and Chatterjee, S. (2010) Design Research in Information Systems: Theory and Practice. Springer Science & Business Media.

[22] Uganda Ministry of Health (2020) Health Sector Strategic & Investment Plan (HSSIP) 2020/21-2024/25.
https://extranet.who.int/countryplanningcycles/planning-cycle-files/ministry-health-strategic-plan-202021-202425

[23] Komugabe, M.A., Caballero, R., Shabtai, I., Yi, Z. and Dodds, Z. (2024) Geospatial and Path Analysis for Enhancing Malaria Control and Primary Healthcare Delivery in Low-Income Nations: A Case Study of Uganda. *American Journal of Epidemiology and Infectious Disease*, **12**, 44-54. https://doi.org/10.12691/ajeid-12-3-3

[24] Project Last Mile (2018) Optimising Last-Mile Delivery in Tanzania's Health Supply.
https://www.projectlastmile.com/resource/how-project-last-mile-is-working-with-the-medical-stores-department-in-tanzania-to-optimize-last-mile-delivery-routes/

[25] BMAU (2015) Continuous Monitoring of Drug Stock-Outs in Uganda's Public Health Sector. Ministry of Finance, Planning, and Economic Development.

[26] Brinkerhoff, D.W. (2004) Accountability and Health Systems: Toward Conceptual Clarity and Policy Relevance. *Health Policy and Planning*, **19**, 371-379.
https://doi.org/10.1093/heapol/czh052

[27] Aregawi, M.W., Maiteki, C., Rek, J.C., Agaba, B., Katureebe, C., Ranjbar, M., *et al*. (2025) Malaria Epidemics and Its Drivers in Uganda in 2022. *Malaria Journal*, **24**, Article No. 235. https://doi.org/10.1186/s12936-025-05351-4

[28] UNIPH (2022) Increasing Stock-Outs of Critical Malaria Commodities in Public Health Facilities in Uganda, 2017-2022.
https://uniph.go.ug/increasing-stock-outs-of-critical-malaria-commodities-in-public-health-facilities-in-uganda-2017-2022/

[29] Muyingo, S., Etoori, D., Lotay, P., Malamba, S., Olweny, J., Keesler, K., *et al*. (2022) The Procurement and Supply Chain Strengthening Project: Improving Public Health Supply Chains for Better Access to HIV Medicines, Uganda 2011-2016. *Journal of Pharmaceutical Policy and Practice*, **15**, Article No. 72.
https://doi.org/10.1186/s40545-022-00467-3

[30] World Health Organization (2024) World Malaria Report 2024.
https://www.who.int/teams/global-malaria-programme/reports/world-malaria-re-

port-2024

[31] Vota, W. (2025) Data-Driven Decision-Making Optimizes Healthcare Supply Chains. https://www.ictworks.org/data-driven-decision-making-health-supply-chain/

[32] Nansubuga, B., *et al*. (2026) Barriers and Facilitators to the Use of DHIS2 Data for Malaria Surveillance in Uganda. PubMed Central (PMC).

[33] DHS Program (n.d.) Malaria Commodity Management. https://link.springer.com/article/10.1186/s12936-019-2682-5