Geospatial Modeling of 1-Hour and 2-Hour Access to Surgical Care in Uganda: A National Scale-Up Analysis.

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Abstract

Background

Equitable access to surgery remains a challenge in low-resource settings. In Uganda, National and Regional Referral Hospitals (NRHs, RRHs) and District Hospitals (DHs) are the primary providers of bellwether surgical procedures, while some Health Centre IV (HCIV, mini-hospitals) currently mostly offer cesarean sections. Expanding HCIV capacity to perform all three bellwether procedures (emergency cesarean section, laparotomy, and open fracture fixation) could significantly improve timely surgical access. The “golden hour” for trauma care and the two-hour standard for bellwether procedures are key benchmarks for surgical access.

Objective

To model population coverage under 1h and 2h access to existing facilities providing Bellwether surgical procedures in Uganda and to evaluate the impact on coverage of equipping HCIVs to perform all Bellwether procedures.

Methods

Using AccessMod 5, we modeled travel times to surgical facilities under two scenarios: (1) Main hospitals comprising National and Regional Referral Hospitals (NRHS, RRHs) and District Hospitals (DHs) only, and (2) Expanded scenario - Main hospitals, and upgraded HCIVs as fully bellwether-capable. Inputs included gridded population count, road networks, land cover, hydrography, and elevation. Expert-based travel speeds were stratified by land cover and road class. We compared unimodal (walking only) and bimodal (walking plus motorized) travel scenarios, estimating population coverage within 1-hour and 2-hour intervals stratified by region.

Results

In the unimodal (walking-only) model, 9.7% of Uganda’s population could reach a main hospital within 1 hour, and 20.4% within 2 hours. When HCIVs were included in the expanded scenario, coverage increased to 18.4% within 1 hour and 37.9% within 2 hours. In the bimodal model, 1-hour access improved from 74.9% with main hospitals alone to 91.6% with HCIVs, a gain of 16.7%. The Northern and Western regions experienced the largest improvements in 1-hour access, with increases of 20.6% and 26.9%, respectively. In the bimodal model, 2-hour access rose from 96.7% with main hospitals only to 98.7% after adding HCIVs.

Conclusion

Geospatial modeling shows that motorized transport substantially improves timely access to surgical care, and equipping HCIVs to perform all bellwether procedures markedly increases 1-hour access, particularly in underserved northern and western districts. Strategic investment in emergency prehospital systems and upgrading HCIVs to bellwether-capable facilities can enhance equity, close regional gaps, and align Uganda with global surgical benchmarks, addressing critical needs in trauma and emergency surgery.

Trial registration

Not applicable

INTRODUCTION

In 2015, the Lancet Commission on Global Surgery (LCoGS) exposed significant global inequalities in surgical access, showing that over six billion people cannot afford surgical care. [1] That same year, the World Health Assembly (WHA) unanimously adopted resolution 68.15, stressing that Universal Health Coverage (UHC) cannot be achieved without major investments in surgical care.[2] As a result, surgical care indicators were added to the World Health Organization's (WHO) Disease Control Priorities list, establishing benchmarks for countries to assess and enhance their surgical services.[3]

In response, the Lancet Commission on Global Surgery (LCoGS) introduced six core surgical indicators as benchmarks to evaluate and track progress in surgical access and quality across countries. [4] These indicators are categorized into three key areas: preparedness for care (access to timely surgery and workforce density), delivery of surgical and anesthesia care (surgical volume and perioperative mortality), and the financial impact of surgery (protection against catastrophic and impoverishing expenditure).[5] Their adoption into the World Bank's World Development Indicators has facilitated their integration into global health monitoring frameworks, ensuring that surgical care remains a central focus in efforts to achieve Universal Health Coverage.[6]

Uganda, a low-income country in East Africa with a population of approximately 45 million, faces significant challenges in meeting the surgical needs of its population.[7] Surgical services in practice are limited to a few facilities, including national and regional referral hospitals, general hospitals, with very few Health Centre IVs (mini-hospitals) having capacity for Bellwether procedures.[8] Previous studies in Uganda, such as the facility-based survey by Albutt et al., have revealed that less than 25% of the population have access to a surgically capable facility within two hours.[9] Moreover, the surgical workforce density remains critically low, and out-of-pocket expenditures for surgical procedures impose substantial financial burdens on households.[9,10]

While significant progress has been made in reporting the LCoGS indicators, there remains a need for more comprehensive and up-to-date evaluations, particularly in low-income countries.[11] Access to timely surgical care, the first indicator, is critically influenced by geographic accessibility, which includes not only the distance to hospitals but also factors like transportation characteristics (modes and speeds of transport), availability and cost of transport, road conditions, and geographical challenges.[12] In 2015, the LCoGS underscored the importance of measuring the population percentage within two hours of a surgical facility, a key indicator of a healthcare system's ability to provide timely surgical care.[1]

However, existing methods for assessing surgical accessibility, such as the Surgeon Over Seas Assessment Tool (SOSAS) tool, have significant limitations. The SOSAS tool, which relies on self-reported travel times, is prone to errors due to sampling biases and recall inaccuracies. Other tools that have been used involve Euclidean distance. These methods often fail to consider essential factors like type of road and land cover and topography, that can significantly alter travel times.[8,13,14] These methods often assume direct, grid-like travel routes, which do not reflect the real-world complexities of natural landscapes and infrastructure, leading to potentially misleading conclusions about accessibility and timely surgical access. Geospatial modeling using least-cost path approaches provide more realistic estimations of travel time and population coverage by incorporating various geographic and infrastructural factors such as road networks, land cover, barriers to movement, elevation, transportation characteristics, and high-resolution spatial distribution of the population.[15,16] Many studies have used this approach to assess accessibility to emergency services and explore scaling up scenarios, for example in Benin and Togo, and in surgery accessibility studies.[17–19]

As Uganda progresses toward the 2030 LCoGS targets, ensuring equitable access to timely surgical care remains a major challenge. Uganda's Strategic Plan for Health Sector Development (2020–2025) has identified improving functionality and adequacy of health infrastructure and logistics in health facilities.[20] Despite prior studies assessing Uganda's surgical capacity, there is limited evidence on how expanding Health Centre IVs (HCIVs) to perform all bellwether procedures could improve emergency surgical access. The current system primarily relies on National Referral Hospitals (NRHs), Regional Referral Hospitals (RRHs) and District Hospitals (DHs), leaving gaps in timely care, particularly for trauma and surgical emergencies in underserved regions.

To address this gap, this study employs geospatial modeling with AccessMod 5 to evaluate the impact of equipping HCIVs to perform all bellwether procedures.[15] Specifically, we compare two scenarios: one where only NRHs, RRHs and DHs provide surgical care, and another where HCIVs are upgraded to handle cesarean sections, laparotomies, and long-bone fracture fixations, the three cardinal bellwether procedures. By calculating 1-hour and 2-hour population coverage, stratified by region, this analysis provides data-driven insights to guide policy decisions aimed at enhancing surgical equity in Uganda.

DATA AND METHODS

Study Site and context

Uganda, a landlocked country in East Africa, has a total land area of approximately 241,038 km² and an estimated population of 45.7 million people as of 2023.[21] Over 70–85% of the population resides in rural areas, where access to healthcare services remains limited.[22] The government health care system, also known as the public health system, is structured into National Referral Hospitals, Regional Referral Hospitals, and the district health system, as shown in Fig. 1. The district health system is further subdivided into health sub-districts and comprises District General Hospitals, Health Centre IVs, III, and II, as well as Village Health Teams. [23]

At the district level, Health Centre IVs (HC IVs) serve populations of around 100,000, providing inpatient care, emergency surgery, and blood transfusion services. Above them, DHs serve approximately 500,000 people, offering additional services such as training, consultation, and research. RRHs cover 2 million people, providing specialized care in areas such as psychiatry, ENT, ophthalmology, and higher-level surgical services. NRHs, serving 10 million people, deliver comprehensive specialist care, alongside teaching and research responsibilities.

Data Sets

Hospital Facilities Data

We obtained a comprehensive list of health facilities in Uganda from the National Health Facility Registry.[24] From this dataset, we extracted all government-owned HCIVs, DHs, RRHs, and NRHs. To facilitate spatial analysis, we retrieved the geographical coordinates of these facilities.[25] Using QGIS, we generated a vector shapefile incorporating administrative boundaries and the corresponding geocodes.[26] Two separate vector layers were created for the Main Hospitals scenario and the Expanded scenario. The main hospitals scenario vector contained only DHs, RRHs, and NRHs and the expanded one included the above main hospitals along with HCIVs.

Geospatial data sets

Various geospatial datasets were utilized to support the analysis, including digital elevation model (DEM), land cover, population distribution, road networks, rivers, water bodies, and administrative boundaries, as shown in Table 1 and illustrated in Supplementary Figures S1-S5.

Roads, rivers, and water bodies were sourced from the latest OpenStreetMap (OSM) 2024 build, with all road classifications included. The DEM was obtained from the Shuttle Radar Topography Mission (SRTM), providing elevation data crucial for terrain analysis. Population distribution data was derived from the WorldPop 2020 UN-adjusted constrained dataset, with a 100m resolution, ensuring high spatial accuracy. Land cover data was retrieved from the Copernicus Global Land Service, which offers 100m resolution land classification layers. Administrative boundaries at regional and district levels were sourced from UN OCHA, providing standardized geopolitical delineations.

All raster data sets were resampled to 100m and projected in the EPSG:32735 - WGS 84 / UTM zone 35S projection.

Table 1
Data sets used and their sources.

Variable	Data Type	Resolution	Citation
Digital Elevation Model	Raster	30m	CGIAR-CSI. SRTM Data. 2022.[27]
WorldPop 2020 UNadj Constrained	Raster	100m	WorldPop.[28]
Roads	Vector		Open Street Map.[29]
Landcover	Raster	100m	Copernicus Global Land Service:[30]
Health Facility Locations	Vector		Uganda National Health Facility Registry.[25]
Barriers (Lakes and Rivers)	Vector		Open Street Map (OSM) [29]

Travel Time Scenarios

Two travel scenarios were modeled:

1. Unimodal model: Walking Scenario: Assumed continuous walking across all land cover and roads to bellwether hospitals.
2. Bimodal model Scenario: This combined walking across land cover and smaller roads (residential, living street, service, track, pedestrian, footway, bridleway, cycleway, steps, and unclassified) with motorized travel on major roads (tertiary and above), as shown in the travel scenario table in Supplementary Table S1 and S2. In this model, individuals first walk to the nearest major road, where motorized transport is assumed to be immediately available.

Using the “Merge landcover” module in Accessmod, a merged land cover map was created by integrating land cover categories with roads, barriers to movement (lakes and rivers) to ensure comprehensive travel modeling.

Determining Travel Speeds

To establish realistic travel speeds for different road types across Uganda, a stakeholder meeting was held in November 2024 at the Ministry of Health within the context of the planning of the emergency obstetric and neonatal care (EmONC) network. Using the approach described in Molenaar et al., [31] we elicited the knowledge of local experts (national and sub-national public health experts, hospital managers, representatives of nurse and medical bodies) from various regions of Uganda about how women in need of EmONC are typically reaching healthcare during health emergencies (modes and speeds of travel). [31] A consensus was reached by all experts that a single travel scenario covering all of Uganda could be used. The travel speeds for the unimodel and bimodel scenarios from that consensus are shown in Supplementary Table S1 and S2. These models assume that patients are travelling from home to the nearest emergency service, a one-way journey.

As AccessMod does not provide measures of uncertainty, we varied travel speeds in both models by ± 20% of the original values based on expert consensus, to define upper and lower bounds of uncertainty around travel speeds. This approach follows the method described by Macharia et. al and Ouma et. al to reflect possible variations while travelling due to weather, traffic, car type, personal preferences, time of the day and other differentials.[32,33]

Developing Gridded Travel Time Raster

A travel time raster was developed using the "Accessibility analysis" module in AccessMod, leveraging expert consensus on travel speeds and incorporating various model scenarios. We used the anisotropic mode for this analysis, whereby the slope corrects walking speeds according to the Tobler's hiking function, and considering transport towards facilities.[15,34] These scenarios generated raster surfaces representing travel times to hospital locations, specifically comparing travel times to Main hospitals (DHs, RRHs and NRHs) alone versus an expanded scenario where both the above-mentioned main hospitals and HC IVs were all functioning as bellwether-capable. A merged land cover map was created by combining land use categories, ordered OSM road classes (trunk, motorway, others in descending speed), and rivers and lakes.

Population Coverage Estimation

Population coverage within 1-hour and 2-hour thresholds was calculated in AccessMod using the Accessibility Coverage module. This tool overlays the travel time rasters (Fig. 2) with the population dataset and computes the proportion of the population able to reach the nearest facility under the defined time cut-offs. We then computed zonal statistics, which provided the percentage of the population able to access a facility under the specified time limits. This approach is described in the AccessMod user manual and aligns with methods applied in previous accessibility studies.

RESULTS

268 hospitals were included in our analysis, comprising 193 Health Centre IVs, and 75 Main hospitals (including 54 District Hospitals, 18 Regional Referral Hospitals, and 3 National Referral Hospitals). The spatial distribution of these facilities across different regions of Uganda is illustrated in Fig. 3.

Accessibility to Surgery (Bellwether procedures).

Unimodel model (Walking only Scenario)

Within 2 hours, 20.4% of Uganda's population can walk to reach the nearest main hospital, while 37.9% can walk to reach either the nearest main hospital or the nearest HC IV if considered as bellwether capable. When stratified by region, accessibility varies significantly, as shown in Table 3 that details the population proportion within 60 minutes and 120 minutes of travel time. This variation is further illustrated in Figs. 2 and 3, which maps district-level accessibility within 1 and 2 hours for main hospitals and HC IVs, when considered all as bellwether capable.

Table 2
Regional accessibility to bellwether hospitals under walking-only scenario with uncertainty intervals (± 20%)

Region	Total Population	Main Hospitals Only (% of population within 60 min)	Main Hospitals Only (% of population within 120 min)	Main Hospitals + HC IVs (% of population within (60 min)	Main Hospitals + HC IVs (% of population within 120 min)
Central	12,739,681	15.7% (11.5–19.8)	34.3% (27.5–40.6)	30.5% (24.1–36.4)	53.1% (45.6–59.8)
Eastern	11,938,542	7.5% (6.0–9.1)	17.3% (13.1–22.0)	15.4% (11.8–19.4)	38.2% (28.2–48.5)
Northern	9,411,758	9.3% (7.6–10.8)	15.8% (13.2–18.4)	13.2% (10.5–15.9)	25.9% (20.8–31.2)
Western	11,641,886	5.7% (4.5–6.9)	12.1% (9.2–15.1)	12.3% (9.3–15.5)	30.7% (22.7–39.1)
Uganda	**45,731,867**	**9.7% (7.5–11.9)**	**20.4% (16.2–24.7)**	**18.4% (14.2–22.4)**	**37.9% (30.1–45.7)**

Bimodel model (Walking then motorized)

In this scenario, 98.7% of the population had access to a surgical hospital within two hours when all main hospitals and HCIVs were considered. Baseline 1-hour access was 74.9% when considering only main hospitals, increasing to 91.6% in the expanded scenario when HC IVs were included. The change in accessibility between these scenarios is detailed in Table 3.

Table 3
National accessibility to surgery (bimodal model) with uncertainty intervals (± 20%)

Scenario	% Population Covered within 1 hour.	% Population Covered within 2 hours
Main Hospitals	74.9% (62.9–83.6)	96.6% (93.3–98.0)
Expanded scenario (main hospitals + HCIVs)	91.6% (84.2–95.1)	98.7% (97.8–99.0)

Impact of Including Health Center IVs on Accessibility

When HCIVs were included in the analysis, 1-hour access to surgical hospitals increased across all regions. The differences in population coverage between main hospitals only and main hospitals plus HCIVs are summarized in Table 4. This is further demonstrated at district level in Supplementary figure S6.

Table 4
Regional impact of including HCIVs on accessibility with uncertainty intervals (± 20%)

Region	Main Hospitals (60 min)	Main Hospitals + HCIVs (60 min)	Increase (60 min)	Main Hospitals (120 min)	Main Hospitals + HCIVs (120 min)	Increase (120 min)
Central	83.74% (75.1–89.5)	94.52% (89.1–96.8)	+ 10.78%	96.83% (95.0–97.4)	98.53% (98.2–98.6)	+ 1.70%
Eastern	85.16% (73.7–91.3)	95.17% (90.1–97.4)	+ 10.01%	98.59% (96.4–99.0)	98.94% (98.7–99.1)	+ 0.35%
Northern	59.03% (46.7–69.6)	79.68% (68.4–86.9)	+ 20.65%	91.41% (84.2–96.1)	97.44% (94.2–98.6)	+ 6.03%
Western	67.47% (51.7–80.5)	94.40% (85.5–97.6)	+ 26.93%	98.48% (95.6–99.2)	99.70% (99.4–99.7)	+ 1.22%

DISCUSSION

We found that 2-hour access to surgery in Uganda was 96.6% to main hospitals and 98.7% to main hospitals with HC IVs when a bimodal model was employed. The Lancet Commission on Global Surgery set a benchmark of 80% for 2-hour access to essential surgical care, based on historical data on maternal emergencies requiring timely intervention.[1] Our findings suggest that Uganda surpasses this benchmark. However, these must be interpreted within the broader context of availability, acceptability, and affordability beyond geographic accessibility lens.[1,35]

Our estimates are considerably higher than those reported by prior studies. For instance, Albutt et al., who found that less than 25% of the population were reported to have access to a surgically capable facility within 2 hours,[9] while Adupa et al. found that only 23.3% of patients reached hospitals for surgery on time.[36] Several factors may explain this discrepancy. Albutt et al. relied on facility-administered surveys, where hospital directors subjectively reported catchment populations reachable within 2 hours, while Adupa et al. collected self reports from patients on timeliness.[36] By contrast, our study employed geospatial modeling to objectively calculate travel times, incorporating high-resolution data on roads, land cover, and population distribution.[8,37]

Beyond methodology, prior studies done differed in scope and fewer hospitals were studied. For instance, Albutt et al. assessed only 16 public hospitals, of which just nine (56%) could perform all bellwether procedures, reflecting existing surgical capacity in 2016. Adupa and colleagues asked patients whether they arrived in time in three hospitals, without clarifying distinct time cut offs. Our analysis modeled a scaled-up scenario in which 56 main hospitals and 193 Health Centre IVs (HCIVs) were upgraded to provide bellwether procedures, demonstrating the potential impact of decentralizing surgical care. This explains the substantial improvements in access (e.g., Northern Region: +20.6% 1-hour coverage). While prior studies highlighted real-world limitations such as inconsistent facility capabilities and resource shortages, our projections assume full operational readiness, illustrating how strategic HCIV expansion could transform Uganda’s surgical system.[9,36,38]

It is important to recognize that prior studies may have captured barriers beyond geography, including delayed decision to seek care, facility capacity, safety and affordability, which our geospatial model does not directly model. For instance, the median time from decision to seek care to reaching a regional referral was 6 hours in a study done in Eastern Uganda.[39] Therefore, in previous studies, their subjective reports may have incorporated delays such as waiting times for transportation or referral bottlenecks which are factors not simulated in our idealized transport scenarios.[40,41] Thus, the major gains from scaling up HCIVs would likely lie in improving 1-hour access, particularly for time-critical emergencies such as trauma, obstetric complications, or bowel perforations, and in enhancing access where motorized transport is unavailable. While geographic access appears largely sufficient in our bimodal model with motorized transport, real-world access is constrained by modes and delays in transport, referral inefficiencies, workforce shortages, and variable facility readiness.

Together, our findings and the previous studies underscore a key insight: geographic proximity alone does not guarantee timely surgical care. Complementary investments in prehospital systems, referral coordination, community awareness, and the operational capacity of lower-level facilities especially HCIVs, are necessary to translate spatial accessibility into actual service delivery. However, systematic assessments of the current readiness of HCIVs remain limited.[42,43] Future assessments should therefore focus on evaluating the current readiness, staffing, and supply chains of HCIVs to determine the feasibility and resources required for them to consistently deliver all bellwether procedures.

Compared to other East African countries using geospatial mapping, Uganda's 2-hour access is comparable to Kenya (98%) and Rwanda and Burundi (100%) but higher than Tanzania (91%) and the Democratic Republic of Congo (93%).[12] South Sudan, at 78%, falls below the Lancet Commission’s target. [12] These differences likely reflect methodology differences and variations in country sizes, healthcare infrastructure, road networks, and geographic and political challenges, with countries like Rwanda and Burundi having smaller land areas and more concentrated healthcare facilities hence higher percentages, whereas Tanzania having the largest land mass, has a lower percentage.[12] Our approach differs from such earlier regional analyses such as Juran et al., where travel speeds were assigned uniformly across countries using static impedance values (e.g., 80 km/hour for major roads, 30 km/hour for urban areas, 4 km/hour for walking across vegetation, and 2 km/hour for desert terrain).[12] By contrast, we derived travel speeds through expert consensus in Uganda, allowing us to account for variation in road conditions and modes of travel. In addition, Juran et al. modeled travel at a spatial resolution of 1 km, while our study employed a finer 100 m resolution, which can alter accessibility estimates by capturing more detailed variation in population distribution, land cover, and infrastructure.[12,44] Furthermore, South Sudan's lower access may be influenced by its sparse healthcare distribution and ongoing political and civil unrest which is associated with movement disturbances and limitations for those seeking access to surgery.[45,46]

In low-resource settings, patients requiring emergency care often rely on non-motorized transportation methods due to financial constraints limiting access to vehicles. Pregnant women in rural villages of Uganda walk several kilometers to the hospital to seek care.[47] Beyond walking, communities in for example rural Nigeria also frequently utilize animal-drawn carts (donkeys, horses, or oxen) for emergency referrals.[48] This was further reported by Avoka et al in Nigeria, where 24 percent of mothers used non-motorized transport, walking to travel for birthcare.[49] In Uganda, when motorized options are available, they most often consist of shared minibus taxis ("matatus") or motorcycle taxis ("boda-bodas"), with private vehicles and formal ambulances being less common.[50,51] Community-level innovations such as bicycle or motorcycle ambulances have also been documented to bridge gaps in emergency transport access in rural areas in Uganda.[47,51]

When using a unimodal model with walking only, only 37.9% of Uganda's population can reach a hospital capable of performing bellwether procedures within two hours. These findings underscore the crucial role of motorized transport in timely surgical care. However, Uganda's reliance on motorized transport is hindered by poor road infrastructure, frequent flooding, and adverse weather conditions, which often make roads impassable. With only approximately a quarter of roads paved, travel becomes especially difficult during the country's long wet seasons.[22,52] Additionally, most Ugandans depend on public transport, which often involves waiting for vehicles to fill up before departure, leading to further delays.[22] Limited functional ambulance availability further compounds the problem, as narrow roads and poor traffic management hinder emergency response.[53] Traffic congestion, particularly during peak hours, exacerbates delays, potentially preventing timely surgical intervention.[22] Addressing these challenges requires investments in road infrastructure, increasing ambulance availability, enforcing right-of-way laws, and raising public awareness to improve emergency transport efficiency.

Health Centre IVs in Uganda can deliver effective surgical and emergency care when supported with staff, equipment, and mentorship. Palabek Kal HCIV, for example, transformed into a fully functional site through donor partnerships, theatre operationalization, and additional staffing, improving maternal and newborn outcomes.[54] Surgical outreach programs like surgical camps by Association of Surgeons of Uganda and trained Clinical Officers in the Health Centre IVs further demonstrate that targeted training and collaboration can expand access to essential surgical services in underserved communities.[55,56]

These experiences highlight the potential of HC IVs as critical hubs for timely, life-saving care in rural Uganda.

This study demonstrates that expanding surgical capacity at HCIVs increased population coverage within 1-hour motorized travel from 74.9% to 91.6%, with the greatest improvement observed in the Northern region (+ 20.6%). The substantial increase in 1-hour access underscores the potential of decentralized surgical services, particularly in rural and underserved areas, in the context of the golden hour, especially for surgical interventions for trauma. The Northern and Western regions, with the lowest baseline access, saw the most significant gains, emphasizing the need for targeted investments to address geographic disparities. However, for many patients, especially in rural areas, motorized transport remains unaffordable, rendering bimodal access theoretical rather than achievable. In addition, ambulance services come at a cost to the patient and their family.[51] Future interventions could integrate financial risk protection (e.g., waived ambulance fees, community transport vouchers) with infrastructure investments.[57,58] This is particularly important in trauma care, where early surgical intervention significantly improves outcomes. Strengthening HCIVs to provide timely emergency procedures could be a key strategy in bridging this gap and optimizing Uganda's emergency surgical care system.

Health System and Policy Considerations

Strengthening HCIVs as bellwether-capable facilities, as well as improving the surgical capacity and readiness of main hospitals to perform bellwether procedures and other complex surgeries, is essential to realize the benefits demonstrated in this study. To achieve this, HCIVs must be equipped with adequate infrastructure, essential surgical supplies, and well-trained personnel. Achieving this will require strong government commitment through strategic resource allocation, workforce expansion, the use of both monetary and non-monetary incentives to attract providers[58], and supply chain strengthening to ensure consistent availability of surgical services at these facilities.

First, addressing human resource challenges is critical. A shortage of trained surgeons, anesthetists, and perioperative staff remains a major barrier to expanding surgical services at HCIVs. Task-sharing models, where non-specialist medical officers receive additional surgical training, have been successfully implemented in other low-resource settings and could be adapted to maximize surgical capacity. Strengthening surgical training programs and incentivizing healthcare workers to serve in rural areas would further support this expansion.

Second, improving emergency referral systems is necessary. While geographic proximity to surgical facilities is important, timely access also depends on the efficiency and affordability of prehospital transport and referral networks. Strengthening emergency medical services, expanding ambulance networks, and improving community-level referral mechanisms could reduce delays in reaching definitive care. Investments in road infrastructure and traffic management policies, including prioritization of emergency transport, would further enhance the effectiveness of these systems.

Third, leveraging geospatial modeling as a policy tool can provide critical evidence to guide surgical scale-up strategies in Uganda and similar settings. Most required datasets, including road networks, land cover, elevation models, and population distribution, are now openly available. The main requirements are local expertise in geospatial tools and closer collaboration with policymakers. Embedding this approach into surgical planning frameworks such as National Surgical, Obstetric, and Anesthesia Plans (NSOAPs) could ensure that modeling evidence directly informs investment decisions and leads to measurable improvements in access.

Finally, strengthening HCIVs and referral systems must be seen within the broader context of health system readiness. Sustained progress will depend not only on geographic accessibility but also on ensuring affordability, acceptability, and quality of care to achieve equitable surgical access nationwide.

Strengths and Limitations

This study has several strengths. It leverages geospatial modeling with realistic assumptions about speeds and modes of transport, within an appropriate geospatial modeling framework to provide a data-driven evaluation of surgical access in Uganda. By incorporating regional stratification, it identifies areas with the greatest need, enabling targeted policy interventions. We consider that our study integrates more realistic travel scenarios than previous studies, because they used local expert knowledge from different parts of the country and the scenarios represented women in needs of EmONC, including a bimodal transport model, making the findings more applicable to Uganda's healthcare landscape. Additionally, this study highlights practical policy implications, demonstrating that equipping HCIVs to perform bellwether procedures significantly improves 1-hour access, aligning with global efforts to enhance surgical equity and meet the Lancet Commission on Global Surgery 2030 targets.

Despite its strengths, this study has several limitations. First, we only included public hospitals. Private healthcare facilities, which also provide surgical services, were not included in the analysis, potentially underestimating overall access. Second, the travel speeds used in the model were based on EmONC stakeholder consultations and may not fully capture real-world variability of road conditions, traffic, or the availability of different transport modes, such as water or air transport. Furthermore, the scenario represents transport during the dry season and does not capture likely changes in travel speeds during the wet season. In order to address this, we introduced uncertainty intervals which could partly account for seasonal variations and other unknown factors.[33] Third, our model assumes that all hospitals are fully equipped to perform bellwether procedures, whereas in reality, gaps in staffing, equipment, and operating room availability may limit their actual capacity even in the main hospitals.[1,40,59] Possible by-passing of the nearest hospital was also not accounted for. Future studies should thus integrate facility-level data on surgical readiness to refine these estimates. Additionally, while this study focuses on geographic accessibility, financial and sociocultural barriers to surgical care remain significant and warrant further investigation.[60] Future work could combine geospatial modeling with qualitative studies to elucidate patient-level barriers (e.g., cultural perceptions of surgery, cost concerns) and health system inefficiencies (e.g., triage delays). Economic evaluations assessing the cost-effectiveness of equipping HCIVs with surgical capacity could also provide valuable insights for policymakers.

Future Directions

To build on these findings, future research should focus on cost-effectiveness analyses to determine the feasibility and sustainability of scaling up surgical services at HCIVs. Additionally, outcome-based studies evaluating whether improved geographic access translates into increased surgical volume, reduced morbidity, and better patient outcomes are needed.

Implementation of a nationwide trauma registry policy could further refine these insights by tracking time to hospitals, procedural volumes, delays within the hospital, and outcomes at HCIVs and referral hospitals.[61] Such data would empower policymakers to align infrastructure investments with community and health facility needs, ensuring that improved gains translate into equitable, timely access to safe and affordable surgical care.

Abbreviations

DEM
Digital Elevation Model
DH
District Hospital
HCIV
Health Centre IV
LMIC
Low- and middle-income countries
NSOAP
National Surgical, Obstetric, and Anesthesia Plan
OSM
OpenStreetMap
RRH
Regional Referral Hospital
WHO
World Health Organization

Declarations

Ethics approval and consent to participate

This study used publicly available secondary datasets and did not involve human participants or identifiable personal data. Therefore, ethical approval and individual consent to participate were not required. All methods were carried out in accordance with relevant guidelines and regulations, including the Declaration of Helsinki.

Consent for publication

Not Applicable.

Availability of data and materials

The datasets used in this study are publicly available as shared in Table 1.

Competing interests

The authors declare that they have no competing interests.

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Author Contributions.

B.K., E.E., and M.G. conceptualized the study. B.K. coordinated the project, led data analysis, and sought technical support from collaborating teams. A.N. curated and verified geocoordinate data. P.C.N. contributed to grammar checks and manuscript revisions. N.R. provided overall supervision, guided the geospatial modeling and analysis, the use of AccessMod, and extensively revised the manuscript. R.L. and A.C. supported the geospatial analysis and contributed to revisions. J.H. contributed to manuscript revisions and alignment with broader global surgery perspectives. D.O. and R.K. provided critical review and input on surgical systems framing. B.K. drafted the initial manuscript, and all authors contributed to revisions and approved the final version of the manuscript.

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Competing interests

The authors declare no competing interests.

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Figures

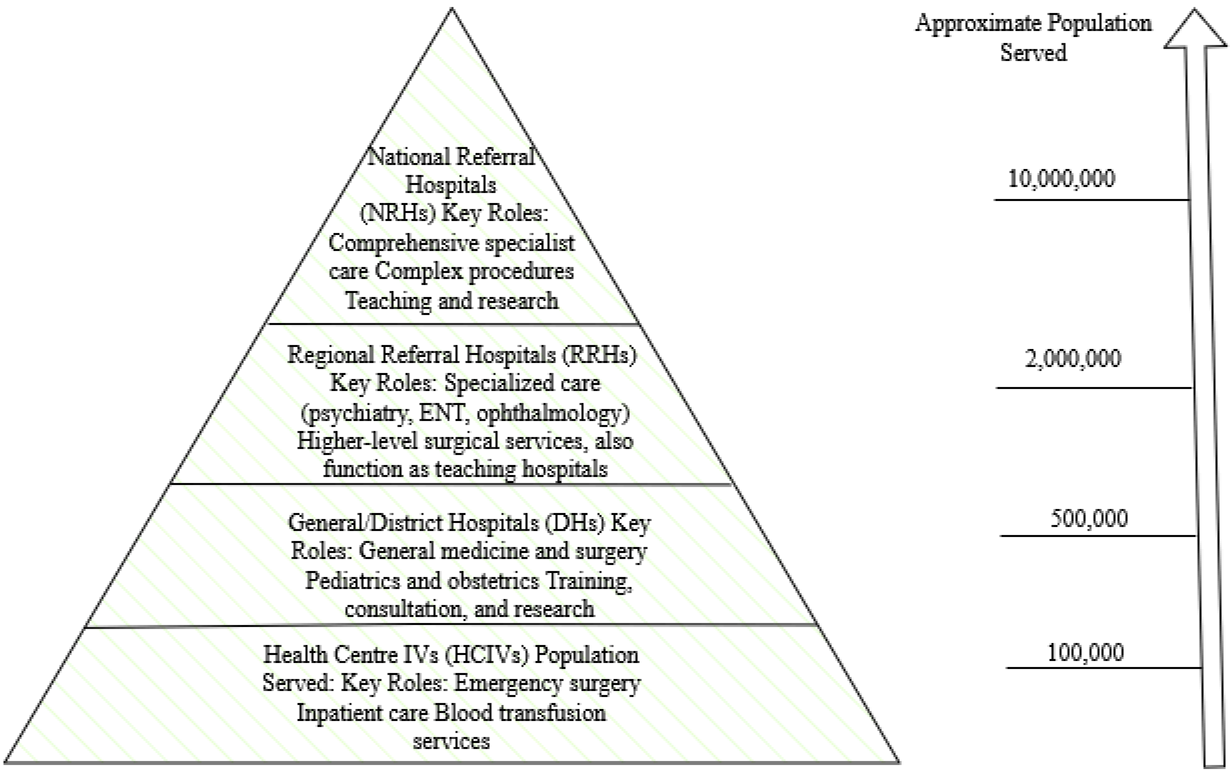

Figure 1

Tiered Surgical System Structure in Uganda.

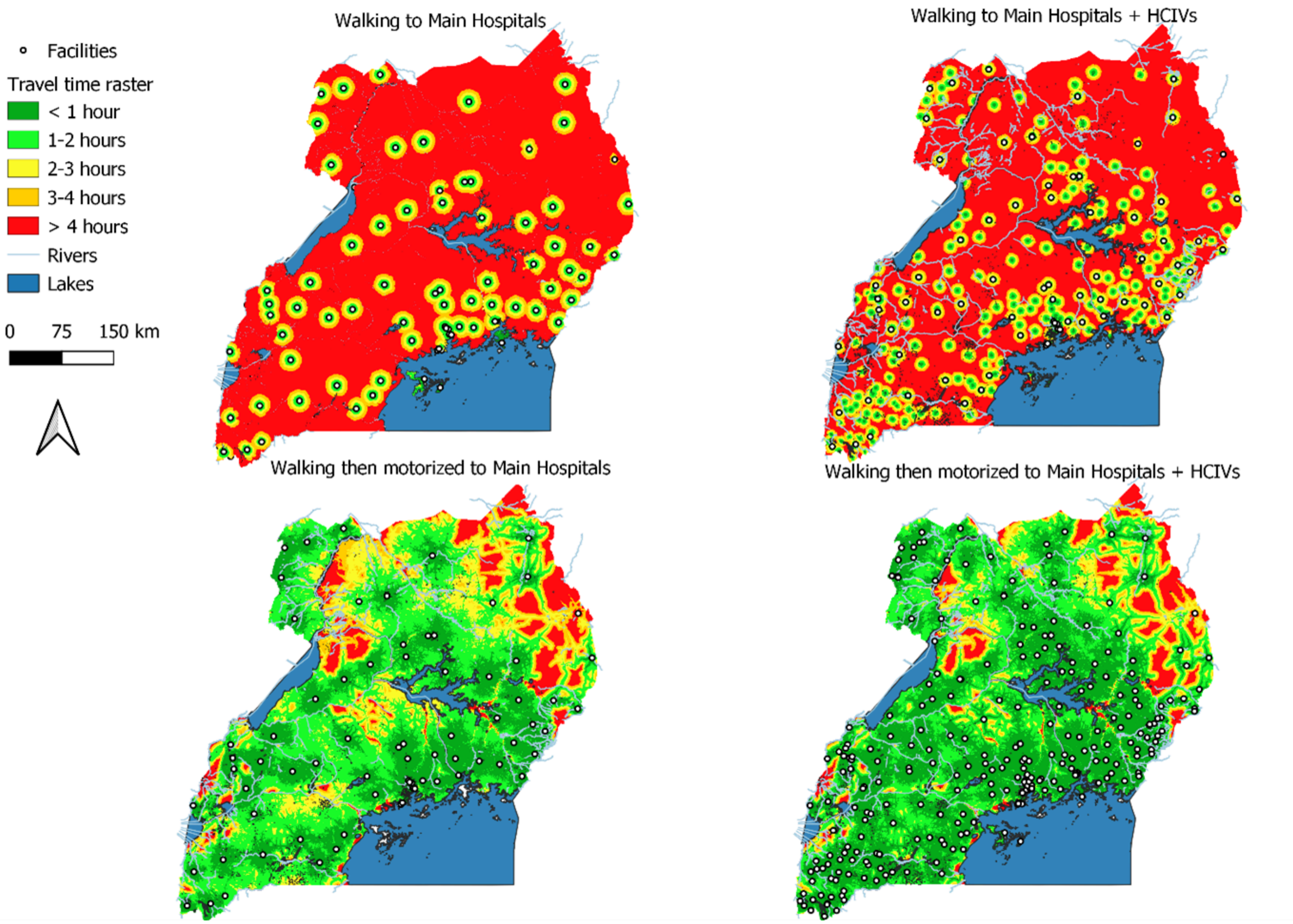

Figure 2

Maps of modeled travel time to the nearest hospital capable of performing bellwether procedures under the unimodal (walking-only) and bimodal (walking plus motorized transport) scenarios, for both 1-hour and 2-hour thresholds.

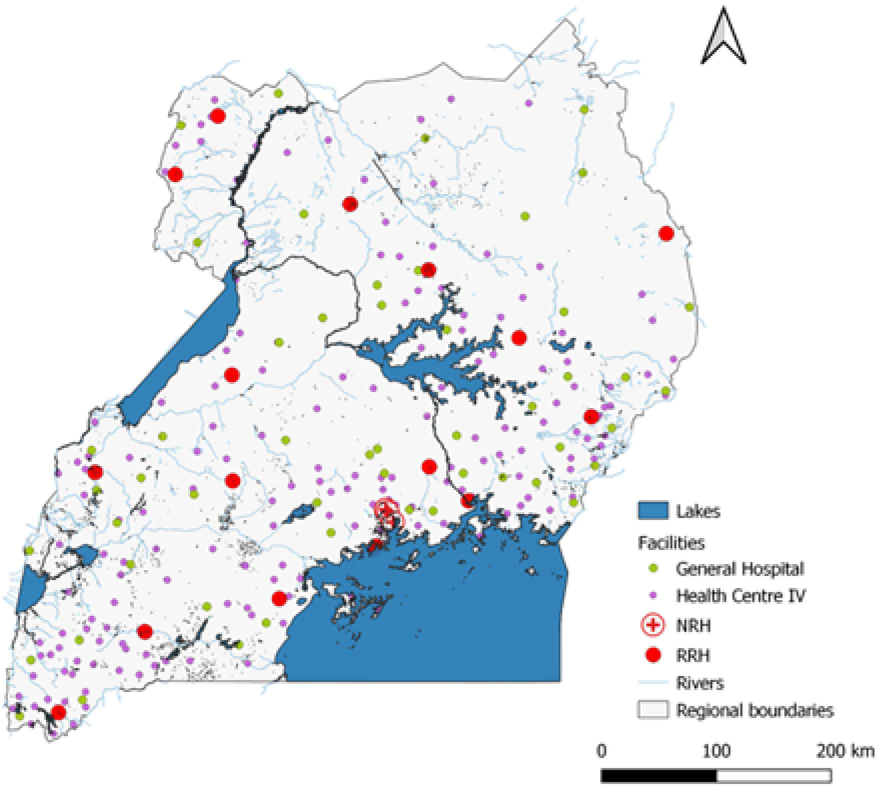

Figure 3

Distribution of the different types of facilities (NRHs, RRHs, DHs, HCIVs) used in the study.

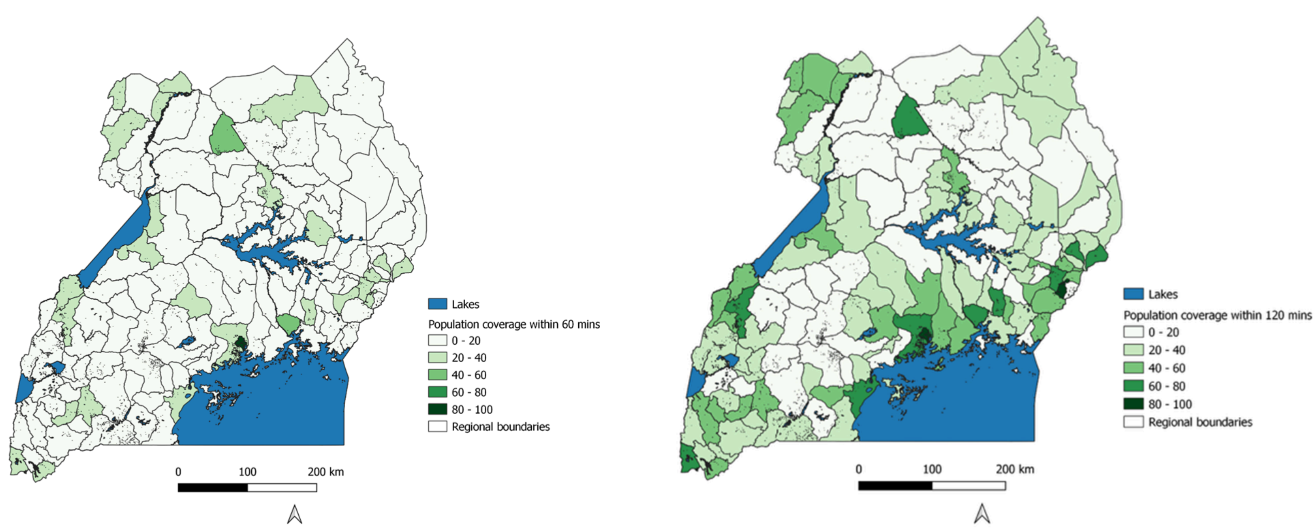

Figure 4

Panel A: Percentage of Ugandans who can reach Main hospitals and HCIVs in the walking only scenario within 1 hr travel. Panel B: Percentage of Ugandans who can reach Main hospitals and HCIVs in the walking only scenario within 2 hrs travel.

Supplementary Files

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