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Enhancing Connectivity via GIS-Based Bike-Sharing Optimization in Kigali City, Rwanda

Jean Marie Vianney Ntamwiza [1*], ***Hannibal Bwire*** [1], ***Alphonse Nkurunziza*** [2]

[1] *Department of Transportation and Geotechnical Engineering, University of Dar es Salaam, Dar es Salaam 35131, Tanzania*

[2] *Department of Civil, Environmental and Geomatics Engineering, University of Rwanda, Kigali P.O. Box 4285, Rwanda*

ABSTRACT

Promoting sustainable mobility and understanding travel demand are critical for rapidly growing cities like Kigali. This research aims to address limitations of traditional transport models by integrating geospatial analysis to support multimodal planning and optimize bike-sharing infrastructure. The study combines the Four-Step Transport Model with Geographic Information Systems (GIS) to enhance spatial disaggregation and identify optimal bike-sharing station locations. It incorporates shortest-path analysis and accounts for topography, road networks, population density, and land use. A household survey of 1377 residents was conducted to validate the model output. High trip generation zones were found in Nyamirambo and Kinyinya, while Nyarugenge, Remera, and Kimironko emerged as strong trip attraction areas. Congestion hotspots were identified at the Muhima, Remera, and Nyabugogo intersections. GIS analysis revealed high biking potential in Kinyinya, Kimironko, and Gatsata, aligning with survey responses. The study proposes 187 new bike-sharing stations in high-priority congestion zones and integrates 19 existing stations to strengthen multimodal connectivity, along with a first and last mile solution. Additionally, 15 key employment and service zones covering 67 km were identified to support efficient travel routes. By reducing the need for petrol-engine vehicle rebalancing, the optimized bike-sharing network supports environmental sustainability in the city. The integration of GIS and transport modeling offers a scalable,

*CORRESPONDING AUTHOR:
Jean Marie Vianney Ntamwiza, Department of Transportation and Geotechnical Engineering, University of Dar es Salaam, Dar es Salaam 35131, Tanzania; Email: ntamwizajeanmarie@gmail.com

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evidence-based framework for active mobility planning in Kigali and other Sub-Saharan cities in similar conditions to Kigali city in Rwanda.

Keywords: Travel Demand Modeling; Four-Step Model; Sustainable Urban Mobility; GIS Tools; Bike-Sharing; Station; Environment

1. Introduction

Bike-sharing has emerged as a viable solution to sustainable urban transport challenges, particularly in developing countries where rapid urbanization, limited infrastructure, and socio-economic disparities complicate mobility systems [1]. Globally, the growth of bike-sharing systems is attributed to their multiple benefits: improved health through increased physical activity and reduced cardiovascular risks, environmental advantages via lowered emissions and noise pollution, and socio-economic benefits through enhanced accessibility to jobs and services and reduced traffic congestion [2,3]. Moreover, bike-sharing contributes to greenhouse gas emission reductions, enhances public health, and minimizes dependency on private vehicles, especially for short trips or first- and last-mile connectivity [4,5].

This mode of transport has proven particularly effective in promoting active transport among diverse user groups. For example, school children increasingly prefer bicycles over school buses, gaining both physical exercise and long-term health benefits such as obesity prevention [6]. The flexibility of the system—offering both regular and electric bikes—ensures inclusivity by accommodating varied physical abilities and adapting to topographic conditions [7]. Additionally, the shared model reduces ownership burdens, allowing users to rent and return bikes at stations across the city [8,9].

While bike-sharing has been widely studied in developed contexts, prior research has predominantly focused on adoption patterns in Central Business Districts (CBDs), the role of the built environment, health outcomes, and user clustering [10]. Many of these studies rely on the traditional Four-Step Transport Model, which—despite its legacy in transportation planning—suffers from oversimplified assumptions and dependence on aggregated data that limit its ability to reflect behavioral dynamics in travel demand [11]. GIS-based approaches, while well-documented for their strength in spatial analysis, are often applied descriptively without integration into advanced transport models [12].

To address these limitations, this study adopts an enhanced methodological framework that integrates the Four-Step Model with geospatial optimization tools in ArcGIS, focusing on spatially disaggregated demand modeling, shortest-path analysis, and location-specific accessibility assessments. This methodological enhancement not only overcomes the weaknesses of traditional models but also introduces innovation through the incorporation of topography, population density, land use, road networks, and household distributions—critical but often neglected variables in African urban contexts [13–15]. Notably, African cities like Kigali are characterized by steep terrain and constrained infrastructure, making spatial factors essential for effective bike-sharing system planning.

Previous studies have shown that station characteristics—including the number of bikes available, station size, and travel time to the nearest station—directly impact accessibility and usage [16–18]. However, in African contexts, limited research has been conducted on optimal station siting based on these factors. Moreover, despite recent advances using machine learning (ML) models for system optimization [19], these approaches often lack the integration of geospatial parameters, such as elevation, road network connectivity, and urban density gradients, which are pivotal for planning in cities like Kigali [19,20].

Recent innovations in global literature offer insights into methodological improvement. For instance, Target-based Stochastic Distributionally Robust Optimization (TS-DRO) has enhanced performance under demand uncertainty [21]; dynamic rebalancing models have improved user satisfaction despite marginal cost increases [22]; and spatial optimization frameworks within Mobility-as-a-Service (MaaS) paradigms have shown significant CO_2 emission reductions through improved station layouts [23]. Nevertheless, these innovations are rarely contextualized to African urban environments, and there remains a critical gap in modeling the spatial logic of bike-sharing networks in conjunction with the real-world distribution of trip generators and attractors.

This study therefore proposes a hybrid framework that bridges the methodological and contextual gaps by applying the Four-Step Model, enhanced through GIS-based spatial disaggregation and accessibility mapping, to optimize bike-sharing station locations across 24 urban zones in Kigali. Unlike prior studies that focused narrowly on built environments or static zoning, this research advances the field by integrating dynamic geospatial analysis with demand forecasting, thereby aligning methodological innovation with real-world urban complexity.

The remainder of this paper is as follows: Section 2 presents the materials and methods, including data sources and modeling procedures; Section 3 discusses the results, including spatial and operational implications; and Section 4 offers conclusions and policy recommendations for enhancing bike-sharing accessibility in Kigali and similar urban contexts.

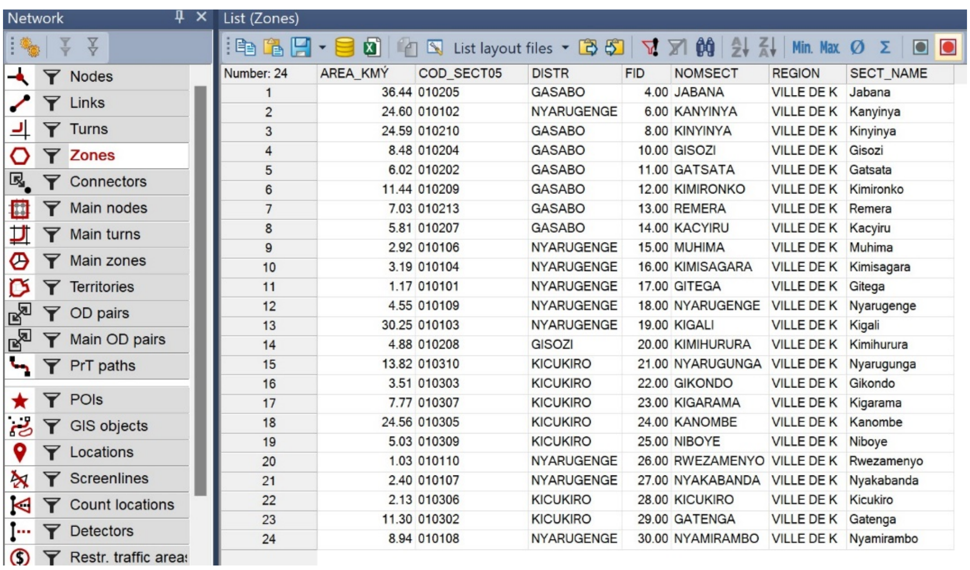
2. Materials and Methods

2.1. Description of the Study Area

The research focuses on Kigali, the capital city of Rwanda, at coordinates 10°58′ South and 30°07′ East, with a population of 1,745,555 residents spanning an area of 730 square kilometers [24]. The population corresponding to 86.9% lives in urban areas [25]. The city is rapidly urbanized and committed to supporting sustainable urban mobility in its three districts: Gasabo, Kicukiro, and Nyarugenge, where different initiatives are being promoted, like car-free zones along with car-free days [25]. Kigali has a diverse topography, including hills, valleys, and flat areas, offering a varied landscape for investigating biking behaviors and infrastructure requirements. Rwanda has different green mobility initiatives such as car-free days, zones, and cycling infrastructure and Kigali city is the leading city in these initiatives in Africa [26]. Notably, all new roads in the city of Kigali are mandated to include cycling lanes separated from vehicle and pedestrian lanes for safety of riders. However, despite these efforts made by the city of Kigali, bike sharing was introduced but has only been adopted. The existing bike-sharing services introduced by GuraRide are operational, with challenges related to station location, station availability, bike availability on station, road network design and their efficient connectivity, and bike-sharing user adoption.

2.2. Data

Data was collected in 24 urban zones with an area corresponding to 251.87 square kilometers representing 34.5% of the total area of the city of Kigali. **Figure 1** provides more details. The area is characterized by high population density, economic activities, and jobs. The mobility of residents in the study area is characterized by public transport, motorcycle taxis, walking, private vehicles and cycling, with non-motorized transport representing 52% [27]. During the road network analysis, we included primary, secondary, and tertiary roads, dedicated bus routes, and high-traffic volumes. More clarifications are detailed in **Figure 2** for this analysis.



Number: 24	AREA_KMÝ	COD_SECT05	DISTR	FID	NOMSECT	REGION	SECT_NAME
1	36.44	010205	GASABO	4.00	JABANA	VILLE DE K	Jabana
2	24.60	010102	NYARUGENGE	6.00	KANYINYA	VILLE DE K	Kanyinya
3	24.59	010210	GASABO	8.00	KINYINYA	VILLE DE K	Kinyinya
4	8.48	010204	GASABO	10.00	GISOZI	VILLE DE K	Gisozi
5	6.02	010202	GASABO	11.00	GATSATA	VILLE DE K	Gatsata
6	11.44	010209	GASABO	12.00	KIMIRONKO	VILLE DE K	Kimironko
7	7.03	010213	GASABO	13.00	REMERA	VILLE DE K	Remera
8	5.81	010207	GASABO	14.00	KACYIRU	VILLE DE K	Kacyiru
9	2.92	010106	NYARUGENGE	15.00	MUHIMA	VILLE DE K	Muhima
10	3.19	010104	NYARUGENGE	16.00	KIMISAGARA	VILLE DE K	Kimisagara
11	1.17	010101	NYARUGENGE	17.00	GITEGA	VILLE DE K	Gitega
12	4.55	010109	NYARUGENGE	18.00	NYARUGENGE	VILLE DE K	Nyarugenge
13	30.25	010103	NYARUGENGE	19.00	KIGALI	VILLE DE K	Kigali
14	4.88	010208	GISOZI	20.00	KIMIHURURA	VILLE DE K	Kimihurura
15	13.82	010310	KICUKIRO	21.00	NYARUGUNGA	VILLE DE K	Nyarugunga
16	3.51	010303	KICUKIRO	22.00	GIKONDO	VILLE DE K	Gikondo
17	7.77	010307	KICUKIRO	23.00	KIGARAMA	VILLE DE K	Kigarama
18	24.56	010305	KICUKIRO	24.00	KANOMBE	VILLE DE K	Kanombe
19	5.03	010309	KICUKIRO	25.00	NIBOYE	VILLE DE K	Niboye
20	1.03	010110	NYARUGENGE	26.00	RWEZAMENYO	VILLE DE K	Rwezamenyo
21	2.40	010107	NYARUGENGE	27.00	NYAKABANDA	VILLE DE K	Nyakabanda
22	2.13	010306	KICUKIRO	28.00	KICUKIRO	VILLE DE K	Kicukiro
23	11.30	010302	KICUKIRO	29.00	GATENGA	VILLE DE K	Gatenga
24	8.94	010108	NYARUGENGE	30.00	NYAMIRAMBO	VILLE DE K	Nyamirambo

Figure 1. Details: Area and Location of 24 Urban Zones.

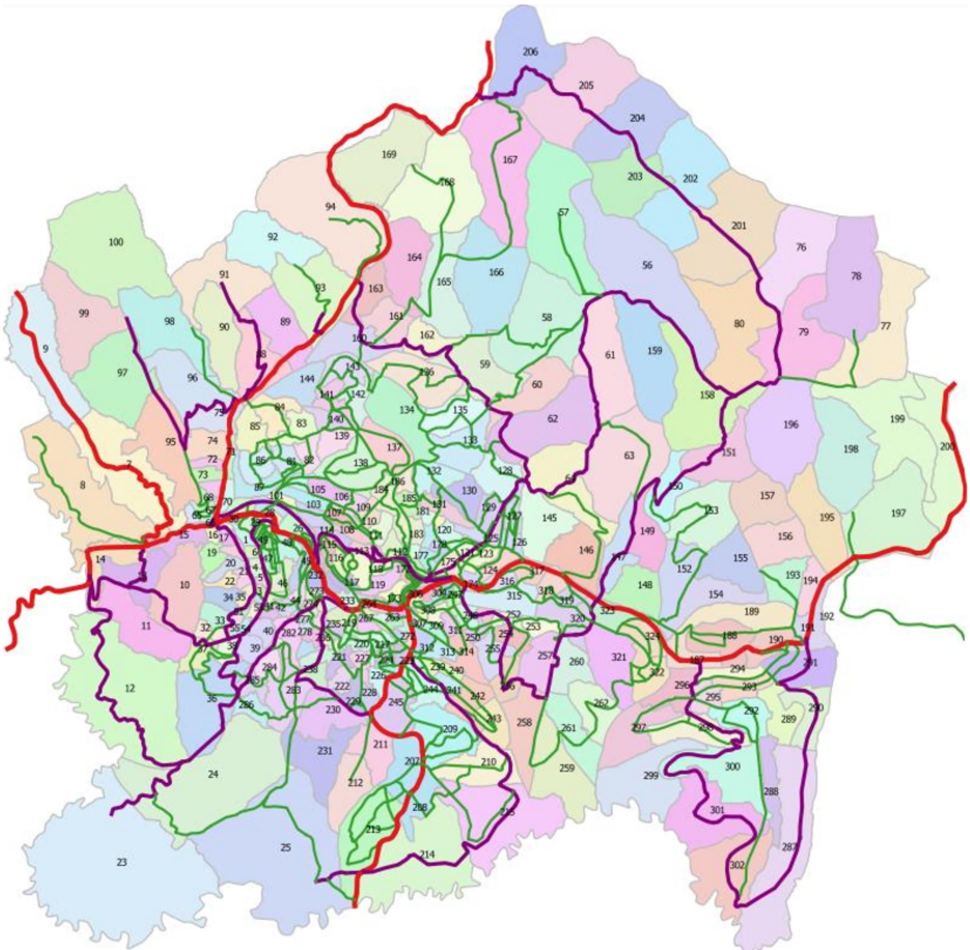


Figure 2. Road Network Details and Locations of Study Zones.

2.3. Method

Various methodologies have been performed in existing materials to improve bike-sharing programs. Among those methodologies, research has proposed machine learning and Internet of Things to manage bike sharing in smart cities [19], optimizing daily operation using resource allocation management [28], and the use of advanced predictive modeling techniques to optimize repair shop operations within bike-sharing systems [29]. However, there is scarce research employing ArcGIS Pro 3.1, a robust Geographic Information System (GIS) software along with four-step modelling, to offer a more comprehensive and effective methodology for enhancing bike-sharing station location to boost accessibility and usage. This research combines those two methodologies to bridge the gap in existing material methodology.

A four-step transport modelling was performed where (i) trip generation has quantified the number of trips originating from each zone and destined for each zone, considering population density, employment opportunities, and land-use patterns. Matrix balancing was used to ensure consistency in trips produced and attracted in each zone, aligning the total number of trips produced with the total number of trips attracted across all 24 zones. The production function calculated trips from a zone by multiplying the average trip production rate by the population of that zone, while the attraction function estimated trips destined for a zone by multiplying the average trip attraction rate by the number of jobs in that zone.

The output is a zonal trip production and attraction matrix, a foundational tool for subsequent steps in travel demand modelling. (ii) Trip distribution connects trip origins to destinations based on travel demand and opportunities. The gravity model was performed to estimate trip flows between zones, considering distance and travel impedance, outputting the Origin-Destination (OD) matrix for all 24 study zones. (iii) mode choice: During the mode choice analysis, a multinomial logit model was performed to determine the proportion of trips made using different transport modes, considering travel cost, travel time, and socioeconomic factors. The utility functions for different modes:

$$\text{Bike} = 0 + 0.29 * \text{Cost Bike} \tag{1}$$

$$\text{Car} = -1.43 + 0.29 * \text{Cost Car} \tag{2}$$

$$\text{Public Transport} = -1.79 * \text{Cost Public Transport} \tag{3}$$

(iv) Traffic assignment: Traffic assignment allocates trips to the transport network based on the shortest path and the cost, considering road network capacity and congestion levels using a user-equilibrium traffic assignment approach. **Table 1** provides more details.

Table 1. Summary of 4 Steps Modelling.

Step Number	Step Name	Description (Brief)	Key Inputs/Outputs
1	Trip Generation	Estimate trip counts by zone	Population, employment, land use
2	Trip Distribution	Match origins with destinations	Travel costs, distance matrices
3	Mode Choice	Select travel modes based on utility/preferences	Travel time, cost, mode availability
4	Route Assignment	Assign trips to routes in the network	Road network, travel time, congestion

Additionally, ArcGIS Pro 3.1 was used to map station location and in shortest path analysis. A dataset was composed by: (i) Administrative boundaries of Kigali city and its districts from the National Land Authority, (ii) Road network and bus station data from the Rwanda Transport Development Agency (RTDA), (iii) Housing footprints dataset from the National Institute of Statistics of Rwanda, (iv) Digital Elevation Model (DEM) acquired from the USGS Explorer, (v) Kigali City Master Plan 2050.

To validate the results, a survey was conducted in the study area to ensure the spatial model aligns with real usage, preferences of users, and their needs, leading to more robust, inclusive, and implementable bike-sharing solutions. The information in **Table 2** was corrected on 1377 residents in Kigali city using a questionnaire in critically identified areas. The questionnaire comprises questions to understand residents' biking preferences, reasons for not preferring biking, influential factors, and preferred locations for biking stations. Both online and offline survey methods were used. To ensure data quality, data were collected in various locations such as higher learning institutions, workplaces, residential areas, CBD, bus stops, and bus stands in critical zones. Each respondent could complete the questionnaire only once. The target was to collect responses from 1400 individuals, achieving a 98% response rate, resulting in 1,377 complete surveys. In comparison, previous researchers like Chen et al. examined free-floating bike-sharing among Nanjing residents [30], distributing 700 questionnaires and analyzing the responses of 453 participants. This research, conducted over 8 months from January to August 2024, utilized data from 1,377 participants to validate the modelling results.

Table 2. Summary of Survey Response from a Randomized Method.

Variable	Description	Answers
1. Gender	Gender of the respondent	Male, Female, Other
2. Occupation	Occupation of the respondent	Free text
3. District	District of residence	Kicukiro, Nyarugenge, and Gasabo
4. Bike Preference	Whether respondents prefer biking over other modes of transport	Yes, no
5. Reasons influencing respondents to choose biking over other modes of transport	To understand the factors influencing the choice	• It is affordable • It is the only available means of transport • It is a convenient mode in avoiding congestion • It is a means of exercise to keep me healthy and fit • It does not pollute the environment

Table 2. *Cont.*

Variable	Description	Answers
6. Non-Cyclist Views	Reasons for not choosing bicycles over other modes of transport	• I prefer a faster mode • I can afford other modes • There is too much risk of injury • Adverse weather conditions • There are no dedicated lanes for cyclists • Bicycles cannot carry my household • I don't own a bike • None above
7. Bike share system preference	Yes or no	To understand if respondents prefer their own bike or bike sharing
8. Preferred Bike Station Locations	Locations where respondents want to see bike stations	• University Center • Near bus stop • Near restaurant • Near taxis park • CBD (Central Business district) • College Park Center • On the gate of the university • Other (please specify)

3. Results

3.1. Trip Generation and Attraction Patterns

The findings on trip generation and attraction in 24 urbanized zones indicated distinct trip generation and attraction patterns. High trip generation zones are Nyamirambo, Jabana, and Kinyinya while Nyarugenge, Kimironko and Remera zones indicated a high trip attraction.

Those zones with high trip generation are characterized by significant residential activity and commuter outflows. In contrast, zones with high trip attractions are key commercial, institutional, and service hubs in Kigali. These findings align with the urban structure in the city where central districts function as employment centres while peripheral areas accommodate residential populations. **Figure 3** provides more details.

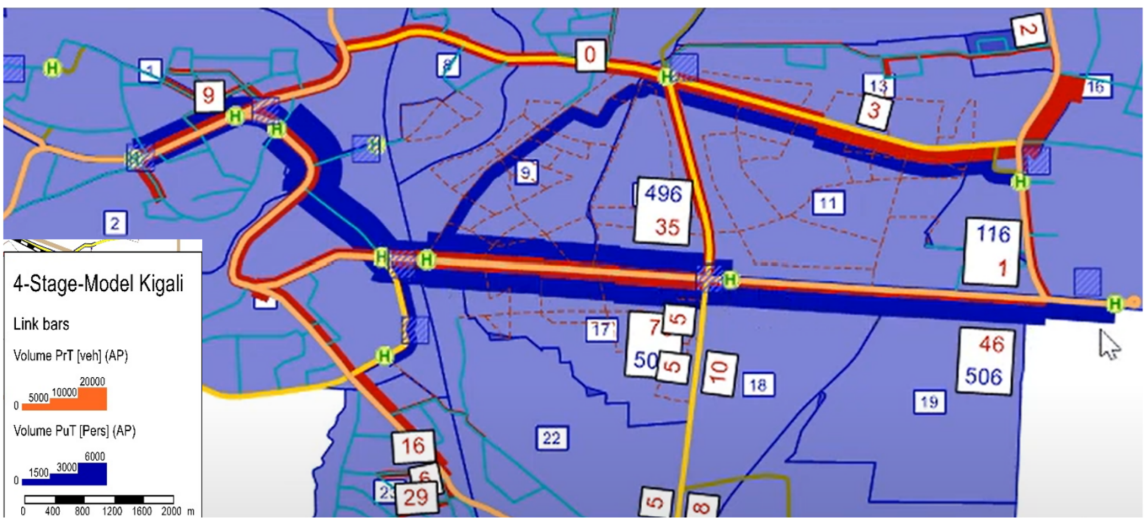


Figure 3. Four-Step Modelling in the City.

3.2. Modal Split and Congestion Hotspots

The mobility in the study area depends on motorized transport and walking, indicating the gap in bike-sharing usage where bike-sharing stations are located far from one another in the study area. The heavy dependence on motorcycles indicated a need for improved last-mile connectivity, while public transport dominance highlights the necessity for multimodal integration in the city. Key congestion hotspots identified are at major intersections with dominance in the zones of Muhima, Remera, Nyabugogo, and Kimironko, zones characterized by flows and mixed land use. We found the gap in station location in the study zones, and we identified bike-sharing additional station locations as an alternative mode to alleviate pressure on road networks and enhance mobility in study zones.

3.3. Bike-Sharing Potential and Proposed Infrastructure

This research has a core contribution to existing material; this contribution is due to the identification of high-potential biking zones in the city of Kigali, which included Kinyinya, Muhima, Kimironko, Jabana and Gatsata zones. These zones provide favourable conditions for bike-sharing expansion, characterized by high trip density, accessibility to key services, and ease of integration with existing transport infrastructure. From those findings, the study identified new bike-sharing stations to support 19 existing ones. The total identified stations are 187 in the study area to support existing ones.

A GIS-based approach, incorporating topography, road networks, and population density, strategically positioned these stations for maximum user convenience and uptake; **Figure 4** indicates new proposed stations and existing stations in yellow. Those stations identified are also based on the slope of the city. A slope higher than 10% discourages riders and leads to the adoption of motorized transport.

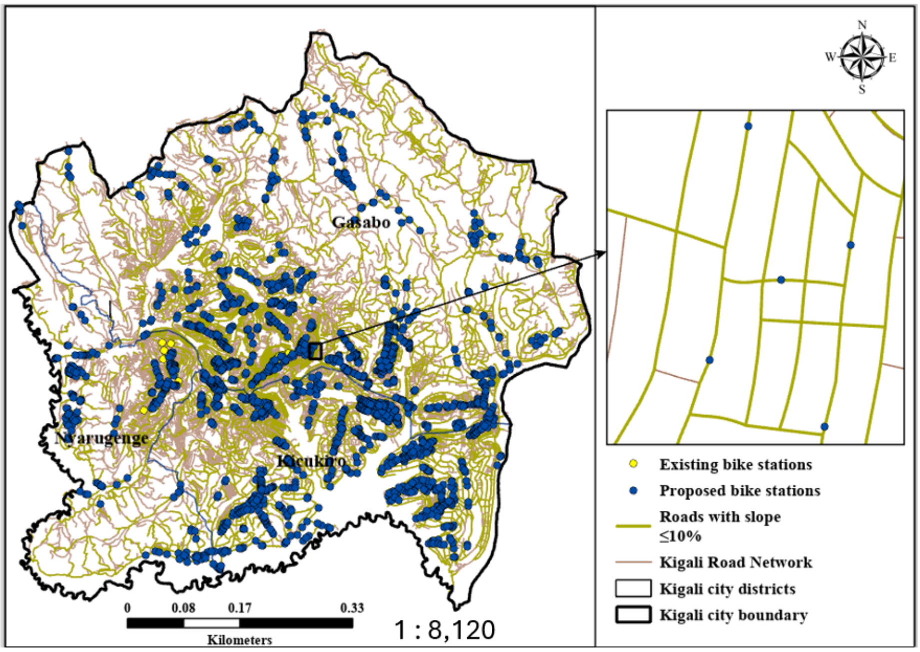


Figure 4. Slope and Road Connectivity Analysis.

This research has used the shortest methods. It identified the road networks of 87km with a slope of less than 10% where riders can easily access key services quickly and use regular bikes or electric bikes based on how riders fit. Then, beyond the study zones, the research recommends using electric bikes to access different corners of the city with slopes greater than 10% and neighbouring cities as the area is characterized by topography and using electric bikes is not an issue when moving in high-topography areas.

Figure 4 demonstrates a data-driven, spatially optimized bike-sharing station deployment strategy in Kigali City, prioritizing stations on gentle slopes and well-connected roads across all city districts. This approach aims to maximize coverage, accessibility, and connectivity, thereby promoting more efficient, convenient, and sustainable cycling as a mode of urban transport.

Figure 5 illustrates the optimized distances and connectivity to key services across the three districts of Kigali City. The color-coded slope classification highlights terrain suitability for cycling: green areas represent gentle slopes (0–10%), yellow indicates moderately steep slopes (10–55%), and red denotes very steep slopes (55–100%).

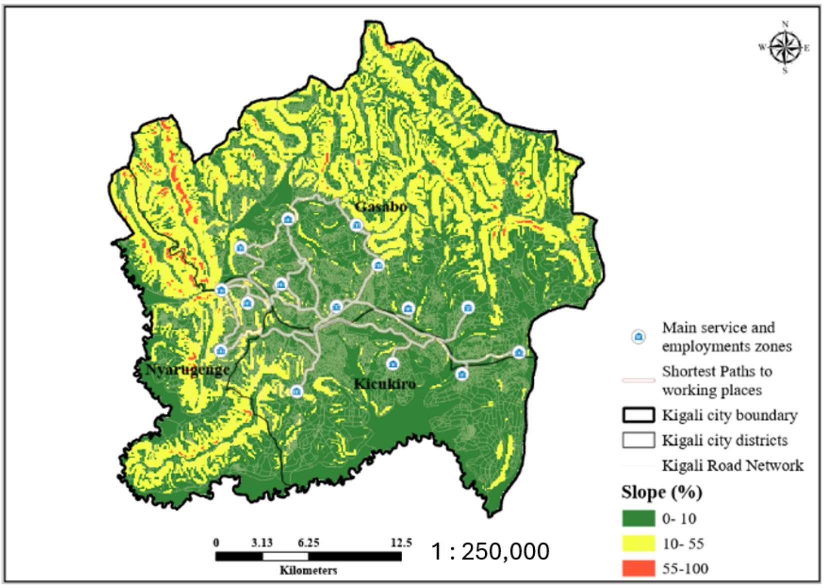


Figure 5. Shortest Path Analysis.

3.4. Bike-Sharing Demand and Accessibility

Results in **Figure 6** indicated that the population density is associated with bike-sharing demand. High household densities, particularly in zones exceeding 4,415.3 households per square kilometer, have exhibited the most significant demand for bike-sharing services in the city of Kigali. Land use analysis pinpointed has indicated key employment and service hubs, such as the Central Business District (CBD) and Kimironko Commercial Centre, as priority areas for station expansion in future directions. This research found that some stations in the city of Kigali are underutilized, and this finding is associated with how existing stations are positioned; some of them are too far from significant transit hubs, leading to their poor utilization, and new stations were identified near major transit hubs and employment centres to provide a foundation for seamless multimodal travel, connectivity and accessibility.

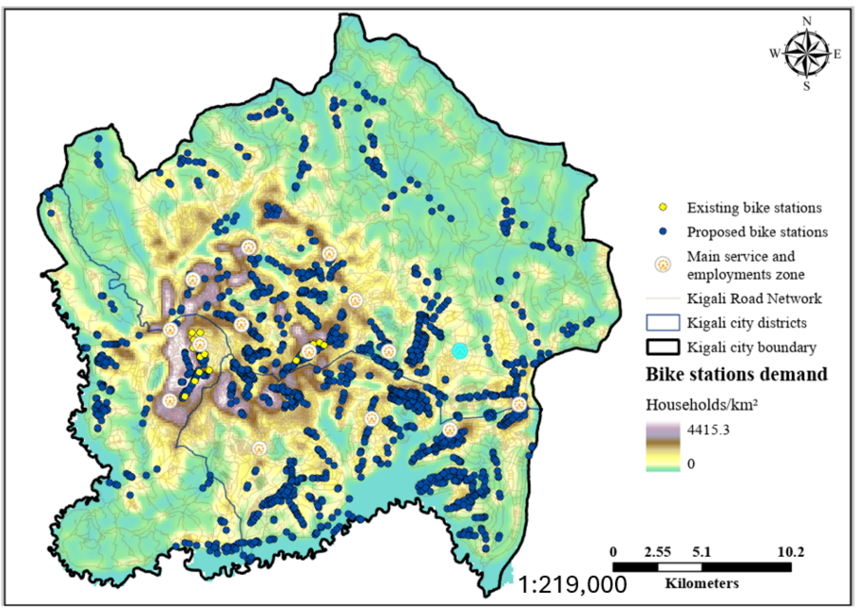


Figure 6. Bike Sharing Demand Analysis.

3.5. Findings from the Survey

Figure 7 illustrates the relationship between bike-sharing ride frequency, education level, and employment status for insights for optimizing station placement and promoting multimodal connectivity. Among individuals with tertiary education, a large portion are either employed (43.4%) or students (32.93%), suggesting that locating bike-sharing stations near universities, working areas and business districts would effectively serve these groups. Co-locating these stations with public transport hubs in such areas further enhances accessibility and encourages regular use. For those with secondary education, the majority are employed (50.35%), followed by students (29.89%), indicating a strong likelihood of daily commuting. This highlights the importance of positioning stations near workplaces and transit nodes to support last-mile mobility. Additionally, the data shows that all respondents with only primary education are employed, pointing to a possible dependence on cycling as an affordable mode of transport. Therefore, equitable station distribution across low-income and underserved neighborhoods is crucial. These findings support a demand-driven and inclusive approach to infrastructure deployment that aligns with the socio-economic profiles and mobility behaviors of various user segments, ultimately improving both reach and efficiency of the bike-sharing system.

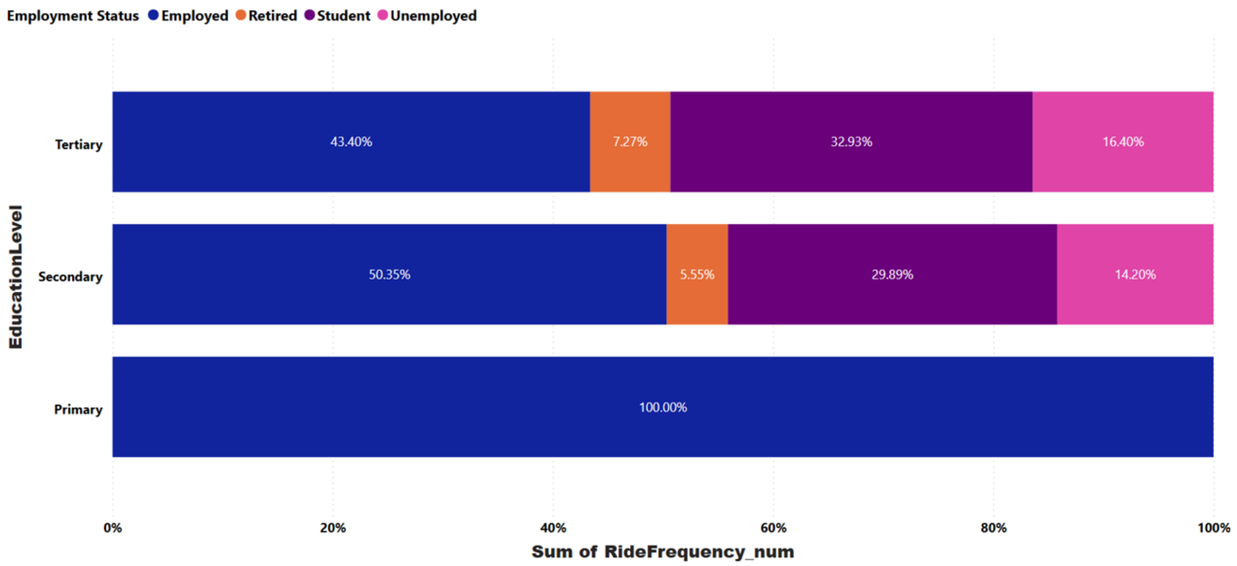


Figure 7. Distribution of Ride Frequency by Education Level and Employment Status.

3.6. Policy and Planning Implications

Bike sharing has been proven to be an active transport mode that contributes to environmental challenges and emission reduction worldwide. The findings from this research indicated the need to promote bike-sharing services as an alternative mode of transport to motorized transport not only in Kigali but in similar cities. This study recommends the expansion of bike-sharing stations in underserved, high-density areas in study zones. It also recommends dedicated cycling lanes for safety, higher ridership, and integrating bike-sharing with public transport through innovative mobility solutions. Future research must explore the user's willingness to adopt bike-sharing and the potential barriers to its implementation to further sustainable urban mobility.

3.7. Identified Gaps and Challenges

This study has identified gaps in existing bike-sharing systems, including (i) a limited station distribution where the current 21 bike stations are too inadequate to meet inter-zonal travel demands, necessitating an expanded network to balance the demand, (ii) terrain constraints where the steep slopes and poor connectivity between major areas like Gatsata- Nyabugogo, Remera – Kimironko and Kicukiro-Niboyi hinder the feasibility of cycling, (iii) digital accessibility barriers where the requirement for smartphones to have access to the bike-sharing system disproportionately excludes low-income residents and finally limit the equitable mobility accessibility.

4. Discussion of Findings

4.1. Discussion

Findings: The findings reveal a clear relationship between slope levels and cycling speed, confirming that higher slopes lead to decreased cycling speeds. This aligns with previous research [20], which demonstrated that commuters tend to prefer motorized transport in areas with steep gradients. In this study, slopes ranging from 0 to 100% were analyzed to identify roads suitable for cycling, particularly for both conventional and electric bikes. The analysis resulted in delineating a proposed road network spanning 87 km with slopes less than or equal to 10%, illustrated in **Figure 4** alongside the 19 existing bike stations (highlighted in yellow). To promote accessibility and convenience, a maximum inter-station distance of 500 meters was maintained, assuming shorter distances can be covered on foot.

4.2. Slope and Road Network Selection

Using Digital Elevation Model (DEM) data, slopes were classified into three categories: gentle (≤10%), steep (10%–55%), and very steep (55%–100%). Bike stations were strategically located only within gentle slope areas to ensure ease of cycling for users of both normal and electric bikes, providing flexibility to choose bike types based on destination topography. Roads within this slope threshold were extracted from Kigali's Road layer and roads shorter than 500 meters were excluded, as these distances can be comfortably covered by walking, optimizing resource allocation.

4.3. Equity in Bike Station Distribution

Horizontal (spatial) and vertical (social) equity principles guided the station placement process. Horizontal equity ensured that stations were evenly distributed according to population density, while vertical equity addressed equitable access across different social groups. Kernel density analysis was employed to identify areas with high household density, guiding the proposal of new stations along selected roads within these zones to maximize coverage and inclusiveness.

4.4. Integration with Service and Employment Nodes

Data from the Kigali City Master Plan 2050 was utilized to identify key service and employment nodes, including commercial zones and public facilities. These nodes served as anchor points for station placement, ensuring that stations are located within a 3 km radius—equivalent to a 30-minute bike ride—from residential neighborhoods. This spatial proximity fosters effective last-mile connectivity and supports daily commuting needs.

4.5. Shortest Path Analysis for Efficient Routing

Employing network analysis tools, the shortest paths between service and employment nodes were calculated while accounting for physical barriers such as steep slopes and inaccessible roads. These constraints were managed using point and line barrier tools to eliminate unsuitable routes, resulting in optimized, terrain-aware cycling corridors that enhance commuter efficiency and safety [31].

4.6. Identified Gaps and Challenges

The study highlights critical gaps in the current bike-sharing system, including limited station distribution, which contributes to increased reliance on motorized vehicles, negatively impacting environmental sustainability. Long walking distances between stations—such as the 8 km gap from Kisimenti to Serena—discourage usage and reduce system efficiency. Moreover, requiring smartphone access to use the bike-sharing scheme restricts accessibility for some user groups, further limiting adoption. With only 19 existing stations, the network coverage remains insufficient to support widespread cycling.

4.7. Advancement Over Previous Studies

Unlike earlier studies that primarily focused on route preferences [32], this research prioritizes slope-based analysis, equitable station distribution, and comprehensive network integration to strategically optimize bike-sharing station locations. While both this study and previous works employ GIS tools [31], the present research advances the field by incorporating the Four-Step Model, enabling more nuanced planning and implementation of new stations. These optimized stations will facilitate bike rebalancing through cycling, reducing dependence on petrol-engine vehicles currently used for this purpose, thereby mitigating environmental impacts.

4.8. Validating the Findings with the Survey from Residents

The survey's demographic profile in **Table 3** indicates a relatively balanced gender distribution among respondents: 41.5% identified as female, 53.5% as male, and 5% chose not to disclose their gender. These results highlight the importance of designing inclusive transport infrastructure that ensures safety and comfort for users of all gender identities. Furthermore, the high proportion of student respondents (47.5%) emphasizes the need to locate bike-sharing stations near educational institutions—an insight supported by 43.5% of respondents identifying university areas as preferred locations for such services, aligning with the model's emphasis on accessibility.

Table 3. Findings from the Survey.

Variable	Description
1. Gender	Females represent 41.5% of respondents, 53.5% are males and 5% do not prefer to say their gender.
2. Occupation	On occupation, 47.5% are students, 15.5% are self-employed, 18.8% are employed, 12.6% are unemployed while 5.6% are retired.
3. District of residence	Among respondents, 27.6% reside in Nyamirambo, Nyarugenge district, 39.5% reside in Gatsata, Kinyinya, Remera, and Kimironko sectors of Gasabo District, while 32.9% reside in Niboye and Kagarama sectors of Kicukiro district.
4. Bike preference as a mode of transport	On biking preference, 60.5% prefer biking while 39.5% do not prefer biking.
5. Why residents prefer biking over other modes of transport	Reason for biking, 30.4% of respondents prefer biking because it is affordable, 15.5% prefer biking as it is the only available mode of transport, 16.8% prefer biking to avoid congestion, 21.4% prefer biking for exercise to keep them healthy and fit while 15.9% prefer biking because it does not pollute the environment
6. Reason for not cycling (non-cyclist views)	The survey has identified 544 respondents as non-biking prefer, 21.1% of them prefer faster mode than biking, 12,1% can afford other mode of transport, 23.8% do not prefer biking because it is too much risk of injury, 12.4% do not prefer biking due to adverse weather condition, 13.7% do not prefer riding due to lack of dedicated lane while only 8.4% stated that bike cannot carry their households.
7. Bike share system preference	On bike sharing preference, respondents corresponding to 80.1% prefer biking while 19.9% do not prefer bike sharing.
8. Three locations where respondents would prefer to pick up and return shared bikes	On location, 48.8% prefer a bike sharing station near the bus stop for their connectivity, 45.5% prefer a bike sharing station near taxi park (bus terminals), 43.5% prefer a bike sharing station in university center, 39% prefer the station near the restaurant.

Spatial distribution data reveals that 27.6% of respondents reside in Nyamirambo (Nyarugenge District), 39.5% in Gatsata, Kinyinya, Remera, and Kimironko (Gasabo District), and 32.9% in Niboye and Kagarama (Kicukiro District). This residential pattern aligns closely with GIS-based analysis, which identified Nyamirambo and Kinyinya as major trip generation zones and Remera and Kimironko as key trip attraction areas. The correlation between these survey results and spatial modeling outputs enhances the credibility of the proposed station locations and suggests the model effectively reflects real-world commuting behavior and demand patterns.

Additionally, the survey reveals strong public support for cycling: 60.5% of respondents expressed a preference for biking, and 80.1% endorsed the idea of bike-sharing services. This signals a significant opportunity for expanding the shared cycling infrastructure in Kigali. Reasons cited for preferring biking include affordability (30.4%), health and fitness benefits (21.4%), reduced congestion (16.8%), and environmental advantages (15.9%)—factors that align with the study's objectives of promoting accessible and environmentally sustainable urban transport.

Conversely, 39.5% who did not prefer biking highlighted key barriers, including safety concerns (23.8%), insufficient infrastructure (13.7%), and adverse weather conditions (12.4%). These concerns validate the study's recommendation to prioritize the development of protected cycling infrastructure, especially in high-demand areas like Muhima, Remera, and Nyabugogo, where congestion poses major challenges and improvements could significantly increase cycling uptake.

Respondents' preferred locations for bike-sharing stations—near bus stops (48.8%), taxi parks (45.5%), university campuses (43.5%), and restaurants (39%)—closely match the spatial modeling results. These preferences underscore the importance of enhancing last-mile connectivity and integrating bike-sharing into public transport network in Kigali. The identification of 15 key employment and service hubs along a 67 km corridor further supports the need to strategically place stations in areas with high functional demand. The existing literature has indicated that the introduction of bike sharing has made groups of students' regular users of bike sharing [33]. In summary, the survey results provide strong empirical validation for model-based station optimization. The clear alignment between user preferences, residential distribution, and GIS-recommended locations demonstrates the value of integrating transport modeling with participatory data. By grounding infrastructure planning in lived experience and user behavior, this study offers a replicable, user-centered framework for promoting sustainable mobility in fast-growing urban environments like Kigali. Future efforts should prioritize eliminating existing barriers, expanding safe cycling routes, and improving multimodal connectivity to encourage greater adoption of non-motorized transport and reduce reliance on private vehicles.

4.9. Comparative Analysis with Existing Research

This study contributes to the growing body of research aimed at addressing spatial inefficiencies and limited accessibility in bike-sharing systems by integrating slope-based analysis, equity-driven station placement, and multimodal connectivity through GIS and transport modeling. Compared to existing research, it advances current methodologies by tailoring optimization strategies to the unique topographic and demographic realities of Kigali.

For example, the study by Yu et al. tackled the mismatch between supply and demand around urban rail transit stations using a SARIMA-LSTM hybrid model to forecast spatiotemporal demand for shared bikes [34]. Their findings highlighted the predictive advantage of hybrid models in guiding allocation strategies. In contrast, our study emphasized physical terrain constraints—particularly slope variations—and road network suitability, which are critical in hilly urban settings like Kigali but often overlooked in flat cities where SARIMA-LSTM is more applicable.

Similarly, Hu et al. proposed a dynamic optimization rebalancing model to minimize rebalancing costs while maximizing user satisfaction [22]. While their focus was primarily on cost and demand balancing, our study extends this by integrating slope analysis and station accessibility equity, ensuring not just operational efficiency but also terrain-aware and socially inclusive infrastructure planning.

Moreover, the work by Giner et al. enhanced operational efficiency in bike-sharing schemes by applying predictive models and optimization algorithms in the city of Barcelona [35]. Although our approach did not explicitly apply such optimization models, it shared a parallel goal by addressing horizontal and vertical equity in station distribution using kernel density analysis and residential clustering, effectively ensuring access in high-demand and underserved areas.

Unlike most previous studies that prioritized route preferences or rebalancing operations [36], our study uniquely integrates spatial slope analysis, employment-service node proximity, and shortest path routing, combined with survey-based user validation. This multi-layered approach reflects real user behavior and commuting patterns and grounds the optimization model in both spatial logic and human-centric needs.

Furthermore, findings from our household survey align with user-focused insights in earlier studies, confirming the importance of locating stations near bus stops, taxi parks, and universities—like recommendations made in studies focusing on first- and last-mile solutions. However, our results go further by incorporating slope constraints, connectivity, and rebalancing considerations into a GIS-based network, offering a comprehensive planning tool for emerging cities with challenging topographies.

In summary, while prior studies offer valuable strategies in profit maximization [37], travel time minimization [38], optimal station location [39], and environmental sustainability [40], this study advances the field by combining those strengths with geospatial slope modeling, multimodal integration, and participatory validation. The resulting framework is context-sensitive and replicable for other topographically complex urban environments seeking to implement inclusive and sustainable bike-sharing systems.

4.10. Limitations

First, the study relied on smartphone-based bike-sharing access, and this excludes segments of the population affected by the digital divide, particularly low-income or older users without access to mobile technology, potentially biasing the accessibility analysis. Second, seasonal variations—such as changes in weather or daylight hours—were not explicitly modeled, which may affect cycling patterns and station usage throughout the year. Third, data collection and survey responses occurred during or shortly after the COVID-19 pandemic, a period marked by unusual travel behaviors and disruptions in public transport usage, which could have influenced demand patterns and user preferences in ways that may not fully represent typical conditions, future research should incorporate real-time mobility data and longitudinal studies to capture dynamic user behaviors and further refine infrastructure planning.

5. Conclusions and Recommendations

This study enhanced the spatial planning of bike-sharing infrastructure in Kigali City by integrating environmental, demographic, and accessibility factors within a GIS-based Four-Step Transport Modeling framework. Key variables—such as terrain slope, road classification, land use, population density, and proximity to key destinations—were analyzed to define an optimized 87 km bikeable road network. This analysis informed the proposal of 187 new bike-sharing stations in high-demand areas, while incorporating 19 existing stations to improve multimodal linkages.

Survey data from 1377 respondents validated the model, revealing strong consistency between its recommendations and public preferences regarding station locations, motivations for biking, and common challenges. This alignment illustrates the effectiveness of combining data-driven modeling with participatory input to shape responsive and inclusive urban mobility solutions. While residents expressed strong support for cycling as an affordable and healthy mode of transport, they also identified barriers such as safety, accessibility gaps, and insufficient station density.

To support implementation, this study outlines several actionable recommendations:

- Pilot Priority Corridors: Launch pilot programs along high-demand, low-slope routes such as Remera–Kimironko–Kinyinya and Nyamirambo–Muhima–Nyabugogo to maximize early adoption and demonstrate proof of concept.
- Targeted Cost-Benefit Investment: Focus initial resources on locations where modest infrastructure upgrades—such as signage, designated lanes, or traffic calming—can yield high returns in user uptake and environmental impact.
- Seamless Integration with Public Transport: Position bike-sharing stations near bus terminals, taxi stands, and education hubs to strengthen first- and last-mile connectivity and reduce rebalancing costs through natural flow.
- Inclusive Access Strategies: Provide alternative access solutions for users without smartphones or mobile payments, particularly in marginalized communities, to promote equity in mobility services.
- Expansion to Peri-Urban Areas: Apply the planning framework to extend bike-sharing services into Kigali's expanding suburbs and underserved neighborhoods to support inclusive urban growth.

Overall, this research supports Kigali's transition toward more sustainable and equitable transportation systems. By combining advanced transport modeling with citizen feedback and strategic investment, policymakers and planners will develop a user-centered, cost-efficient bike-sharing network aligned with Kigali's environmental goals and mobility equity targets. Future research should explore usage trends over time, leverage real-time mobility data, and assess broader economic impacts to support long-term growth and resilience of the system.

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Conflicts of Interest

The authors declare no conflict of interest.

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