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Research Article

Modelling Local Demand and Locational Configuration in Floating Catchment Area Measures of Spatial Accessibility

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Abstract

The modelling of catchment-based instead of local demand and optimal instead of sub-optimal character (i.e., locational configuration) of service delivery systems, commonly done in Floating Catchment Area (FCA) measures, generate spatial accessibility indices that might be misleading. The ability of recent FCA measures, three-step (3S) FCA, Modified (M) two-step (2S) FCA, and Balanced (B) FCA to capture local demand and locational configuration was examined in hypothetical systems and Rural Wards of Dodoma Urban District and found to be less appealing. The resulting 3SFCA, M2SFCA, and BFCA spatial accessibility indices inconsistently varied with the local demand or locational configuration. Thus, the study proposed a Modified (M) 3SFCA measure to effectively capture local demand and locational configuration. The proposed M3SFCA measure was implemented in hypothetical systems and Rural Wards of Dodoma Urban District and found to generate spatial accessibility indices that logically varied with local demand and locational configuration. The service users (or households) with low local demand or closer to service providers (or water points) are characterized by higher spatial accessibility indices and vice versa. This characterization of spatial accessibility indices is more realistic and essential for effective monitoring of progress made on the global and national development goals.

Keywords: Locational configuration, Local demand, Geographic Information System, Spatial accessibility, Floating Catchment Area

Introduction

Floating catchment area (FCA) accessibility measure uses a moving square (Peng 1997) or a circular window of a particular threshold distance around a service provider or service user to define catchment areas and evaluate the spatial accessibility of services or commodities as supply-to-demand ratios (Wang 2000; Luo 2004). A simple FCA measure (Peng 1997; Wang 2000; Luo 2004) moves a catchment area to each service user's location, and the supply-to-demand ratio is determined. Unlike container-based measures, the simple FCA measure captures the interaction between service providers and service users across the pre-defined jurisdiction boundaries. However, according to W. Luo and Wang (2003), the simple FCA measure has two shortcomings. First, it fails to penalize supply from service providers accessed by service users within and outside the catchment area (Luo and Wang 2003). Secondly, it does not exclude service users within the catchment area, walking longer than the threshold distance (Luo and Wang 2003). The two-step (2S) FCA measure developed by Radke and Mu (2000), adapted by W. Luo and Wang (2003) and applied elsewhere (Kanuganti et al. 2016; Wu et al. 2018; Mentes, et al., 2019; Liu et al. 2020), addresses the two shortcomings in the simple FCA. The 2SFCA measure defines catchment areas twice, once around service providers to compute the supply-to-demand ratios and once around service users to aggregate the supply-to-demand ratios (Radke and Mu 2000; Luo and Wang 2003). W. Luo and Qi (2009) enhanced (E) the 2SFCA measure by incorporating travel impedance weights to the demand and supply sides in the first and second steps. However, the 2SFCA and its enhanced version are criticized for overestimating or underestimating supply and demand as they do not incorporate competition schemes. They ignore the effect of nearby service providers on service users' demand for supply at a particular service provider. Few studies (Wan et al. 2012; Luo 2014; Paez et al. 2019; Subal et al. 2021) have incorporated the competition scheme in the 2SFCA measures.

Wan et al. (2012) proposed a three-step (3S) FCA incorporating selection weights to minimize demand overestimation in the 2SFCA and E2SFCA measures. Their selection weights assume that the supply at a service provider and demand at a service user are respectively shared service users and service providers within the respective catchment areas proportional to travel impedance (Wan et al. 2012). In addition to travel impedance, J. Luo (2014) assumes that service users consider supply capacity when choosing where to get services, thus adopting the Huff-based selection weights (Huff 1963). The J. Luo's (2014) 3SFCA measure was further refined in Subal et al. (2021) replacing instead of complementing travel impedance weights with selection weights during demand allocation procedure. For service providers of uniform capacity, Huff-based selection weights (Luo 2014; Subal et al. 2021) are equal to selection weights based on travel impedance (Wan et al.

2012). Delamater (2013) showed that instead of the sub-optimal both 2SFCA and 3SFCA measures capture optimal character of service delivery systems, and thus, they fail to properly capture the location configuration. This shortfall was further illustrated by Tao et al. (2020) for 2SFCA and Hierarchical (H) 2SFCA measures. However, it is not known whether the refinement made by Subal et al. (2021) to the 3SFCA measure addresses the failure to properly capture the locational configuration. Furthermore, the selection weights in the third step of 3SFCA measures fail to properly capture the competitiveness of service users on supply (Rekha et al. 2017; Shah et al. 2017; Paul and Edwards 2019; Kim et al. 2021; Zhou et al. 2021) and lead to supply double apportioning, resulting into supply deflation for service users with multiple service providers within their catchment areas. To capture the locational configuration of service delivery systems, Delamater (2013) proposed the modified (M) 2SFCA measure that considers both relative and absolute travel impedance. Contrary to the E2SFCA measure, in the first step of the M2SFCA measure, the travel impedance weight is incorporated in the numerator and pairwise instead of catchment-based supply-to-demand ratios are calculated. However, instead of the demand and supply at the respective interacting pair of a service user and a service provider, the demand and supply within the respective catchment area are considered. The cancellation of travel impedance weights in demand allocation with those in supply aggregation, shown by Delamater (2013) to be the reason for the failure of FCA measures to properly capture location configuration, happens to one-to-one but not many-to-many interaction of service users and service providers. Therefore, by retaining these weights in the M2SFCA measure, the failure of FCA measures to properly capture locational configuration might be fully addressed for one-to-one but not many-to-many interaction of service users and service providers. Furthermore, the interpretation of spatial accessibility indices generated by FCA measures including 2SFCA, 3SFCA and M2SFCA as supply-to-demand ratios is shown by Paez et al. (2019) to be misleading and meaningless due to demand and supply inflation/deflation.

To eliminate demand and supply inflation/deflation, Paez et al. (2019) proposed what Desjardins et al. (2022) and Pereira et al. (2021) call a Balanced (B) FCA measure. Their BFCA uses row-normalized travel impedance weights to proportionally allocate demand at service users to accessible service providers, and column-normalized travel impedance weights to proportionally allocate supply at service providers to service users. Similar to selection weights in the 3SFCA measure, the row- and column-normalized weights determine service providers' competitiveness on demand and service users' competitiveness on supply. However, unlike the selection weights in supply aggregation, the column-normalized weights correclty determine service users' competitiveness on supply. Similar to Subal et al. (2021), Cromley and Lin (2022) adopt Huff model in the calculation of row- and column-normalized weights by adding the attraction of service providers. Since column-normalized weights replace instead of complementing travel impedance weights in supply aggregation, two shortfalls are observed. Firstly, as in the 3SFCA measure, the supply is double apportioned. Secondly, the absolute effect of travel impedance is not captured. Specifically, the locational configuration of actual service delivery systems is not captured because the supply at service providers allocated to service users is not penalized regardless of the travel impedance. Furthermore, it is observed that total instead of local demand in all existing families of FCA measures is modeled as the demand within catchment areas and not at individual service users is considered when calculating supply-to-demand ratios. Thus, this study further examines the ability of 3SFCA, M2SFCA and BFCA to properly capture location configuration and local demand, and proposes a FCA measure that simultaneously and coherently captures the locational configuration and local demand. The proposed FCA measure is then tested in the hypothetical service delivery system and Rural Wards of Dodoma Urban district.

Examining the Performance of Existing FCA Measures in Hypothetical Systems

In this section, the most recent FCA measures: the 3SFCA, M2SFCA and BFCA are implemented in five hypothetical systems to show how they model local demand and locational configuration. Each hypothetical system is a simple configuration of three service users: 1, 2 and 3 and two service providers: *a* and *b* as shown in Figure 1. System # I is progressively changed into systems # II and # III by moving service user 1 towards service provider *b* while maintaining its travel distance to service provider *a*. In systems # I to # III, the demand P_i at each service user is 200 people and the supply capacity S_j at each service provider is 1. System # III is changed into system # IV by moving 100 people from service user 3 to service user 2, hence, increasing the demand at service user 2 to 300 people, and reducing the demand at service user 3 to 100 people. In system # V, the distance from service users to service providers is twice that in system # IV.

Examining the Performance of the 3SFCA Measure in Hypothetical Systems

In this section, the study examines the effect of the refinement made to the 3SFCA measure by Subal et al. (2021) in capturing the locational configuration of hypothetical systems. To further check the effect of selection weight misspecification in capturing the locational configuration, the 3SFCA measure is implemented in two ways: as 3SFCA – I and 3SFCA – II, with and without selection weight misspecification respectively. The two approaches differ in calculating selection weights for supply apportioning in the third step of the 3SFCA measure.

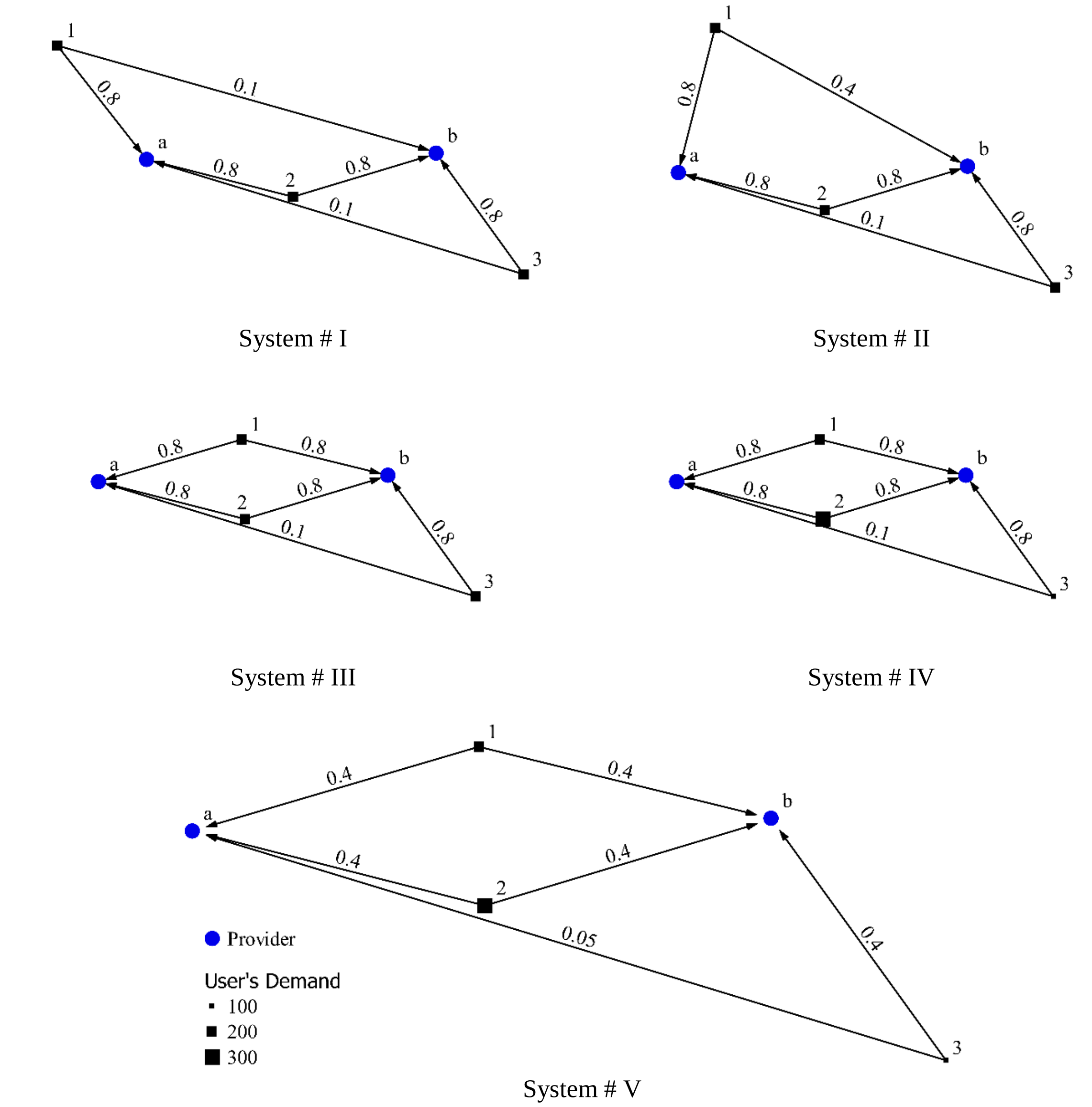


Fig. 1. Hypothetical Systems # I to # V with hypothetical data. The magnitude of the demand at users 1, 2, and 3 is shown in the legend, varying from 100 to 300 people, while the capacity of each provider is 1. The travel impedance weights are labeled on the lines connecting service users with service providers.

Since service providers *a* and *b* in hypothetical systems # I to # V in Figure 1 are of the same capacity, in the first step of both 3SFCA – I and 3SFCA - II, selection weights for demand apportioning are calculated using Eq. (1) as in Wan et al. (2012)

$$G_{ij}^{i} = \frac{f(d_{ij})}{\sum_{j\epsilon\{d_{ij}\leq d_o\}} f(d_{ij})} = \frac{f(d_{ij})}{f(d_{i1}) + f(d_{i2}) + f(d_{i3}) + ...} \quad \text{(Eq. 1)}$$

where G_{ij}^{i} is the selection weight for demand apportioning (measuring the competitive advantage of service provider j over demand at service user i) and $f(d_{ij})$ is a travel impedance weight.

In the second step of both 3SFCA – I and 3SFCA – II, the supply-to-demand ratios at service providers *a* and *b* in hypothetical systems # I to # V are determined as in Subal et al. (2021). However, in addition to the supply-to-demand ratios, in the second step of the 3SFCA – II, the selection weights for supply apportioning are determined using Eq. (2) to eliminate the misspecification.

$$G_{ij}^{j} = \frac{f(d_{ij})}{\sum_{i\epsilon\{d_{ij}\leq d_o\}} f(d_{ij})} = \frac{f(d_{ij})}{f(d_{1j}) + f(d_{2j}) + f(d_{3j}) + ...} \quad \text{(Eq. 2)}$$

where G_{ij}^{j} is the selection weight for supply apportioning (measuring the competitive advantage of service user i for supply at service provider j) and $f(d_{ij})$ is a travel impedance weight.

In the third step of the 3SFCA – I, at each service user in hypothetical systems # I to # V, supply-to-demand ratios at service providers a and b are aggregated as in Wan et al. (2012) to obtain the respective spatial accessibility indices. In the third step of the 3SFCA – II, selection weights calculated using Eq. (2) in the second step instead of Eq. (1) in the first step are used to apportion supply-to-demand ratios from service providers to service users.

Examining the Performance of the M2SFCA Measure in Hypothetical Systems

In the first step of the M2SFCA, supply-to-demand ratios at pairs of service providers a and b and service users 1, 2 and 3 in the hypothetical systems # I to # V are determined as in Delamater (2013). In the second step of the M2SFCA, at each service user in hypothetical systems # I to # V, pairwise instead of catchment-based supply-to-demand ratios are aggregated as in Delamater (2013) to generate spatial accessibility indices at the respective service users.

Examining the Performance of the BFCA Measure in Hypothetical Systems

As in Paez et al. (2019), before determining and aggregating the supply-to-demand ratios, the row- and column-normalized weights are determined. Then, supply-to-demand ratios at service providers a and b in hypothetical systems # I to # V are determined as in Paez et al. (2019). Finally, as in Paez et al. (2019), spatial accessibility indices at service users in hypothetical systems # I to # V are determined by summing up supply-to-demand ratios at service providers a and b.

Proposing a FCA Measure to Capture Locational Configuration and Local Demand

Based on the existing FCA measures, the study proposes a Modified (M) 3SFCA measure that avoids supply double apportining and properly captures the locational configuration and local demand. As in Wan et al. (2012) and Paez et al. (2019), it is assumed that supply at service providers is shared by service users within the catchment areas proportional to travel impedance. Demand from service users is shared by service service providers within catchment areas proportional to travel impedance. Thus, the proposed measure adopts the selection weights G_{ij}^{i} defined by Eq. (1) for apportioning the demand at a service user i to service providers within the catchment area. The selection weights G_{ij}^{i} are identical to balancing factors W_{ij}^{i} in the BFCA measure. However, instead of aggregating demand shares at service providers and finding supply-to-demand ratios, the proposed measure uses the selection weights G_{ij}^{j} defined by Eq. (2) to allocate supply from service providers to service users within catchment areas, and determines using Eq. (3) the supply-to-demand ratios for the interacting pairs of service users and service providers. The selection weights G_{ij}^{j} are identical to balancing factors W_{ij}^{j} in the BFCA measure.

$$R_{ij} = \frac{S_{ij}}{D_{ij}} = \frac{S_j G_{ij}^{j}}{P_i G_{ij}^{i}} \qquad \text{(Eq. 3)}$$

where, R_{ij} is the pairwise supply-to-demand ratio, S_{ij} is the supply at service provider j apportioned to service user i, D_{ij} is the demand at service user i apportioned to service provider j, S_j is the supply capacity at service provider j, P_i is the demand at service user i, G_{ij}^{j} is the selection weight measuring the competitive advantage of service user i over supply at service provider j, and G_{ij}^{i} is the selection weight measuring the competitive advantage of service provider j over demand at service user i.

The calculation of the R_{ij} using Eq. (3) is implemented in two steps. In step one, catchment areas are defined around service users, the respective G_{ij}^{i} are calculated using Eq. (1) and the demand at such service users is proportionally allocated to service providers within the respective catchment areas. In step two, catchment areas are defined around service providers, the respective G_{ij}^{j} are calculated using Eq. (2), the supply at such service providers is proportionally allocated to service users within the respective catchment areas, and the respective pairwise supply-to-demand ratios (R_{ij}) are calculated.
Finally, catchment areas are defined around service users and R_{ij} at interactions within the respective catchment areas are aggregated as in Luo and Qi (2009) and Delamater (2013) using Eq. (4) to get spatial accessibility indices at the respective service users.

$$A_i = \sum_{j \in \{d_{ij} \leq d_o\}} R_{ij} f(d_{ij}) \qquad \text{(Eq. 4)}$$

where, A_i is the spatial accessibility indices at service user i, R_{ij} is the pairwise supply-to-demand ratios, d_{ij} is the travel impedance, $f(d_{ij})$ is a travel impedance weight, and d_o is the threshold travel impedance.
It is observed that the floating catchment areas are defined three times, twice in the implementation of Eq. (3) and once in the implementation of Eq. (4). Hence, the name Modified Three-step Floating Catchment Area (M3SFCA) is derived.

Examining the Performance of the M3SFCA Measure in Hypothetical Systems

In the first step of the proposed M3SFCA, catchment areas are defined around service users 1, 2 and 3 in hypothetical systems # I to # V in Figure 1, the competitiveness of service providers a and b on demand at service users 1, 2 and 3 are calculated using Eq. (1) and used to apportion demand from service users 1, 2 and 3 to service providers a and b. In the second step, catchment areas are defined around service providers a and b in hypothetical systems # I to # V, service users' competitiveness on supply at service providers a and b are determined using Eq. (2) and used to apportion supply from service providers a and b to service users 1, 2 and 3. Then, the supply at service providers a and b apportioned to service users 1, 2 and 3 are divided by the respective apportioned demand using Eq. (3) to determine the respective pairwise supply-to-demand ratios. In the third step of the M3SFCA, pairwise supply-to-demand ratios are penalized with the respective travel impedance weights and summed up using Eq. (4) to determine spatial accessibility indices at service users 1, 2 and 3 in hypothetical systems # I to # V.

Examining the Performance of FCA Measures in Rural Wards of Dodoma Urban District

Study Area and Data

Dodoma Urban District is a Capital City of Tanzania, with a total population of 410,956 as per 2012 census, of which 197,320 lived in 19 Rural Wards and 213,636 in 18 Urban Wards. Since the 2016 decision of the fifth Government of Tanzania to run the Capital City in Dodoma Urban District, the District has been experiencing a rapid population increase with potentially higher demand for water supply. However, Dodoma Urban District is in the zone with smallest proportion of water points in Tanzania (World Bank 2018). The District is also in a semi-arid area with little annual rainfall of about 400 mm to 600 mm falling between December and April, making groundwater the main source of water supply to her inhabitants. Nine out of 19 Rural Wards were randomly selected to define the study area. A total of 228 water points in the study area, labeled Rural Wards in Figure 2, were extracted from an excel file obtained from the Directory of Rural Water Supply (DRWS) of Tanzania through Government Basic Statistics Portal. Out of the 228 available water points, 70 water points were randomly selected using a two-stage stratified sampling. Then, the study defined catchment areas of radii of 400 m [i.e., an optimal walking distance to water points specified in the National Water Policy of Tanzania (United Republic of Tanzania 2002)] around the 70 water points to delineate study zones.

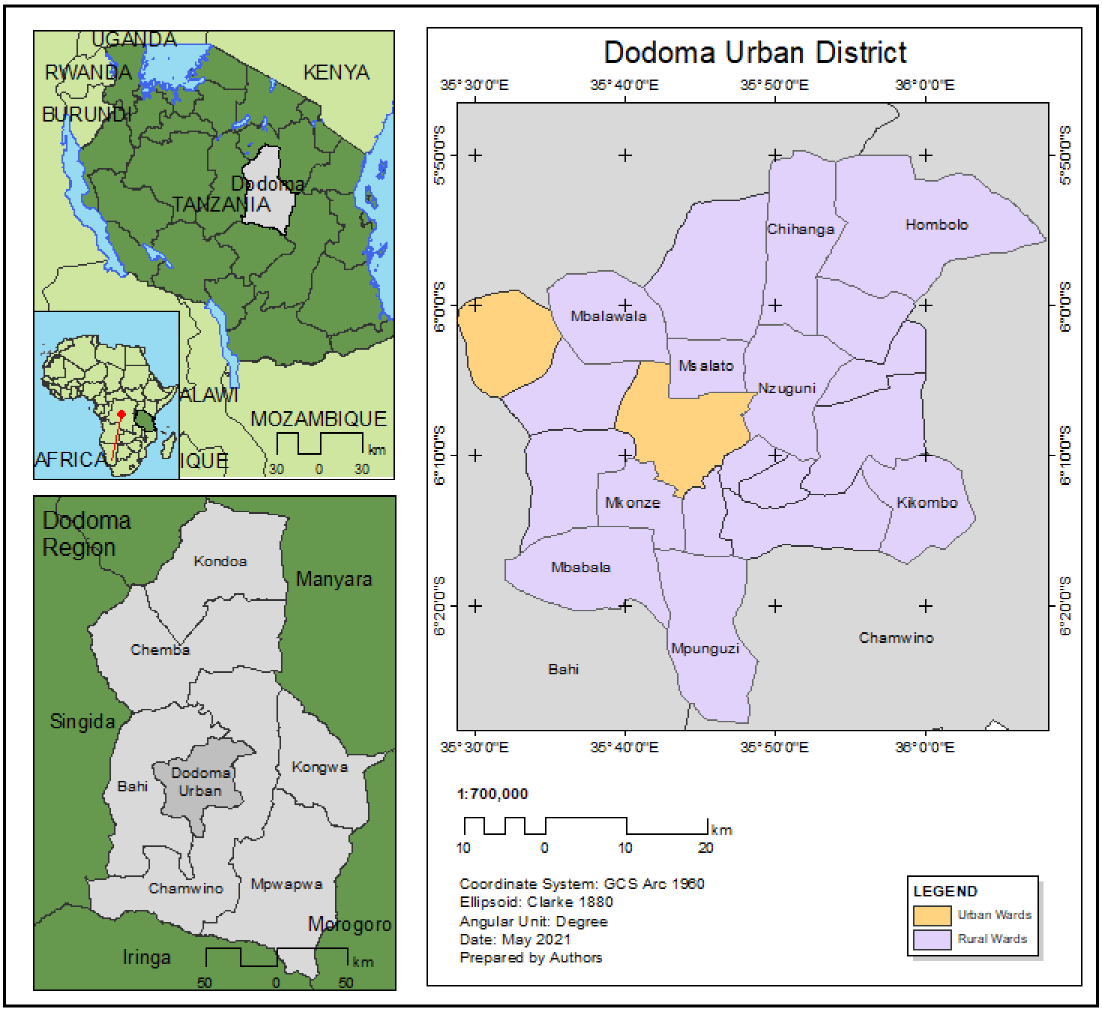


Fig. 2. The Study Area consisting of 9 Rural Wards (i.e., the Labelled Wards) which were sampled from 19 Rural Wards in Dodoma Urban District.

The delineated study zones are distinct regions formed by non-intersecting and dissolved intersecting (i.e., overlapping) catchment areas. The delineated study zones were coded using three letters followed by four numerals, uniquely identifying them. For example, SRW0902 represent a study zone 02 in the selected rural ward 09. During the field survey, it was observed that six out of 70 water points did no longer exist. In addition, apart from the remaining 64 water points, other 79 water points not in the DRWS water point dataset were reported by households as their main water sources, thus making a total of 143 water points in the study zones. Functional and non-functional water points were assumed to have full and zero capacities and assigned a value of 1 and 0 respectively. These water points were coded by two letters WP signifying a water point, followed by two numerals identifying a study zone and other two numerals identifying a water point in the study zone. For example, WP0907 is a water point 07 in a study zone 09. A total of 5349 building units within the delineated study zones were digitized in Google Earth to obtain the household dataset. A household survey was carried out for 344 households sampled from the 5349 digitized households to obtain their respective size, which is used to define the demand. Households were coded by two to three letters identifying a ward where a household resides, followed by three numerals uniquely identifying a household in a Ward. For example, MP290 is a household 290 in Mpunguzi Ward. Then, for each surveyed household, a Voronoi polygon was created and respective household size (i.e., demand) was assigned to each un-surveyed household within the Voronoi polygon

Examining the Performance of the M3SFCA Measure in Rural Wards of Dodoma Urban District

Before the first step of the M3SFCA measure, distance that households in Rural Wards of Dodoma Urban District walk to water points within 400 m, a maximum walking distance specified by the National Water Policy of Tanzania, are determined. Then, continuous travel impedance weights are determined as in Mahuve and Tarimo (2022) using zonal weights and walking distances. Zonal weights of 1, 0.68 and 0.22, representing a slow distance decay which is ideal for rural areas are adopted from W. Luo and Qi (2009) for circular-shaped inner $(0\,m < d_{ij} \leq 125\,m)$ zone and ring-shaped central $(125\,m < d_{ij} \leq 275\,m)$ and outer $(275\,m < d_{ij} \leq 400\,m)$ zones, respectively. Finally, the spatial accessibility of water points at households in Rural Wards of Dodoma Urban District are determined using Eq. (1) to (4) as in the hypothetical systems # I to # V using QGIS 3.10.5 tools.

Examining the Performance of 3SFCA, M2SFCA and BFCA Measures in Rural Wards of Dodoma Urban District

The procedures followed in implementing the 3SFCA, M2SFCA, and BFCA methods are as in hypothetical systems # I to # V and in Subal et al. (2021), Delamater (2013), and Paez et al. (2019) respectively.

Results

Spatial Accessibility Indices in Hypothetical Systems

The spatial accessibility indices generated by 3SFCA – I, 3SFCA – II, M2SFCA and BFCA for the hypothetical systems are presented in Tables 1 and 2. Logically, in hypothetical system # I, service user 2 should have the highest access to service providers a and b than service users 1 and 3 as it is closest to service providers a and b. Service users 1 and 3 should have equal access to service providers a and b because service user 1 is much closer to service provider a as service user 2 is to service provider b and much farther from service provider b as service user 3 is from service provider a. As service user 1 is progressively moved towards service provider b, its distance to service provider b decreases, thus, becoming much competitive for supply at service provider b. Hence, the spatial accessibility index at service user 1 should progressively increase from hypothetical systems # I to # III, while decreasing at service users 2 and 3. As 100 people are moved from service user 3 to service user 2, the spatial accessibility indices at service users 2 and 3 should respectively be less and higher in hypothetical system # IV than in hypothetical system # III. The spatial accessibility index at service user 1 should be higher than that at service user 2 in hypothetical systems # IV and # V. The overall spatial accessibility indices should progressively increase from systems # I to # IV. The spatial accessibility indices at service users 1, 2 and 3, and the overall spatial accessibility index should be less in hypothetical system # V than in hypothetical system # IV because service users are much farther from service providers.

Table 1. Spatial accessibility indices at service users 1 to 3 (i.e., A_1 to A_3) and overall spatial accessibility indices (i.e., A_{ov}) generated by the 3SFCA – I and 3SFCA – II measures in the Hypothetical Systems # I to # V

System	3SFCA – I				3SFCA – II			
	A_1	A_2	A_3	A_{ov}	A_1	A_2	A_3	A_{ov}
I	0.00239	0.00264	0.00239	0.00742	0.00125	0.00250	0.00125	0.00500
II	0.00247	0.00272	0.00211	0.00730	0.00170	0.00240	0.00095	0.00505
III	0.00286	0.00286	0.00194	0.00766	0.00239	0.00239	0.00075	0.00553
IV	0.00271	0.00271	0.00214	0.00756	0.00222	0.00222	0.00080	0.00524
V	0.00136	0.00136	0.00107	0.00379	0.00111	0.00111	0.00041	0.00263

However, the spatial accessibility indices in Table 1 generated at service users 1, 2 and 3 by the 3SFCA – I measure illogically respond to the reconfiguration of hypothetical systems # I to # III.Specifically, instead of decreasing, the spatial accessibility index at service user 2 progressively becomes larger in systems # II and # III. The spatial accessibility index at service user 1 in hypothetical systems # IV and # V equals to, and not higher than that at service user 2, signifying the failure to capture local demand. The overall spatial accessibility index decreases in hypothetical system # II, increases in hypothetical system # III and decreases again in hypothetical systems # IV and V. In contrast, the spatial accessibility indices generated by the 3SFCA – II measure consistently changes with the reconfiguration of hypothetical systems # I to # III. As expected, in hypothetical systems # II and # III, the spatial accessibility indices progressively becomes larger at service user 1, and smaller at service users 2 and 3. The overall spatial accessibility index progressively becomes larger in hypothetical systems # II and # III. However, similar to 3SFCA – I, in system # IV and # V, instead of higher, service user 1 has the same spatial accessibility index as service user 2. This implies that the 3SFCA – II captures the sub-optimal nature (i.e., the locational configuration) of service delivery systems, but not the local demand. This attribute of the 3SFCA – II to capture the sub-optimal nature of service delivery systems is also observed in the study area as illustrated in Section 3.2. It is therefore suggested that the failure of the 3SFCA measure to capture sub-optimal nature of service delivery systems might be due to the selection weights misspecification, and not the exclusion of absolute travel impedance as asserted by Delamater (2013).

The spatial accessibility indices in Table 2 generated by the M2SFCA and BFCA measures at service users 1, 2, and 3 consistently change with the reconfiguration of hypothetical systems # I to # III. However, instead of increasing progressively, the overall spatial accessibility index generated by the M2SFCA measure drops from 0.00758 in hypothetical system # I to 0.00739 in hypothetical system # II, then increases to 0.00780 in hypothetical system # III.

Table 2. The spatial accessibility indices at service users 1 to 3 (i.e., A_1 to A_3) and overall spatial accessibility index (i.e., A_{ov}) generated by the M2SFCA and N2SFCA measures in hypothetical systems # I to # V

System	M2SFCA				BFCA			
	A_1	A_2	A_3	A_{ov}	A_1	A_2	A_3	A_{ov}
I	0.00191	0.00376	0.00191	0.00758	0.00176	0.00313	0.00176	0.00665
II	0.00228	0.00348	0.00163	0.00739	0.00242	0.00300	0.00140	0.00682
III	0.00322	0.00322	0.00137	0.00780	0.00301	0.00301	0.00117	0.00719
IV	0.00290	0.00290	0.00136	0.00716	0.00277	0.00277	0.00123	0.00677
V	0.00145	0.00145	0.00068	0.00358	0.00277	0.00277	0.00123	0.00677

Further, instead of decreasing, the spatial accessibility index generated by the BFCA measure at service user 2, increases slightly from 0.00300 in hypothetical system # II to 0.00301 in hypothetical system # III. Instead of decreasing, the spatial accessibility indices of 0.00277, 0.00277 and 0.00123 generated by the BFCA measure at service users 1, 2 and 3 in hypothetical system # IV remain the same in hypothetical system # V. This also indicates the failure to capture sub-optimal character of service delivery systems. This failure is however attributed to the incorporation of relative instead of absolute travel impedance weights in BFCA measure. As in the 3SFCA measure, local demand is not captured as service users 1 and 2 in both hypothetical systems # IV and # V are of uniform spatial accessibility index regardless of their difference in demand levels.

The spatial accessibility indices generated by the M3SFCA measure proposed in this study are presented in Table 3. Unlike the 3SFCA, M2SFCA, and BFCA measures, the M3SFCA measure properly models both the locational configuration and local demand.

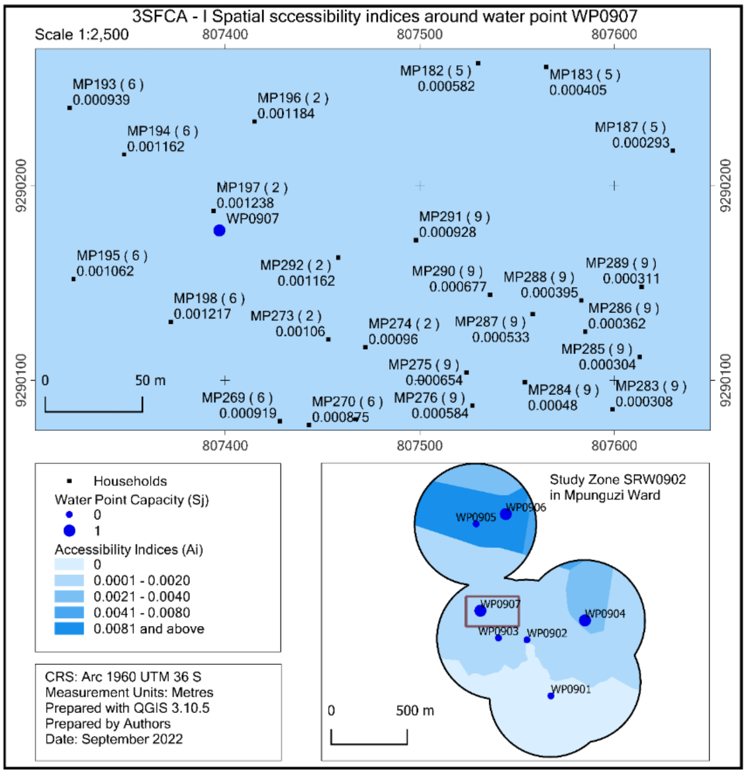
Table 3. Spatial accessibility indices at service users 1 to 3 (i.e., A_1 to A_3) and overall spatial accessibility (i.e., A_{ov}) generated by the M3SFCA measure in hypothetical systems # I to # V

System	A_1	A_2	A_3	A_{ov}
I	0.00238	0.00752	0.00238	0.01228
II	0.00402	0.00696	0.00207	0.01305
III	0.00640	0.00640	0.00180	0.01487
IV	0.00640	0.00427	0.00361	0.01428
V	0.00320	0.00213	0.00180	0.00713

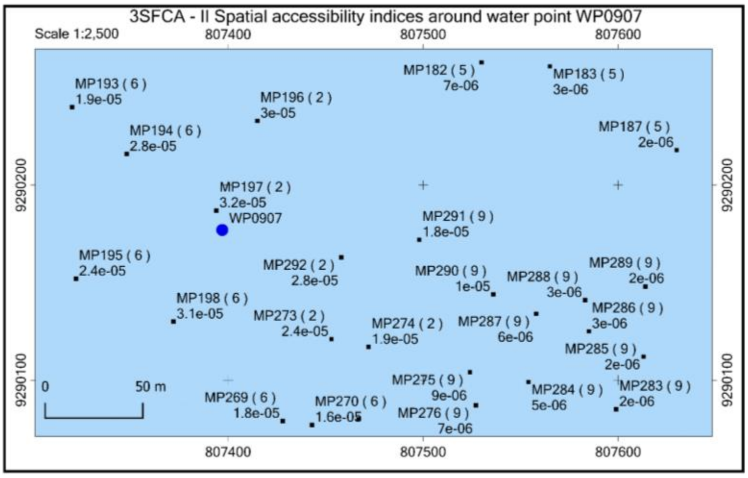
As expected, the spatial accessibility index at service user 1 increases from 0.00238 in hypothetical system # I to 0.00402 and 0.00640 in hypothetical systems # II and # III, respectively. The spatial accessibility indices at service users 2 and 3 decreases from 0.00752 and 0.00238 in hypothetical system # I to 0.00696 and 0.00207 in hypothetical system # II and 0.00640 and 0.00180 in hypothetical system # III. In both hypothetical systems # IV and # V, the spatial accessibility index at service user 1 is higher than that at service user 2. The spatial accessibility index at service user 3 increases from 0.00180 in hypothetical system # III to 0.00361 in hypothetical system # IV. The spatial accessibility indices are lower in hypothetical system # V than in hypothetical system # IV.

Spatial Accessibility Indices in Rural Wards of Dodoma Urban District

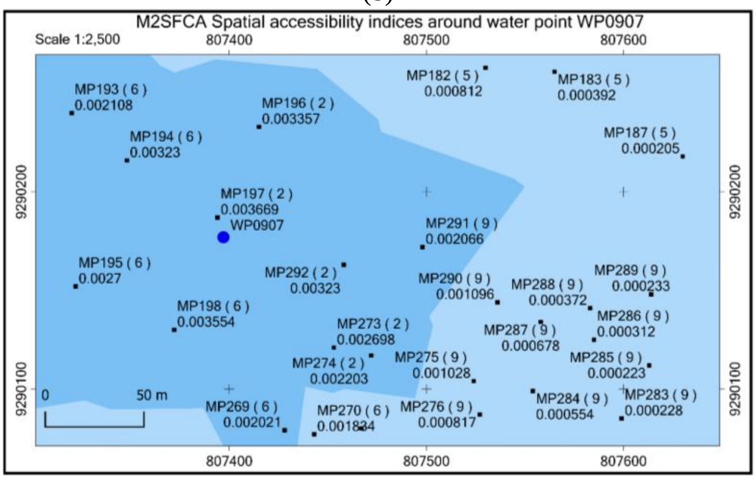
For legibility, the spatial accessibility indices generated by the 3SFCA – I, 3SFCA – II, M2SFCA, BFCA and M3SFCA measures at households around water point WP0907 are presented in Figure 3 (a) to (e). Households around water point WP0907 are of heterogenous size and travel distance, requiring a proper incorporation into FCA measures.


3SFCA - I Spatial sccessibility indices around water point WP0907
Scale 1:2,500
807400
807500
807600
9290200
9290100
MP193 (6)
0.000939
MP196 (2)
0.001184
MP182 (5)
0.000582
MP183 (5)
0.000405
MP194 (6)
0.001162
MP187 (5)
0.000293
MP197 (2)
0.001238
WP0907
MP291 (9)
0.000928
MP195 (6)
0.001062
MP292 (2)
0.001162
MP290 (9)
0.000677
MP288 (9)
0.000395
MP289 (9)
0.000311
MP198 (6)
0.001217
MP273 (2)
0.00106
MP274 (2)
0.00096
MP287 (9)
0.000533
MP286 (9)
0.000362
MP285 (9)
0.000304
MP275 (9)
0.000654
0
50 m
MP269 (6)
0.000919
MP270 (6)
0.000875
MP276 (9)
0.000584
MP284 (9)
0.00048
MP283 (9)
0.000308
Households
Water Point Capacity (Sj)
0
1
Accessibility Indices (Ai)
0
0.0001 - 0.0020
0.0021 - 0.0040
0.0041 - 0.0080
0.0081 and above
CRS: Arc 1960 UTM 36 S
Measurement Units: Metres
Prepared with QGIS 3.10.5
Prepared by Authors
Date: September 2022
Study Zone SRW0902
in Mpunguzi Ward
WP0905
WP0906
WP0907
WP0904
WP0903
WP0902
WP0901
0
500 m

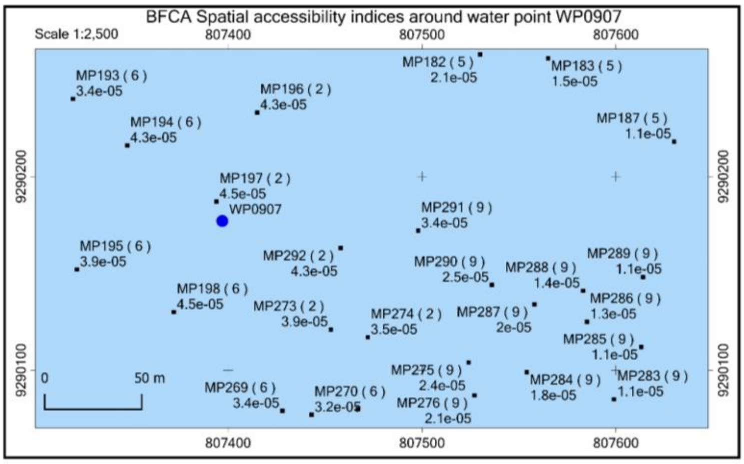
(a)


3SFCA - II Spatial accessibility indices around water point WP0907
Scale 1:2,500
807400
807500
807600
9290200
9290100
MP193 (6)
1.9e-05
MP196 (2)
3e-05
MP182 (5)
7e-06
MP183 (5)
3e-06
MP194 (6)
2.8e-05
MP187 (5)
2e-06
MP197 (2)
3.2e-05
WP0907
MP291 (9)
1.8e-05
MP195 (6)
2.4e-05
MP292 (2)
2.8e-05
MP290 (9)
1e-05
MP288 (9)
3e-06
MP289 (9)
2e-06
MP198 (6)
3.1e-05
MP273 (2)
2.4e-05
MP274 (2)
1.9e-05
MP287 (9)
6e-06
MP286 (9)
3e-06
MP285 (9)
2e-06
0
50 m
MP275 (9)
9e-06
MP284 (9)
5e-06
MP283 (9)
2e-06
MP269 (6)
1.8e-05
MP270 (6)
1.6e-05
MP276 (9)
7e-06

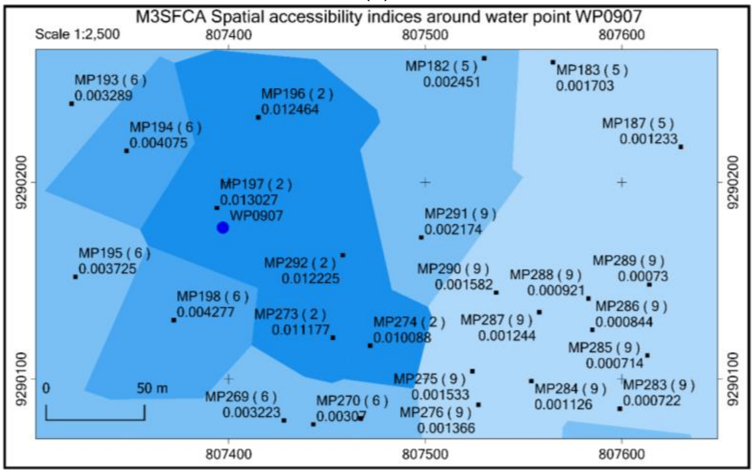
(b)


M2SFCA Spatial accessibility indices around water point WP0907
Scale 1:2,500
807400
807500
807600
9290200
9290100
MP193 (6)
0.002108
MP196 (2)
0.003357
MP182 (5)
0.000812
MP183 (5)
0.000392
MP194 (6)
0.00323
MP187 (5)
0.000205
MP197 (2)
0.003669
WP0907
MP291 (9)
0.002066
MP195 (6)
0.0027
MP292 (2)
0.00323
MP290 (9)
0.001096
MP288 (9)
0.000372
MP289 (9)
0.000233
MP198 (6)
0.003554
MP273 (2)
0.002698
MP287 (9)
0.000678
MP286 (9)
0.000312
MP274 (2)
0.002203
MP275 (9)
0.001028
MP285 (9)
0.000223
0
50 m
MP269 (6)
0.002021
MP270 (6)
0.001834
MP276 (9)
0.000817
MP284 (9)
0.000554
MP283 (9)
0.000228

(c)



(d)



(e)

Fig. 3. Spatial accessibility indices generated by (a) 3SFCA – I, (b) 3SFCA – II, (c) M2SFCA, (d) BFCA and (e) M3SFCA measures at households around water point WP0907 in study zone SRW0902. The black squares are households with their IDs and Size, i.e. demand, (in brackets) shown by the upper label and the spatial accessibility indices generated by the respective FCA measure by the lower label. The blue dots are water points labeled by their IDs

The distance that households in Figure 3 (a) to (e) walk to water point WP0907 are presented in Table 4. Since functional water points in the study area are of uniform capacity of 1, and neither household's purchasing power nor affordability level is incorporated into FCA measures, the resulting spatial accessibility indices should vary with household's demand (i.e., household size) and walking distance. That is, the highest spatial accessibility index should be observed at households with the smallest household size or the shortest walking distance and decrease with the increase in either household size or walking distance. However, the same spatial accessibility indices of 0.001162, 0.000028, 0.00323 and 0.000043 in Figure 3 (a) to (d) are respectively generated by the 3SFCA – I, 3SFCA – II, M2SFCA and BFCA measures at households MP292 and MP194 in Table 4. Similarly, the same spatial accessibility indices of 0.000007 and 0.000021 in Figure 3 (b) and (d) are generated by the 3SFCA – II and BFCA measures at households MP182 and MP276 in Table 4.

Table 4. Household size (P_i) and distance (d_{ij}) (m) that household i walk to water point j

i	P_i	j	d_{ij}	i	P_i	j	d_{ij}
MP182	5	WP0907	158.382	MP273	2	WP0907	79.196
MP272	5	WP0907	119.620	MP274	2	WP0907	96.047
MP193	6	WP0907	99.488	MP292	2	WP0907	62.586
MP194	6	WP0907	62.626	MP275	9	WP0907	146.485
MP195	6	WP0907	79.058	MP276	9	WP0907	158.113
MP198	6	WP0907	53.235	MP183	5	WP0907	187.825
MP269	6	WP0907	102.786	MP284	9	WP0907	175.308
MP270	6	WP0907	110.072	MP287	9	WP0907	166.643
MP196	2	WP0907	58.822	MP290	9	WP0907	142.863
MP197	2	WP0907	10.441	MP291	9	WP0907	101.123

**Households MP194 and MP292 are of nearly 63 m and MP182 and MP276 are nearly 158 m walking distance*

Instead of decreasing, the spatial accessibility indices of 0.000582 and 0.000812 in Figure 3 (a) and (c) generated by the 3SFCA – I and M2SFCA measures at household MP182 increase to 0.000584 and 0.000817 at MP276. As in hypothetical systems # IV and # V, these observations indicate the failure of 3SFCA, M2SFCA and BFCA measures to capture local demand. Thus, the spatial accessibility indices generated by 3SFCA, M2SFCA and BFCA measures might be understated, and hence, misinforming planners and policy makers when developing programs or strategies to improve spatial accessibility of services or commodities.

Unlike the hypothetical systems # I to # III, the response of the 3SFCA, M2SFCA, BFCA and M3SFCA measures to locational reconfiguration is not checked. However, as expected, highest spatial accessibility indices of 0.000816, 0.000014, 0.00160 and 0.000030 in Figure 3 (a) to (d) generated by the 3SFCA – I, 3SFCA – II, M2SFCA and BFCA measures are observed at MP272, followed by those of 0.000582, 0.000007, 0.000812 and 0.000021 at MP182 and those of 0.000405, 0.000003, 0.000392 and 0.000015 at MP183. The observed variation of spatial accessibility indices at households MP272 to MP182 and MP183 conform with Tobler's first law of Geography – "everything is related to everything else, but near things are more related" (Tobler 1970). However, the BFCA measure is found to be less sensitive to small difference in walking distance among households. For example, the same spatial accessibility index of 0.000043 in Figure 3 (d) is observed at MP196 and MP292, while that of 0.000034 is observed at MP193 and MP269. As in hypothetical systems # III and # IV, the insensitivity of BFCA is attributed to the incorporation of relative instead of absolute travel impedance.

As in hypothetical systems # I to # V, the spatial accessibility indices generated by the M3SFCA measure in Figure 3 (e) vary according to walking distance and local demand. For households with the demand of 2, 5, 6 and 9, the highest spatial accessibility indices are observed at the respective households MP197, MP272, MP198 and MP291, with the shortest walking distance. As in the 3SFCA, M2SFCA and BFCA measures, the spatial accessibility indices of 0.003443 at MP272 in Figure 3 (e) decreases to 0.002451 at MP182 and 0.001703 at MP183 as walking distance increases. A similar decrease in spatial accessibility indices is observed from households MP197 to MP274, MP198 to MP270, and MP291 to MP284. Similar to spatial accessibility indices in Bauer and Groneberg (2016), Dai and Wang (2011), Mahuve and Tarimo (2022), Subal et al. (2021) and Xia et al. (2019), the spatial accessibility indices generated by the M3SFCA measure vary according to Tobler's law of Geography.

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Table 5. Household distribution in different levels of (a) M3SFCA (b) 3SFCA – I (c) 3SFCA – II (d) M2SFCA and (e) BFCA spatial accessibility defined by frequency (Freq.) (in numbers/count) and cumulative frequency (Cumm. Freq.) (in count and %)

SPAI	Freq.	Cumm. Freq.	
		Count	%
0	1583	1583	30.6
0.0001 – 0.0020	1094	2677	51.8
0.0021 – 0.0039	548	3225	62.4
0.0040 – 0.0080	400	3625	70.2
0.0081 and above	1540	5165	100.0

(a)

SPAI	Freq.	Cumm. Freq.	
		Count	%
0	1583	1583	30.6
0.0001 – 0.0020	2997	4580	88.7
0.0021 – 0.0039	335	4915	95.2
0.0040 – 0.0080	225	5140	99.5
0.0081 and above	25	5165	100.0

(b)

SPAI	Freq.	Cumm. Freq.	
		Count	%
0	1911	1911	37.0
0.0001 – 0.0020	3237	5148	99.7
0.0021 – 0.0039	6	5154	99.8
0.0040 – 0.0080	4	5158	99.9
0.0081 and above	7	5165	100.0

(c)

SPAI	Freq.	Cumm. Freq.	
		Count	%
0	1583	1583	30.6
0.0001 – 0.0020	2841	4424	85.7
0.0021 – 0.0039	340	4764	92.2
0.0040 – 0.0080	348	5112	99.0
0.0081 and above	53	5165	100.0

(d)

SPAI	Freq.	Cumm. Freq.	
		Count	%
0	1583	1583	30.6
0.0001 – 0.0020	3515	5098	98.7
0.0021 – 0.0039	32	5130	99.3
0.0040 – 0.0080	19	5149	99.7
0.0081 and above	16	5165	100.0

(e)

**The spatial accessibility indices (SPAI) of 0, 0.0001 to 0.0020, 0.0021 to 0.0039 and 0.0040 and above respectively indicates no supply, insufficient supply, moderate supply and optimal to excessive supply at households.*

In contrast to spatial accessibility indices generated by the 3SFCA, M2SFCA and BFCA measures, as expected, the spatial accessibility index of 0.012225 generated by the M3SFCA measure at MP292 in Figure 3 (e) decreases to 0.004075 at MP194. Similarly, the spatial accessibility index of 0.002451 at MP182 in Figure 3 (e) decreases to 0.001366 at MP276. This observation signifies the robustness of the M3SFCA measure in modeling local demand. Hence, the M3SFCA spatial accessibility indices are more realistic and reflective of both locational configuration and local demand. Furthermore, they are higher than 3SFCA, M2SFCA and BFCA spatial accessibility indices. The number (proportion) of households with different levels of spatial accessibility indices generated by 3SFCA, M2SFCA, BFCA and M3SFCA measures is presented in Table 5.

With both the 3SFCA, M2SFCA, BFCA and M3SFCA measures in Table 5 (a) to (d), about 30 percent of households in the study area have no water supply due to lack of functional water points within a threshold distance of 400 m, specified in the National Water Policy of Tanzania (United Republic of Tanzania 2002). More than 60 percent of households have access to insufficient or moderate supply, and less than 8 percent have access to optimal or excess supply when the 3SFCA, M2SFCA and BFCA measures were implemented in the study area. That is, more than 60 percent of households get half or less supply than the required amount, while 8 percent get the required amount of supply or higher. On the other hand, in Table 5 (e), nearly 32 percent of households have access to insufficient or moderate supply, and about 38 percent of households have access to optimal or excess supply when the M3SFCA measure was implemented in the study area. That is, 32 percent of households get half or less supply than the required amount, while 38 percent get the required amount of supply or higher. It is further observed that the number of households with insufficient or moderate access to supply is relatively very small, nearly two-thirds, while that with optimal or excess access to supply is relatively very large, nearly five times, in the M3SFCA measure than in the 3SFCA, M2SFCA and BFCA measures

Discussion and Conclusion

This study examined the ability of the 3SFCA, M2SFCA and BFCA to capture both locational configuration and local demand in the hypothetical systems and Rural Wards of Dodoma Urban District. The resulting spatial accessibility indices inconsistently varied with both locational configuration and local demand due to the selection weight misspecification and inclusion of catchment-based instead of local demand in the 3SFCA measure; exclusion of selection weights and inclusion of catchment-based instead of local demand in the M2SFCA measure; and the incorporation of relative instead of absolute travel impedance and catchment-based instead of local demand in the BFCA measure. The study proposed the 3SFCA - II and successfully eliminated the selection weight misspecification in the 3SFCA measure. However, the 3SFCA – II spatial accessibility indices logically varied with the locational configuration, but not the local demand.

Hence, to capture both locational configuration and local demand, the study further proposed a M3SFCA measure and implemented it in the hypothetical systems and Rural Wards of Dodoma Urban District. The study noted a logical response of the M3SFCA measure to locational configuration and local demand in both the hypothetical systems and the study area. The resulting M3SFCA indices are of higher values at service users (or households) with shorter walking distance or smaller demand, and vice versa. To a greater extent, they are a reflection of the actual spatial accessibility of service points in hypothetical systems and water points in Rural Wards of Dodoma Urban District. They therefore provide reliable information to planners and policy makers in designing and monitoring performance of national and international development programs and strategies that would effectively improve the spatial accessibility of services or commodities. Furthermore, the M3SFCA measure could easily be employed in a GIS environment to determine spatial accessibility of other services/supply in different places.

In contrast, the 3SFCA, M2SFCA and BFCA measures might be overstating the number of households with insufficient or moderate access to supply, and understating the number of households with optimal or excess access to supply. Hence, they might be exaggerating the effort required to improve spatial accessibility of services/supply at households in the study area. Thus, their resulting spatial accessibility indices might be less reliable for tracking progress made towards national and global targets, and effective planning of where in the study area to cover what supply deficit.

However, both the M3SFCA and the existing FCA measures assume that households are of uniform capacity (i.e., purchasing power/affordability). That is, the capacity of the supply side, and not the demand side is considered. Thus, by excluding household capacity, they might be leading into supply inflation at households with lower capacity, and deflation at households with higher capacity.

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