Water Research 243 (2023) 120316

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

A fuzzy inference-based index for piped water supply service quality in a complex, low-income urban setting

Marie Gaiffe [a,*,1], Camille Dross [a,1], Espoir Bwenge Malembaka [b,c], Ian Ross [d], Oliver Cumming [d], Karin Gallandat [d]

[a] Department of Environmental Sciences and Engineering, Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne 1015, Switzerland
[b] Department of Epidemiology, Johns Hopkins University, Baltimore, MD 21205, USA
[c] Centre for Tropical Diseases and Global Health (CTDGH), Université Catholique de Bukavu, Bukavu, Democratic Republic of the Congo
[d] Department of Disease Control, London School of Hygiene and Tropical Medicine, Keppel St, London, WC1E 7HT, United Kingdom

ARTICLE INFO

Keywords:
Water supply
Infrastructure
Wash
Service
Fuzzy inference
Cholera

ABSTRACT

Sustainable Development Goal (SDG) 6 calls for universal access to safely managed drinking water services. We studied the evolution of the water supply service between January 2017 and December 2021 in the town of Uvira (South Kivu, Democratic Republic of the Congo) where large investments were made to improve the water supply infrastructure during this period, including a new 2,000-m^3 tank, 56 community taps and 1,191 private taps. Across 16 geographic clusters in the town, we assessed water service accessibility, water quantity, continuity, and affordability, based on data provided by the construction team and the utility. We combined these dimensions into a single index ranging 0–100% according to rules defined using the fuzzy inference Mamdani method. Our results show that despite substantial increases in accessibility (i.e. proportion of households with a private tap or within 200 m of a community tap), overall service quality remained unsatisfactory, with a maximum index value of 38.1%, and worsened in many parts of the town due to limitations of the water production capacity after major flooding events and persistent electricity supply issues. The estimated amount of water supplied per user per day remained under 20 L during >95% of the observation period, with a decreasing trend. Pumps operated 58% of the time on average and the frequency of days without electricity supply increased over time. Our study highlights the important gap between upgrades in water supply infrastructure and improvements in the quality of service. The analysis of potential future scenarios for Uvira indicates that increasing production capacity is priority to improve overall service quality. Our results demonstrate that meeting SDG6 will be challenging in complex urban settings and will not only require sustained investments in water supply infrastructure but also in systems management and in energy supply.

1. Introduction

The United Nations' Sustainable Development Goal (SDG) 6 is to "ensure availability and sustainable management of water and sanitation for all" by 2030 (United Nations General Assembly, 2015). Levels of drinking water services are defined and monitored by the World Health Organisation (WHO) and the United Nations' Children's Fund (UNICEF) Joint Monitoring Programme (JMP) to assess progress towards the SDG and, in 2020, it was reported that two billion people still lacked access to "safely managed" drinking water services (WHO and UNICEF, 2021).

Safe water supply services help to reduce the transmission of various diarrhoeal diseases by preventing waterborne exposure to pathogens and by ensuring the availability of sufficient water to practice adequate hygiene (Cairncross and Feachem, 2018). According to global estimates, 1.4 million (95% CI: 1.3–1.5) diarrhoeal deaths were due to inadequate water, sanitation and hygiene access in 2019 (Wolf et al., 2023). There is

---

Abbreviations: AFD, French Agency for Development (Agence Française de Développement); cap, *Capita* (in "litres per capita per day", L/cap/day); CDF, Congolese francs; CI, Confidence interval; DRC, Democractic Republic of the Congo; GPS, Global Positioning System; IWA, International Water Association; JMP, Joint Monitoring Programme; km, Kilometre; L, Litre; NGO, Non-governmental organisation; OCHA, United Nations' Office for the Coordination of Humanitarian Affairs; SDG, Sustainable Development Goal; UNICEF, United Nations'Children's Fund; VF, Veolia Foundation; WHO, World Health Organisation.

* Corresponding author.
E-mail address: marie.gaiffe@epfl.ch (M. Gaiffe).

[1] These authors have contributed equally to this work.

https://doi.org/10.1016/j.watres.2023.120316
Received 5 December 2022; Received in revised form 26 June 2023; Accepted 4 July 2023
Available online 5 July 2023
0043-1354/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

historical evidence from Europe, North America and Asia that urban water supply infrastructure contributed to reducing mortality from infectious diseases (Cutler and Miller, 2005; Floris and Staub, 2019; Ogasawara and Matsushita, 2018). Piped water supply on premises can reduce diarrhoeal disease risk by 21% (95% CI: 0–40%) compared to the use of an unimproved water source and that this reduction could be as high as 52% (95% CI: 13–74%) when microbiologically safe water was provided (Wolf et al., 2022).

Assessing the quality of water supply services for users/consumers is complex but critical to improving utility performance and to inform public health and urban infrastructure development policies (Balfaqih and Nopiah, 2015; Kayser et al., 2013; Soppe et al., 2018). Existing methods for the evaluation of water supply services such as the International Water Association (IWA) Performance Indicator System (Alegre et al., 2017) or Aquarating in Latin America (Krause et al., 2018) have been used widely in middle- and high-income settings with the aim to support improvements in utility performance. These approaches remain relatively complex and time-consuming, requiring detailed operational, financial and institutional data. Such information, which is used to assess utility performance across a range of indicators (e.g.% non-revenue water), is often lacking in low-income settings (van den Berg and Danilenko, 2017).

Providing a single, composite index of water service quality can help monitor and communicate changes, and facilitates benchmarking analyses (Kayser et al., 2013; Vilanova et al., 2015). However, generating an index leads to a loss of information and there are methodological challenges related to the aggregation of different variables and to the definition of weights (Kayser et al., 2013). There is no standard index for the quality of water supply services; the non-governmental organisation IRC proposes to take the lowest value amongst four key indicators – namely, quantity, quality, accessibility, and reliability – as the 'index' value reflecting overall water service quality (Moriarty et al., 2011). This approach has the advantages of being simple and transparent for users but the resulting index is based on a single component, thus not reflecting all dimensions of the water service. With the Aquarating tool, pre-specified weights can be used to calculate an average based on percentage scores obtained for each component of the performance assessment (Krause et al., 2018), however this requires having access to detailed information across 8 areas of utility performance and is more suitable for relatively advanced, institutionally mature water utilities. Other approaches reported in the scientific literature to generate aggregated performance indexes for water supply services mostly rely on Data Envelopment Analysis and Analytical Hierarchy Processes, which both require compliance with statistical independence assumptions for the index components (Kayser et al., 2013; Palomero et al., 2022; Vilanova et al., 2015). Recently, work has also been conducted to integrate broader, cross-sectoral definitions of water services performance into quantitative frameworks or indexes reflecting urban water security and climate resilience (Hughes, 2022; Krueger et al., 2020).

In undertaking an impact evaluation of large-scale improvements to water supply infrastructure on cholera in the town of Uvira (Democratic Republic of the Congo), a key assumption was that the water supply service would improve over time as construction works were rolled out in different areas (or "clusters") in the town of Uvira (Gallandat et al., 2021). However, unforeseen events including major flooding in April 2020 and the Covid-19 pandemic disrupted implementation of the infrastructure improvement programme and restricted the water production capacity. We therefore sought to assess in more detail changes over time and space in the quality of the piped water supply service.

As we started gathering information from the utility on the water supply service in Uvira, we faced challenges related to data availability and granularity. We also needed to combine complementary datasets that could not be considered statistically independent (e.g. hours of pumping and volume of water delivered to users). Here, we use the established Mamdani method (E.H. Mamdani, 1974), a robust and flexible fuzzy inference method, and build on a previous application to investigate urban water supply in Lebanon (Karnib, 2015), to develop an index of piped water supply service quality. Our main reasons for selecting the Mamdani method were that (i) it can be tailored to transfer non-quantitative, "expert-based" knowledge onto a quantitative scale, which is useful to reflect a relatively complex water supply system and (ii) it allows to integrate components that are not statistically independent into a single index value and thus enabled us to exploit all relevant data at our disposal (E. H. Mamdani, 1974).

The objectives of the work presented herein were to evaluate and describe, via an aggregated index value, the evolution of the water supply service quality in Uvira between 2017 and 2021. We also discuss how the index approach may be applied to inform efficient water supply service improvements and investments in low-resource, complex urban settings with limited data availability.

2. Methods

2.1. *Study site*

Located in South Kivu, Democratic Republic of the Congo (DRC), on the shores of Lake Tanganyika, Uvira is a town of approximately 280′000 inhabitants characterised by high levels of poverty, insecurity, and limited access to basic services (Town of Uvira, 2020; UK Aid, 2021; Vlassenroot, 2013). Uvira is also a "cholera hotspot" (Lessler et al., 2018). In 2014, the French Agency for Development (AFD) and the Veolia Foundation (VF) initiated a project to improve the water supply infrastructure in Uvira, which is operated by the publicly owned company REGIDESO S.A. As part of a stepped-wedge cluster randomised trial designed to evaluate the epidemiological impacts of the project (Gallandat et al., 2021), the town was divided into 16 clusters, which were also used as reference to describe the water supply service in this manuscript (Fig. 2). Construction works were implemented and documented by cluster, and focused on clusters 5 to 16 until December 2021, with clusters 1 to 4 receiving the intervention as part of a later project phase. The project included the construction of a new 2000-m^3 tank and an upgrade of the main water treatment plant and pumping station. Approximately 24 km of new pipes were installed and 10 km of existing pipes were rehabilitated. Furthermore, between September 2019 and December 2021, 56 new community taps were built, 1191 new private connections were installed and 717 existing private connections were rehabilitated. Extensive disruptions to planned construction works were caused by the Covid-19 pandemic and extreme flooding events in April 2020, which destroyed the main water intake for the town. As a result, the new tank was not fully utilised and the water production capacity remained limited until December 2021. A mandate was given to the NGO ADIR to organise the management of community taps.

2.2. *Index components*

Four dimensions of the water supply service quality were included, considering data availability in the Uvira context and drawing from JMP and WHO normative definitions derived from Sustainable Development Goal indicator 6.1 for safely managed water services (WHO and UNICEF, 2021): accessibility, quantity, continuity, and affordability. An optimal service – leading to an index of water service quality of 100% – would be accessible on premises, with water available in sufficient quantity (>100 L/cap/day), continuously (24/24 h), at a price that does not cause hardship to users (WHO and UNICEF, 2021, 2021). Each service dimension is defined below along with a description of the types of information available at our study site. We did not include water quality as a dimension because of a lack of relevant, reliable data.

2.2.1. *Accessibility*

Accessibility was defined as the percentage of residential buildings in each cluster with access to at least "basic" water supply according to JMP definitions (WHO and UNICEF, 2021), i.e. either with a tap on premises or located within 200 m from a community tap. The 200 m limit was used as a proxy for a round trip of less than 30 min assuming a total walking time of approximately 5–10 min and 20–25 min for queuing and filling containers, which is conservative compared to the queuing times reported by the seven respondents using community taps in our 2021 survey (Gallandat et al., 2022). Based on estimates from a household survey conducted in Uvira in August 2021, 70% of the 57,327 structures extracted from a recent high-resolution satellite image (Pleiades P1A, acquired between 26th February and 16th March 2020, courtesy of Dr Andrew Azman, Johns Hopkins University) were randomly selected and considered as residential buildings (Bwenge Malembaka et al., 2021). The construction plans and follow-up data including GPS coordinates for each new and rehabilitated tap were used to determine the number of buildings connected to the water supply network. Supplementary information provided by the NGO ADIR on the condition and operation of community taps in August 2021 was also used to determine which community taps were functional. Residential buildings amongst those without a private tap that were located within 200 m from a functional community tap were identified by spatial intersection.

2.2.2. *Quantity*

Quantity was defined as the estimated average volume of water (L) delivered per person per day in each cluster. This was calculated as the total volume of water supplied in each cluster divided by the estimated number of REGIDESO service users in that cluster, including private and shared household taps, as well as community taps:

$$LCD_C = \frac{V_{C,m}}{\left(\left(\sum_{i=1}^{11}(k_i * i) * \mu_{HH} * I_C\right) + \left(\mu_{HH} * U_{P,C}\right)\right) * d_m}$$

where:

LCD_C is the average volume (L) delivered per person per day in a given cluster C
$V_{C,m}$ is the volume (L) of water supplied in cluster C in month m (based on billing information)
k_i is the proportion of household taps used by i household(s), with i taking values between 1 and 11 (Table SI1, based on survey data)
μ_{HH} is the mean household size in Uvira (based on survey data)
I_C is the number of household (individual) taps in cluster C
$U_{P,C}$ is the estimated number of households using a community (public) tap in cluster C, based on the location of residential buildings
d_m is the number of days in month m

The volume of water supplied in each cluster for a given month (V_C) was determined based on REGIDESO billing information, which included metered and unmetered consumption. The consumption of individual users could be assigned to clusters based on geographic coordinates available from the construction team or using the taps' identification numbers to approximate the location; 7.5% of taps for which consumption was available for at least 1 month could not be assigned to a cluster and were excluded from the analysis.

The estimated number of REGIDESO service users in each cluster included both community and private tap users, accounting for the common practice of sharing taps. According to a household survey conducted in Uvira in September 2021, 53.3% of household (individual) taps were used by one household only, while 46.7% were shared with neighbours, serving between 2 and more than 10 households (Gallandat et al., 2022). The distribution estimated based on survey data (i.e. the proportion k_i of household taps used by 1, 2, 3, i… up to 11 households) was applied to all clusters (Table SI1) and a mean household size μ_{HH} of 7 individuals was used.

The number of community tap users was estimated as follows, assuming that one residential building is equivalent to one household: (i) a number of residential buildings corresponding to the number of households using or sharing a private tap were randomly identified as private tap users; (ii) the number of remaining residential buildings located within 200 m of a functional community tap was multiplied by the mean household size of 7 individuals. A sensitivity analysis was conducted to check the effect of varying the household size from 5 to 7 (range of household sizes estimated based on different surveys conducted in Uvira between 2016 and 2021 by the research team (Bwenge Malembaka et al., 2021; Gallandat et al., 2022; Jeandron et al., 2019)).

2.2.3. *Continuity*

Continuity was defined as the percentage of time (hours per month) where pumps functioned according to operational records from the centralised REGIDESO pumping station. This reflects water production hours in Uvira and is used as an indirect measure of water availability to users in absence of more granular, household-level information on the evolution of this component over time. It was defined at the town level.

2.2.4. *Affordability*

Affordability was defined as the percentage of households within a given cluster who purchased water at an affordable price from REGIDESO. This was determined by comparing the monthly amount invoiced for REGIDESO water with an estimate of average household income. Assumptions regarding the number of households sharing taps were made based on survey data as described above for the quantity component. For shared taps, it was assumed that taps where the largest volumes of water were supplied were used by the largest number of households and that the total amount invoiced was split equally between households, which appears to be common practice in Uvira. An "affordable" price was defined as one where the amount paid for water by a household was less than 5% of the average household income (WHO and UNICEF, 2021). A median monthly household income of approximately US$ 88 (CDF 175,500), estimated based on a household survey conducted in Bukavu (the nearest city in South Kivu, DRC) in May 2021 (Nodalis, 2021). Sensitivity analyses were performed to confirm the stability of this index component with affordability thresholds varying from 3% to 7% and to assess the assumption that costs were split equally between households, as other cost-sharing models have been documented in the literature (e.g. where tap owners pay less than other households (Zuin and Nicholson, 2021)). In particular, we evaluated a scenario where 80% of the costs were equally split between neighbours for taps used by 2 to 4 households and all costs were equally split between neighbours when 5 or more households shared the tap.

The components were assessed on a monthly basis for the period of observation, between January 2017 and December 2021. The months of April and May 2020 were excluded from the analysis due to a six-week water supply interruption caused by extreme flooding events (OCHA, 2020).

Scenarios were developed considering potential future developments, including further network extensions (improving accessibility), increases in the production capacity (with a corresponding increase in quantity), and better service continuity. The effect of modifying one or several components at a time was tested with the situation in December 2021 as reference. No scenario was developed for affordability given the absence of known, planned changes in tariffs and the limited room for improvement of that component.

2.3. *Fuzzy inference system*

The Mamdani method consists of three steps: (i) fuzzification, where input values are transformed into categorical variables (e.g. "high", "low") through membership functions (Zadeh, 1965); (ii) fuzzy inference, where a system of rules is defined that determines an aggregated function based on the categorical values attributed to each individual component (Mamdani, 1974); (iii) defuzzification, where the final index value is determined based on the geometry of the aggregated function. Each of these steps is detailed below.

2.3.1. *Fuzzification*

The range of possible values for each component (input variables) and for the index (output variable) was divided into five categories: “very low”, “low”, “medium”, “high”, and “very high”. Membership functions characterised by three to four parameters were defined for each variable and each category (Fig. SI1, Table SI2). WHO (World Health Organization et al., 2020) and SPHERE standards (Sphere Association, 2018) informed thresholds for the “quantity” component. The functions for the other components (accessibility, continuity, and affordability) and the index itself were structured around quartiles, as in (Karnib, 2015).

2.3.2. *Rules definition*

A system of 25 rules was developed where each individual rule consisted of 1–2 antecedents determining the value of the index: “If C1 is X and/or C2 is Y, then I is …”, with C1, C2 representing components of the index, X, Y their input values, and I the index (Table SI3). For example, rule #4 defines that “If accessibility is low AND if quantity is low, then INDEX is low”. The system was designed following the principle that accessibility and quantity take precedence over continuity and affordability, because the latter have little meaning when a tap is not accessible or only limited volumes of water are available. The index can therefore not have a value of “medium” or higher if accessibility or quantity are categorised as “low” or “very low”, independently of the continuity and affordability status (Fig. SI2).

2.3.3. *Defuzzification*

The final index value was defined by using the centre of gravity defuzzification method (Leekwijck and Kerre, 1999), whereby it corresponds to the abscissa of the centre of mass of the fuzzy inference function. It ranges from 0 to 100%, with higher values denoting a better quality of water service.

2.4. *Software*

Data were initially entered into Microsoft Excel (2016, Redmond, WA, USA). All spatial analyses were performed using QGIS (v3.16.15, Hannover, Germany), except for the preparation of Fig. 2 in ArcGIS (10.8.1, Redlands, CA, USA). The “mamfis” function was used in MATLAB (R2021a, Natick, MA, USA) to apply the Mamdani method (File SI1).

3. Results

3.1. *Accessibility*

In the clusters targeted by the AFD/VF project (5 to 16), accessibility of the water supply service improved substantially, with increases of 26 to 94% over the observation period (Fig. 1(a)). As of December 2021, accessibility exceeded 68% in clusters 5 to 15 and reached 100% in four clusters (6, 7, 9, and 10), suggesting that all residential buildings in these clusters either had a private tap or were within 200 m of a community tap. Accessibility remained low (2.9–13.1%) in clusters 1 to 4, where no intervention was implemented during the observation period.

3.2. *Quantity*

The estimated average volume of water available per person per day remained below 20 L/p/day for 95% of the observation period (January 2017-December 2021) (Fig. 1(b)). A maximum of 24.8 L/p/day was estimated in cluster 6 in March 2018. Comparing annual averages over the observation period shows that the amount of water available per person decreased in all but one cluster (1) between 2017 and 2021

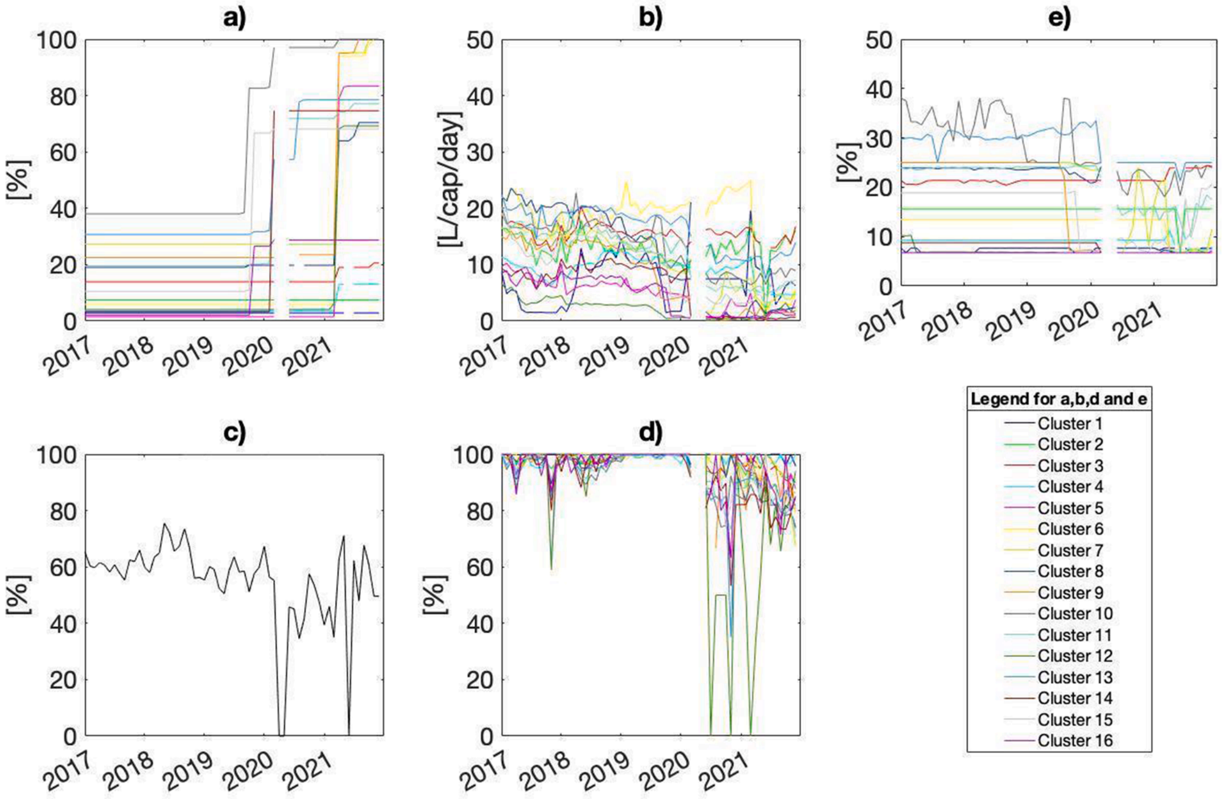


Fig. 1. Evolution of the water supply service between January 2017 and December 2021. (a) accessibility; (b) quantity; (c) continuity – at town level; (d) affordability; (e) index.

Table 1
Annual mean volume of water (L) available per person per day (standard deviation based on monthly means) and difference between the first and last year of observation in each cluster.

Cluster	2017		2018		2019		2020		2021		Difference 2021–2017
1	3.1	(2.4)	8.4	(3.9)	8.5	(4.5)	6.9	(1.8)	7.8	(4.5)	4.7
2	13.6	(2.3)	13.7	(2.0)	12.0	(1.1)	11.8	(1.9)	13.0	(4.3)	*−0.6*
3	15.6	(2.1)	16.8	(1.5)	15.6	(0.5)	15.1	(1.0)	14.8	(1.4)	*−0.8*
4	9.0	(1.6)	10.3	(1.6)	10.9	(0.9)	9.3	(0.5)	6.4	(2.8)	*−2.6*
5	8.1	(1.5)	6.5	(1.3)	5.5	(0.8)	2.5	(1.7)	1.9	(1.4)	*−6.1*
6	19.4	(3.0)	18.3	(1.5)	20.5	(1.5)	21.6	(1.6)	8.5	(9.6)	*−11.0*
7	15.9	(1.1)	15.1	(0.9)	12.3	(2.2)	5.7	(3.0)	4.7	(1.7)	*−11.2*
8	21.2	(1.2)	19.4	(1.2)	12.8	(3.8)	4.3	(7.0)	2.0	(0.9)	*−19.2*
9	14.1	(1.1)	13.9	(0.7)	8.3	(3.4)	1.5	(2.0)	1.6	(0.5)	*−12.6*
10	17.0	(1.2)	17.2	(1.9)	14.0	(2.8)	8.7	(1.6)	7.9	(1.1)	*−9.1*
11	16.5	(1.3)	16.2	(1.4)	13.6	(1.1)	7.7	(3.3)	5.8	(0.6)	*−10.7*
12	4.4	(1.2)	3.1	(0.5)	2.0	(1.0)	0.4	(0.2)	1.2	(1.0)	*−3.2*
13	19.0	(2.1)	19.7	(0.5)	18.2	(0.6)	13.3	(3.0)	11.2	(1.5)	*−7.8*
14	7.9	(1.0)	10.1	(1.1)	9.2	(1.0)	2.3	(3.6)	0.5	(0.1)	*−7.4*
15	13.4	(3.3)	15.4	(1.5)	11.1	(3.2)	3.9	(0.7)	5.0	(1.7)	*−8.4*
16	7.5	(1.1)	7.8	(0.4)	5.3	(2.2)	0.8	(0.4)	1.0	(0.3)	*−6.5*
Town	16.5	(1.5)	16.8	(0.5)	14.0	(1.7)	8.0	(1.9)	14.0	(0.9)	*−2.5*

(Table 1), likely due to the limited water production capacity.

Modifying the household size from 7 to 5 for the estimation of water quantity per person resulted in a difference under 1 percentage point in the index value in 79% of all observations ($n = 758$); the index value increased by more than 5 percentage points in 9% of cases ($n = 86$) and by more than 10 percentage points in 3% of cases ($n = 29$). Differences tended to be larger in clusters with fewer community taps.

3.3. *Continuity*

Pumps at the main water treatment plant were operational between 34.6 and 75.5% of the time based on monthly averages between January 2017 and December 2021 (Fig. 1(c)), including operation using electricity supplied through the network (87.9%) and through back-up generators (12.1%). The mean across all months between January 2017 and March 2020 was 60.9%; it decreased to 51.0% when considering the period post-flooding, from June 2020 to December 2021.

3.4. *Affordability*

The water service remained affordable for a majority (>70%) of users between January 2017 and December 2021, although increased variability and an overall decreasing trend was observed in several clusters after June 2020 (Fig. 1(d)).

Moving the affordability threshold from 5 to 3% of the household caused a difference smaller than 1 percentage point in the index value in 91% of the observations and greater than 10 percentage points in 0.1% of the observations. Modifying the cost-sharing assumptions so that tap owners would pay less than other users changed the index value by 1 percentage point or less in 58% of the observations, by up to 5 percentage points in 30% of the observations, and by more than 10 percentage points in 5% of the observations.

3.5. *Water service quality index*

3.5.1. *Evolution between 2017 and 2021*

The index of water supply service quality reached a maximum of 38.1% in January 2017 and in April 2018 in cluster 10, while remaining under 10% during more than 95% of the observation period in clusters 1, 4, 5, 12, 14, and 16 (Fig. 1(e), Fig. 2). Considering annual averages between 2017 and 2021, the index remained unchanged in two clusters (5 and 16), slightly increased in two clusters (1 and 3, where population decreased but no change to the water supply infrastructure was documented), and decreased in all other clusters (Table 2).

3.5.2. *Future scenarios*

Simulating an increase in accessibility alone up to 100% had no effect on the index value, except in clusters 1 to 3 which continued to have very low values (<11%) in December 2021 (Fig. 3). Simulating an increase in quantity alone up to 25 L/cap/day raised the index to 50% in all clusters where accessibility was already >68% (clusters 5 to 15). With a further increase up to 40 L/cap/day, the index reached >68% in those clusters. In clusters 1 to 3, where accessibility remained under 11% until December 2021, increasing water quantity had no effect on the index value (Fig. 3). Increasing continuity, alone or in combination with other components, had no influence on the index (Fig. 3).

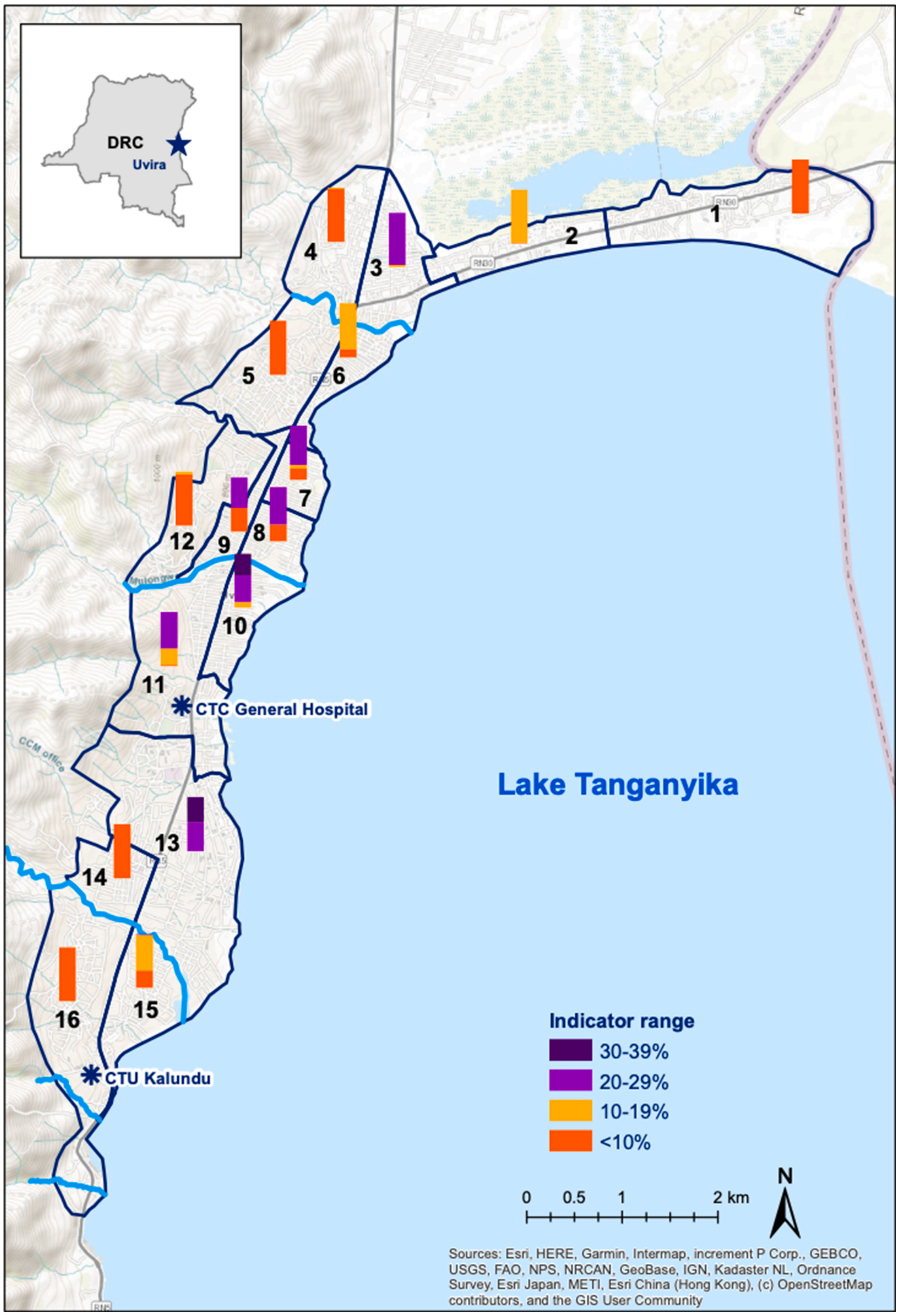
4. Discussion

We assessed the evolution of the water supply service in the town of Uvira between January 2017 and December 2021. For each month, we combined information regarding the changes in infrastructure (new connections), the volumes of water delivered, the hours of water production, and the financial values invoiced to users into a single index value through a fuzzy inference method. This work highlights a disconnect between water supply infrastructure and service improvements, while illustrating an easy-to-use, robust and flexible approach to assessing past and potential future changes in a piped water supply service.

4.1. *Water supply service evolution*

Large investments were made to improve the water supply infrastructure in Uvira and this resulted in substantial increases in accessibility in the targeted areas. However, the quality of the service and, in particular, water quantity and continuity, remained unsatisfactory. Concretely, this means that many households gained access to a tap nearby or on premises but were unable to collect water in sufficient quantity or in a reliable manner. The water service quality index remained low and tended to decrease over the observation period; it had comparatively higher values in the clusters located in areas of lower elevation (near the lake) and close to the main water treatment plant.

Reasons for the observed discrepancy between accessibility increases and service improvements likely include: (i) implementation challenges and disruptions due to major flooding events that affected Uvira in April 2020, which prevented the commissioning of central infrastructure (water intake, reservoir) and limited the water production capacity at the same time as the number of service users increased; (ii) the absence of improvements to the electricity supply, which is closely interlinked with continuity issues; (iii) insufficient staff capacity and training, resulting in the suboptimal operation of the main pumping station and



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Fig. 2. Map of Uvira showing the location of key water supply infrastructure and the division by clusters. The bar in each cluster shows the percentage of time where the index was <10%, 10–19%, 20–29%, and 30–39% between January 2017 and December 2021.

water quality testing. These observations from the Uvira project support three recommendations.

First, plans to improve water supply need to consider all aspects of service provision, from water intake to point of delivery, as well as the effect of interventions on existing and potential new users. In Uvira, the installation of new taps went ahead despite delays in the commissioning of a new tank and with a reduced water production capacity following the destruction of the main water intake during extreme flooding. This led to less water being available for existing users. The poor service quality likely negatively impacted the demand for new connections, too. Anecdotal observations suggest that temporary service improvements led to a surge in the number of requested tap installations.

Second, investments need to be coordinated across sectors. In Uvira, water supply interruptions are linked to an unreliable power supply to operate the pumps. Improving the water supply service requires solving the power supply issues – and involving relevant stakeholders for this. Investments in new assets should arguably be delayed unless conditions for their installation and operation, including sufficient energy supply, is available.

Third, allocating sufficient resources for capacity strengthening is key to ensure adequate operation, maintenance, and monitoring of the systems by water utility staff, and that complex infrastructure projects

Table 2

Annual mean of the monthly water supply service index (standard deviation), in%, and difference between first and last year of observation in each cluster.

Cluster	2017		2018		2019		2020		2021		Difference 2021–2017
1	7.0	(0.4)	7.4	(0.4)	7.4	(0.4)	7.6	(0.3)	7.5	(0.4)	0.5
2	15.6	(0.0)	15.6	(0.0)	15.6	(0.0)	15.6	(0.0)	14.9	(2.6)	*−0.7*
3	21.1	(0.4)	21.1	(0.3)	21.4	(0.0)	21.4	(0.0)	22.3	(2.0)	1.2
4	9.3	(0.0)	9.3	(0.0)	9.3	(0.0)	9.3	(0.0)	8.3	(1.3)	*−1.0*
5	6.7	(0.0)	6.7	(0.0)	6.7	(0.0)	6.7	(0.0)	6.7	(0.1)	0.0
6	13.5	(0.0)	13.5	(0.0)	13.5	(0.0)	13.5	(0.0)	8.8	(2.9)	*−4.7*
7	25.0	(0.0)	25.0	(0.0)	24.8	(0.4)	15.5	(7.7)	10.6	(5.7)	*−14.4*
8	23.9	(0.1)	23.8	(0.2)	23.3	(0.8)	11.8	(7.7)	6.8	(0.2)	*−17.1*
9	25.0	(0.0)	25.0	(0.0)	18.8	(8.7)	6.9	(0.2)	6.7	(0.0)	*−18.3*
10	34.2	(2.7)	33.7	(3.3)	27.2	(5.0)	22.8	(2.2)	21.8	(2.3)	*−12.4*
11	23.9	(0.2)	23.9	(0.1)	24.1	(0.1)	17.8	(4.1)	14.8	(2.7)	*−9.1*
12	7.7	(1.5)	6.8	(0.0)	6.8	(0.1)	6.7	(0.0)	6.7	(0.1)	*−1.0*
13	29.9	(1.7)	30.0	(0.3)	31.5	(0.9)	26.6	(3.3)	24.7	(1.1)	*−5.2*
14	8.8	(0.0)	8.8	(0.0)	8.8	(0.0)	7.1	(0.9)	6.7	(0.0)	*−2.0*
15	18.9	(0.0)	18.9	(0.0)	16.9	(4.5)	8.0	(1.1)	12.5	(5.4)	*−6.3*
16	6.7	(0.0)	6.7	(0.0)	6.7	(0.0)	6.7	(0.0)	6.7	(0.0)	0.0
Town	21.1	(0.4)	21.0	(0.3)	22.1	(1.3)	20.9	(2.9)	15.3	(3.1)	−5.8

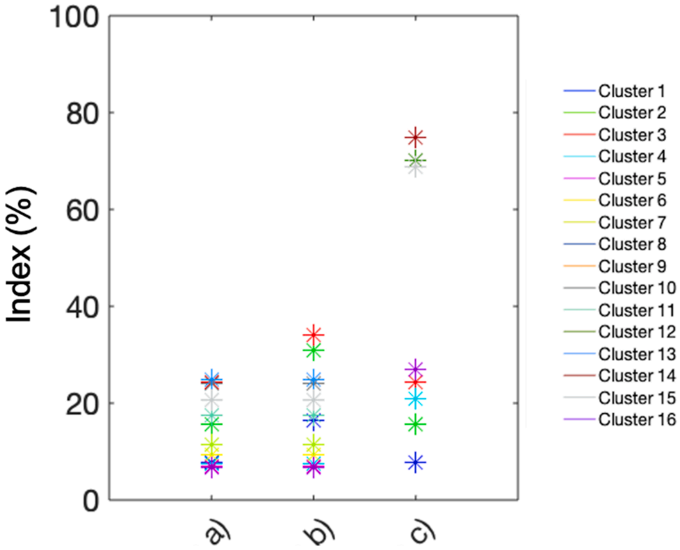


Fig. 3. (a) Situation in December 2021 (baseline); (b) effect of increasing accessibility to 100%; (c) effect of increasing quantity to 40 [L/cap/day].

meet the goal of delivering improved services to target populations. In Uvira, two aspects reflected training needs and suboptimal operating procedures: pumps remained shut down even in presence of staff at times where the power supply was available with sufficient voltage, which reduced the water production and affected the service continuity. And while chlorine testing was conducted with pool testers, no clear protocol seemed to be in place, so that the sampling locations, frequency and method, and testing times, remained unclear. To our knowleddge, no other type of water quality testing was conducted on a regular basis. This suggests limited control over the quality of the water supplied through the network and is also why water quality is not integrated as an index component in this work.

We considered affordability by estimating monthly water bills as a proportion of monthly household income, a commonly-applied method (WHO and UNICEF, 2021). There are two possible reasons for the variability and decline in affordability seen from mid-2020: (i) REGIDESO's national tariffs are defined in US$ but user invoices are in CDF, and the exchange rate changed substantially in May-July 2020; (ii) tariffs increased in 2021. The strengths of our approach are that it provides a reasonable proxy without investing in costly new data collection, and is therefore likely to be more broadly applicable. However, it has limitations, firstly in that households purchase water from multiple sources, especially in times of intermittency. Our household survey data from 2021 show that approximately half (49%) of the households reporting a tap outside their house or compound as primary drinking water source used at least one alternative source. Any financial expenditure on non-REGIDESO water would not be captured in our index, possibly meaning affordability is worse than it seems although free water sources (river, lake, rain) were the most common alternative sources. Secondly, the economic costs of accessing water can be important (e.g. travel/queuing time), as can the coping costs of dealing with intermittent supply which can be financial (e.g. storage materials, purchasing from vendors) and non-financial (e.g. additional travel time) (Burt et al., 2018). Thirdly, a misleadingly positive picture may be interpreted when basing affordability on existing water volumes when such volumes are known to be sub-optimal as our water quantity analyses demonstrate. For example, for a household of 7 people, using the December 2021 tariff, a consumption of 25 L/cap/day or higher would exceed the 5% affordability threshold used in our analysis.

We developed future scenarios based on expected developments in Uvira, including the construction of a new, permanent water intake (increasing production capacity) and the use of the new 2000-m^3 storage tank at full capacity (improving resilience to electricity shortages), which are both expected by end of 2023. Simulations suggest that water quantity – i.e. production capacity – is the main limiting factor, or priority for improvement, as of December 2021 in clusters where works have already been implemented to enhance service accessibility (reaching >68% in clusters 5–15). While continuity is critical from a health risk perspective, it had limited influence on the overall water service quality in our simulations. This was mostly due to accessibility remaining incomplete and quantity very low in most clusters, and to the fact that fuzzy inference rules were defined to lower the index in case of intermittent supply but did not foresee increases in the index for improvements in continuity alone.

4.2. Methodological considerations

The Mamdani method has been applied across multiple sectors to produce synthetic performance indexes (e.g. to evaluate bottled water quality (Asgari et al., 2021) or manufacturing systems (Pourjavad and Mayorga, 2019)). However, to our knowledge, only one example of application to water services has been published to date, related to urban water supply in Lebanon (Karnib, 2015). Generating a single index value provides advantages in terms of communication and for the evaluation of complex interventions. In the Uvira project, the index will be integrated into an epidemiological model to assess the impacts of changes in the water supply service on cholera and diarrhoeal diseases (Gallandat et al., 2021).

Existing tools for the assessment of water service quality typically require extensive, time-consuming data collection following a strict framework (e.g. Aquarating with 8 themes and 101 prespecified performance indicators (Krause et al., 2018)). Advantages of the Mamdani method include its flexibility, as index components can be selected based on data availability and quality. The method also allows combining components or datasets with different structures, time scales, and geographic scopes, as well as variables that are not statistically independent. This makes it particularly suitable for settings where data may need to be collected retrospectively. The method is relatively easy to use, as predefined functions exist (MathWorks France, 2018); we are sharing the MATLAB code file used in this work (SI File 1).

4.3. Limitations

The work presented in here had several limitations. The customised definition of the index, including membership functions and system of rules, is somewhat subjective despite using WHO/JMP standard references as a starting point and limits the benchmarking possibilities across settings. All data used in our analyses were collected retrospectively from utility reports, which was convenient but not easily verifiable and may not have reflected user-level experiences. Data on water quality (i.e. measured chlorine concentrations) could not be included in our analyses due to a lack of clarity regarding sampling and testing methods, and water quality is therefore not reflected in the index. The assessment of water quantity available per user was based on billing information (including unmetered consumption) and rough assumptions (everyone uses the same amount), and did not account for the use of multiple water sources. Likewise, the continuity of the service was assessed indirectly by using water production times, at town level, as no data was available to evaluate the situation at cluster or user level for this component; the service reliability (i.e. whether water was available at predictable times) could not be assessed. We used household survey data wherever possible to develop assumptions and triangulate results.

5. Conclusions

Our study describes the evolution of the water supply service over five years in the town of Uvira, a complex urban setting where cholera is endemic and where a major investment was made to expand access to safe drinking water services. We used a robust and flexible method to synthesise multiple dimensions of the piped water supply service in a single index value. The analysis reveals a significant gap between expanding infrastructure and meaningful changes in service quality and demonstrates the challenges in achieving and monitoring progress towards the SDG 6 indicator of universal access to “safely managed” drinking water services. Our study highlights the importance of cross-sectorial coordination and investment in the necessary institutional capacity to ensure that water infrastructure projects realise actual changes in service quality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The Matlab code is shared in SI. All relevant data will be available on OSF (https://osf.io/76sev/?view_only=e96559353c004ca7ad048b68c42cd380).).

Acknowledgments

The work presented in this manuscript was initiated as a “Design Project” in the Environmental Sciences and Engineering section of the Swiss Federal Institute for Technology Lausanne (EPFL). We are grateful to EPFL professors Andrea Rinaldo and François Golay, who provided valuable guidance in the early development stages of the work presented herein. We would like to thank REGIDESO staff from the Provincial Bureau in Bukavu and from the Uvira Mulongwe water production plant for their kind cooperation and data sharing, as well as the Veolia Foundation, African German Consulting, Arab Contractors and their teams for the careful documentation of construction works.

This work was supported by the French Agency for Development (ref. EVA/364–2015) and the Veolia Foundation (ref. 13/14 HD 1123).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2023.120316.

References

Alegre, H., Baptista, J.M., Cabrera, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W., Parena, R., 2017. Performance indicators for water supply services: third edition. Water Intell. Online 15. https://doi.org/10.2166/9781780406336, 9781780406336–9781780406336.

Asgari, G., Komijani, E., Seid-Mohammadi, A., Khazaei, M., 2021. Assessment the quality of bottled drinking water through mamdani fuzzy water quality index. Water Resour. Manag. 35, 5431–5452. https://doi.org/10.1007/s11269-021-03013-z.

Balfaqih, H., Nopiah, Z.M., 2015. Performance measurement factors for water supply: a systematic review. In: Proceedings of the Presented at the the 2nd ISM International Statistical Conference 2014 (ISM-II): Empowering the Applications of Statistical and Mathematical Sciences. Pahang, Malaysia, pp. 770–775. https://doi.org/10.1063/1.4907526.

Burt, Z., Ercümen, A., Billava, N., Ray, I., 2018. From intermittent to continuous service: costs, benefits, equity and sustainability of water system reforms in Hubli-Dharwad, India. World Dev. 109, 121–133. https://doi.org/10.1016/j.worlddev.2018.04.011.

E. Bwenge Malembaka, F. Jones, J. Dent Hulse, P. Musole Bugeme, J. Saidi Mufitini, B. Bashige Rumedeka, C. Hutchins, M. Demby, J. Knee, S. Hedge, E. Lee, K. Gallandat, A. Azman, 2021. Campagnes de vaccination orale de masse contre le choléra dans le contexte de la pandémie de la COVID-19 à Uvira, République Démocratique du Congo: enquête de couverture 11 mois après la vaccination. Report available from E. Bwenge Malembaka (ebwenge1@jhu.edu) upon request.

S. Cairncross, R. Feachem, 2018. Environmental health engineering in the tropics - water, sanitation and disease control, 3rd edition. ed.

Cutler, D., Miller, G., 2005. The role of public health improvements in health advances: the twentieth-century United States. Demography 42, 1–22. https://doi.org/10.1353/dem.2005.0002.

Floris, J., Staub, K., 2019. Water, sanitation and mortality in Swiss towns in the context of urban renewal in the late nineteenth century. Hist. Fam. 24, 249–276. https://doi.org/10.1080/1081602X.2019.1598460.

K. Gallandat, A. Jeandron, I. Ross, J. Mufitini Saidi, B. Bashige Rumedeka, L.K. Lumami Kapepula, S. Cousens, E. Allen, A. Macdougall, O. Cumming, 2021. The impact of improved water supply on cholera and diarrhoeal diseases in Uvira, Democratic Republic of the Congo: a protocol for a pragmatic stepped-wedge cluster randomised trial and economic evaluation. 10.1186/s13063-021-05249-x.

K. Gallandat, C. Hutchins, I. Ross, E. Bwenge Malembaka, V. Lumami Kapepula, P. Musole Bugeme, J. Mufitini Saidi, P. Mapendo Lwaboshi, O. Cumming, 2022. Evaluation de l’impact sur les maladies diarrhéiques de l’amélioration de l’approvisionnement en eau de la ville d’Uvira, République Démocratique du Congo (RDC). Enquête auprès des ménages sur les pratiques domestiques liées à l’eau. Report available from K. Gallandat (karin.gallandat@lshtm.ac.uk) upon request.

Hughes, S., 2022. A multidimensional approach to evaluating the vulnerability of drinking water systems. J. Environ. Policy Plan. 24, 210–226. https://doi.org/10.1080/1523908X.2021.2000377.

Jeandron, A., Cumming, O., Kapepula, L., Cousens, S., 2019. Predicting quality and quantity of water used by urban households based on tap water service. NPJ Clean. Water 2, 1–9. https://doi.org/10.1038/s41545-019-0047-9.

Karnib, A., 2015. Evaluation of the quality of service of the water supply delivery in Lebanon. J. Water Sanit. Hyg. Dev. 5, 17–27. https://doi.org/10.2166/washdev.2014.057.

Kayser, G., Moriarty, P., Fonseca, C., Bartram, J., 2013. Domestic water service delivery indicators and frameworks for monitoring, evaluation, policy and planning: a review. Int. J. Environ. Res. Public Health 10, 4812–4835. https://doi.org/10.3390/ijerph10104812.

M. Krause, E. Cabrera Rochera, F. Cubillo, C. Diaz, J. Ducci, 2018. Aquarating: an international standard for assessing water and wastewater services. https://publications.iadb.org/publications/english/document/Aquarating-An-International-Standard-for-Assessing-Water-and-Wastewater-Services.pdf. (accessed: 27.06.2022).

Krueger, E.H., Borchardt, D., Jawitz, J.W., Rao, P.S.C., 2020. Balancing security, resilience, and sustainability of urban water supply systems in a desirable operating space. Environ. Res. Lett. 15, 035007 https://doi.org/10.1088/1748-9326/ab6c2d.

W.V. Leekwijck, E.E. Kerre, 1999. Defuzzification: criteria and classification. Fuzzy Sets Syst.. 20.

Lessler, J., Moore, S.M., Luquero, F.J., McKay, H.S., Grais, R., Henkens, M., Mengel, M., Dunoyer, J., M'bangombe, M., Lee, E.C., Djingarey, M.H., Sudre, B., Bompangue, D., Fraser, R.S.M., Abubakar, A., Perea, W., Legros, D., Azman, A.S., 2018. Mapping the burden of cholera in sub-Saharan Africa and implications for control: an analysis of data across geographical scales. Lancet North Am. Ed. 391, 1912–1914. https://doi.org/10.1016/S0140-6736(17)33050-7.

Mamdani, E.H., 1974. Application of fuzzy algorithms for control of simple dynamic plant. Proc. Inst. Electr. Eng. 121, 1585. https://doi.org/10.1049/piee.1974.0328.

MathWorks France, 2018. Mamdani fuzzy inference system "mamfis". URL https://fr.mathworks.com/help/fuzzy/mamfis.html (accessed 1.9.22).

P. Moriarty, C. Batchelor, C. Fonseca, A. Klutse, A. Naafs, K. Nyarko, C. Pezon, A. Potter, R. Reddy, M. Snehalatha. 2nd Edition. 2011. Ladders for assessing and costing water service delivery. IRC International Water and Sanitation Centre. https://fr.ircwash.org/sites/default/files/Moriarty-2011-Ladders.pdf.

Nodalis, 2021. Survey of household income in Bukavu, South Kivu, DRC. Detaillsl available from the French Agency for Development (AFD).

OCHA, 2020. République Démocratique du Congo: inondations à Uvira : rapport de situation #4 (8 juin 2020) - Democratic Republic of the Congo [WWW Document]. ReliefWeb. URL https://reliefweb.int/report/democratic-republic-congo/r-publique-d-mocratique-du-congo-inondations-uvira-rapport-de-2 (accessed 6.15.20).

Ogasawara, K., Matsushita, Y., 2018. Public health and multiple-phase mortality decline: evidence from industrializing Japan. Econ. Hum. Biol. 29, 198–210. https://doi.org/10.1016/j.ehb.2018.04.001.

Palomero, J.A., Almenar-Llongo, V., Fuentes-Pascual, R., 2022. A composite indicator index as a proxy for measuring the quality of water supply as perceived by users for urban water services. Technol. Forecast. Soc. Change 174, 121300. https://doi.org/10.1016/j.techfore.2021.121300.

Pourjavad, E., Mayorga, R.V., 2019. A comparative study and measuring performance of manufacturing systems with Mamdani fuzzy inference system. J. Intell. Manuf. 30, 1085–1097. https://doi.org/10.1007/s10845-017-1307-5.

Soppe, G., Janson, N., Piantini, S., 2018. Water Utility Turnaround Framework. World Bank, Washington, DC. https://doi.org/10.1596/30863.

Sphere Association, 2018. The Sphere Handbook - Humanitarian charter and minimum standards in disaster response. https://www.spherestandards.org/handbook-2018/ (accessed 01.09.22).

Town of Uvira, 2020. Offical population records shared by Uvira administrative authorities.

UK Aid, REACH, 2021. Evaluation Rapide | Sécurité alimentaire. Zone de Santé d'Uvira, Sud-Kivu. Aires de Santé de Kalundu, Saint-Paul et Kabindula. https://repository.impact-initiatives.org/document/reach/f26aede7/REACH_RDC_Factsheet_FSLA-Uvira_Oct2021-1.pdf (accessed: 08.07.23).

United Nations General Assembly, 2015. UN resolution 70/1. Transforming our world: the 2030 agenda for sustainable development. [WWW Document]. URL https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/291/89/PDF/N1529189.pdf?OpenElement (accessed 10.29.22).

van den Berg, C., Danilenko, A., 2017. Performance of Water Utilities in Africa. World Bank, Washington, DC. https://openknowledge.worldbank.org/server/api/core/bitstreams/7d2cde98-bdca-5319-adf3-b505da3d07e6/content (accessed 08.07.23).

Vilanova, M.R.N., Magalhães Filho, P., Balestieri, J.A.P., 2015. Performance measurement and indicators for water supply management: review and international cases. Renew. Sustain. Energy Rev. 43, 1–12. https://doi.org/10.1016/j.rser.2014.11.043.

K. Vlassenroot, 2013. South Kivu identity, territory, and power in the eastern Congo. Rift Valley Institute. https://www.refworld.org/docid/5270e9fb4.html (accessed 08.07.23).

WHO, UNICEF, 2021. The measurement and monitoring of water supply, sanitation and hygiene (WASH) affordability - a missing element of monitoring of sustainable development goal (SDG) targets 6.1 and. 6.2. WHO ISBN: 978-92-400-2328-4. https://washdata.org/reports/unicef-who-2021-affordability-wash-services-full (accessed 08.07.23).

WHO, UNICEF, 2021. Progress on household drinking water, sanitation and hygiene. ISBN: 978 92 4 003084 8. https://www.who.int/publications/i/item/9789240030848 (accessed 08.07.23).

Wolf, J., Hubbard, S., Brauer, M., Ambelu, A., Arnold, B.F., Bain, R., Bauza, V., Brown, J., Caruso, B.A., Clasen, T., Colford, J.M., Freeman, M.C., Gordon, B., Johnston, R.B., Mertens, A., Prüss-Ustün, A., Ross, I., Stanaway, J., Zhao, J.T., Cumming, O., Boisson, S., 2022. Effectiveness of interventions to improve drinking water, sanitation, and handwashing with soap on risk of diarrhoeal disease in children in low-income and middle-income settings: a systematic review and meta-analysis. Lancet 400, 48–59. https://doi.org/10.1016/S0140-6736(22)00937-0.

Wolf, J., Johnston, R.B., Ambelu, A., Arnold, B.F., Bain, R., Brauer, M., Brown, J., Caruso, B.A., Clasen, T., Colford, J.M., Mills, J.E., Evans, B., Freeman, M.C., Gordon, B., Kang, G., Lanata, C.F., Medlicott, K.O., Prüss-Ustün, A., Troeger, C., Boisson, S., Cumming, O., 2023. Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. Lancet North Am. Ed. 401, 2060–2071. https://doi.org/10.1016/S0140-6736(23)00458-0.

World Health Organization, Howard, G., Bartram, J., Williams, A., Overbo, A., Fuente, D., Geere, J.A., 2020. Domestic Water quantity, Service Level and Health. 2nd ed. World Health Organization, Geneva. ISBN: 978-92-4-001524-1. https://www.who.int/publications/i/item/9789240015241 (accessed 08.07.23).

Zadeh, L.A., 1965. Fuzzy sets. Inf. Control 8, 338–353.

Zuin, V., Nicholson, M., 2021. The impact of pro-poor reforms on consumers and the water utility in Maputo. Mozambique. Water Alternatives 14 (1), 158–185. https://www.water-alternatives.org/index.php/alldoc/articles/vol14/v14issue1/608-a14-1-3/file (accessed 08.07.23).