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## Estimating domestic self-supply groundwater use in urban continental Africa

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## LETTER

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## Abstract

Self-supply of groundwater for domestic use in urban sub-Saharan Africa (SSA) is common, but the extent to which it is practiced is unknown. We developed an open data based GIS method for continental Africa (without islands) using groundwater storage, depth to groundwater, aquifer productivity, and population density data. Furthermore, we developed proxies for public supply network coverage and socio-economic status, incorporating restriction measures for groundwater use. Our results indicate that in 2015 about 369 million urban inhabitants (~79% of the total urban population) of continental Africa could *potentially* supply themselves with groundwater. However, the *likely* number of urban inhabitants using groundwater obtained via self-supply was less: about 150 million (~32% of the total urban population). With the novel GIS based methodology presented here, the urban population using self-supply groundwater for domestic use can be determined, which is essential to inform policy and practice, and to influence public investment.

## 1. Introduction

Urban self-supply, here defined as households in cities sourcing their own water supplies from where it can be found beyond public water distribution networks is common practice in urban Africa (Grönwall *et al* 2010). Besides local hydrogeological conditions and climate (e.g. precipitation excess), urban self-supply of groundwater is determined by the availability of other water sources and the spatial development of a city (Adelana *et al* 2008). Income distribution also plays a role (Liddle *et al* 2016, Foster *et al* 2018), as the cost of sinking a borehole tends to be primarily affordable by the more affluent who invest in their own water source to cope with reliability failures of the public water supply system (Chakava *et al* 2014, Foster *et al* 2018). Furthermore, as utilities are usually not able to keep up with ongoing rapid urbanization, piped networks are often concentrated in the city centre and older parts of town (Peloso and Morinville 2014, Smiley 2016) leaving others to seek alternatives.

Yu *et al* (2019) developed a model that predicts fairly well where people are using so-called

unimproved sources (namely unprotected wells and surface water), and in doing so addressed the spatial dimensions of urban water access. So did Pullan *et al* (2014), who analysed the spatial distribution of households with access to so-called improved water supply within an urban area by mining Demographic and Health Survey data and assessing the inequalities of distribution.

It has been demonstrated that self-supply is common and critical in: (i) (peri-)urban areas and informal settlements (Allen *et al* 2006, Liddle *et al* 2016); (ii) for those that are often left out of the network coverage; (iii) those, insufficiently served and/or (iv) those who chose to go off-grid (Adeniji-Oloukoi *et al* 2013, Kulabako *et al* 2010, Smiley 2013, Nganyanyuka *et al* 2014, Grönwall 2016, Komakech and de Bont 2018, Grönwall and Danert 2020). Grönwall *et al* (2010) estimated that more than 30% of the urban population of a number of African and south Asian countries depends on wells or other types of groundwater abstraction facilities as their principal source of drinking water. Practicing self-supply from groundwater has implications for drinking water safety and

the health of users (e.g. Lapworth *et al* 2017, Fayiga *et al* 2018) and can result in groundwater level decline and aquifer depletion (e.g. Mjemah *et al* 2009, Walraevens *et al* 2015).

Based on national surveys and census data, the Joint Monitoring Programme (JMP; WHO/UNICEF 2017) presents the percentage of the urban population (aggregated at national scale) using groundwater point sources (i.e. springs, dug wells and boreholes) as their primary source of drinking water. This data underestimates the actual use of groundwater point sources, as the data do not include the use of secondary sources. Secondly, wells used as primary sources may not be reported if the government or city administration considers them to be illegal (Grönwall *et al* 2010, Foster *et al* 2018). Thirdly, the data does not indicate whether the point sources are private or public. Consequently, groundwater use obtained via self-supply cannot be estimated. The best available information for groundwater use and dependence in sub-Saharan Africa (SSA) comes from case studies of a limited number of cities that have focused on water access dynamics in specific peri-urban or informal settlements (Smiley 2013, Nganyanyuka *et al* 2014; Grönwall 2016, Komakech and de Bont 2018, Nastar *et al* 2018).

Given the rapid urban expansion on the African continent, which will continue for decades (UNDESA (United Nations, Department of Economic and Social Affairs, Population Division 2019), this paper sets out to better understand the extent of domestic self-supply groundwater use in urban continental Africa. This knowledge is essential to inform policy and practice, as well as influence public investment.

The objective of this paper is to present a method and estimates for the Urban population Using Groundwater obtained via Self-supply (UUGS) for the entire African continent (without islands). We limit ourselves to urban domestic self-supply; rural self-supply, and water for business and industry is beyond the scope of this paper. We develop a methodology to estimate both *maximum* UUGS and *likely* UUGS. We validate our method with reliable data on UUGS obtained from seven cities across Africa. By using a set of simple assumptions about who self-supply users are and where they live, this paper should fuel interest, and also trigger further research on the validity of these proxies and enable more robust models to be developed and tested in the future.

## 2. Methods

Our methodology is GIS-based and uses open data, because of its availability across entire continental Africa with uniform quality. We first describe the data sources and proxies, and then detail the methodology used to determine the maximum UUGS and the likely UUGS.

### 2.1. Open data and proxies

Urban population of continental Africa was taken from three sources: (i) the 2015 Gridded Population of the World version 4 with a 1 km spatial resolution (CIESIN (Center for International Earth Science Information Network) 2017), (ii) the 2015 population from the Global Human Settlement Population layer (GHS-POP) with a resolution of 250 m, and (iii) the 2015 gridded population data from the High Resolution Settlement Layer (HRSL) with a resolution of 30 m (Facebook Connectivity Lab and Center for International Earth Science Information Network—CIESIN—Columbia University 2016). More details are in (table S1 available online at [stacks.iop.org/ERL/15/1040b2/mmedia](http://stacks.iop.org/ERL/15/1040b2/mmedia) of the supplementary information (SI). Definitions on urban population densities differ—we considered a gridded area urban when its population density was  $> 300$  inhabitants/km<sup>2</sup>. The total urban population for continental Africa obtained in this way was 470 million, which closely corresponded to the 2015 estimates from UN-DESA and UN-HABITAT (468 and 471 million, respectively).

Groundwater potential was taken from GIS layers of the Groundwater Maps of Africa (Macdonald *et al* 2012). We used layers groundwater storage, depth to groundwater and aquifer productivity. The data covers continental Africa (without islands) with a spatial resolution of 5 km.

Surface waters were obtained from OpenStreetMap (OSM; downloaded from <http://download.geofabrik.de/in> June 2019 and January 2020), using all features (values) available in the categories (keys) waterways and water bodies.

Socioeconomic status as a spatially available parameter does not exist, so we developed a proxy, whereby we assumed that low socioeconomic areas depended on springs and hand-dug wells, which are controlled by depth to groundwater. In addition, we assumed that middle and high socioeconomic status areas can also access private boreholes and that their access is controlled by aquifer productivity ( $> 1 \text{ l s}^{-1}$ ; see figure 1). To develop the proxy, spatial distributions and concentrations of luxury amenities and green areas, available in OSM, were determined in QGIS, using Kernel density functions (QGIS Development Team (2020) QGIS User Guide Release 3.4 2020). Luxury amenities include hotels, banks, ATMs, swimming pools, cinemas, jewellery stores, shopping malls and museums. Green areas such as parks and golf courses were also included, as the distribution of green spaces in cities is influenced by the socioeconomic status of neighbourhoods (Rigolon *et al* 2018). The resulting density map was then classified according to income distribution, creating a distribution of high, middle and low socioeconomic status, guided by the World Bank generated indicator 'Income share held by subgroups of population indicated by deciles or quintiles' (World Bank 2018).

An example of spatial distribution of luxury amenities and green areas as well as a map of the spatial socioeconomic status of Kampala (figure S1) and guiding text (chapter S2.1) is provided in the SI.

Spatial information on access to a public water supply network does not exist, so we developed another proxy, whereby we assumed, that new and/or more distant (from the city centre) urban developments will be less likely to have public water infrastructure, and therefore more likely depend on self-supplied groundwater. The steps to arrive at this proxy, including a detailed example (Kampala) are described in chapter S2.2 (SI). Briefly, based on data for network supply coverage and 2015 urban population data, we estimated the number of inhabitants served by a networked water supply. Secondly, we determined the areal extent of the city as a function of time from 1995–2015 with a 5 to 10-year frequency. Thirdly, the time-dependent urban boundaries of each city were overlain on the 2015 Gridded Population map (see above).

We then determined the 2015 urban population within each of those boundaries and which best compared to the 2015 inhabitants covered by the public water supply. The area inside the best fitting urban extent boundary was assumed to have access to a piped network and the area outside to have a poor public network coverage and/or reliability. The latter was named *lag-area of the public water supply*. Our method assumes that development of the public supply network follows urban sprawl and outward growth and only depends on time as the factor—though this is certainly not the whole picture. Network development (or lack of thereof) also depends on socioeconomic status (e.g. new affluent areas may be connected sooner than new low-income areas and slums) or on hydraulic characteristics, like elevation, or presence of natural hydraulic barriers (mountains or ridges). In addition, water demand management and water resources constraints are increasingly setting limits for further expansion of piped distribution. However, for simplicity, we did not include these parameters in the determination of the lag-area.

## 2.2. Maximum urban population using groundwater obtained via self-supply ( $G_M$ )

$G_M$  is the *maximum* urban population to use groundwater obtained via self-supply in an area across the entire African continent, or, the urban population potentially using groundwater via self-supply.  $G_M$  [inhabitants/km<sup>2</sup>] was determined by: for each km<sup>2</sup>.

$$G_M = F_M U. \quad (1)$$

$F_M$  indicates the *maximum* proportion of the population that could access groundwater via self-supply. It has a value between 0 and 0.95, based on a conditional algorithm depicted in figure 1 (fourth column

from the left). The algorithm considers the parameters [groundwater storage], [depth to groundwater], and [aquifer productivity].  $F_M$  was given a value dependent on the combination of these parameters.

In order to reduce computation time, we reduced the range of  $F_M$  values into four discrete values: 0, 33%, 67%, and 100% of the maximum range value. Together, these values define the maximum chance of using groundwater obtained via self-supply (Tables S5 and S6 (SI)).  $U$  is the urban population per km<sup>2</sup> (Gridded Population of the World version 4). There are different ways to determine the extent of a city or urban area (e.g. areal, administrative boundaries). We chose to define the urban extent as a cluster of contiguous 1 km<sup>2</sup> ‘pixels’ in the Gridded Population of the World version 4 closest to the location of the city marker available in OSM with a population > 300 inhabitants/km<sup>2</sup>. In case of a particular city or one urban area,  $G_M$  was expressed as a percentage of the total population of that city by dividing by its total population, which we named  $G_{M\%}$ . We determined  $G_M$  for the entire African continent and  $G_{M\%}$  for a selected number (10; see below) of cities.

## 2.3. Likely urban population using groundwater obtained via self-supply ( $G_L$ )

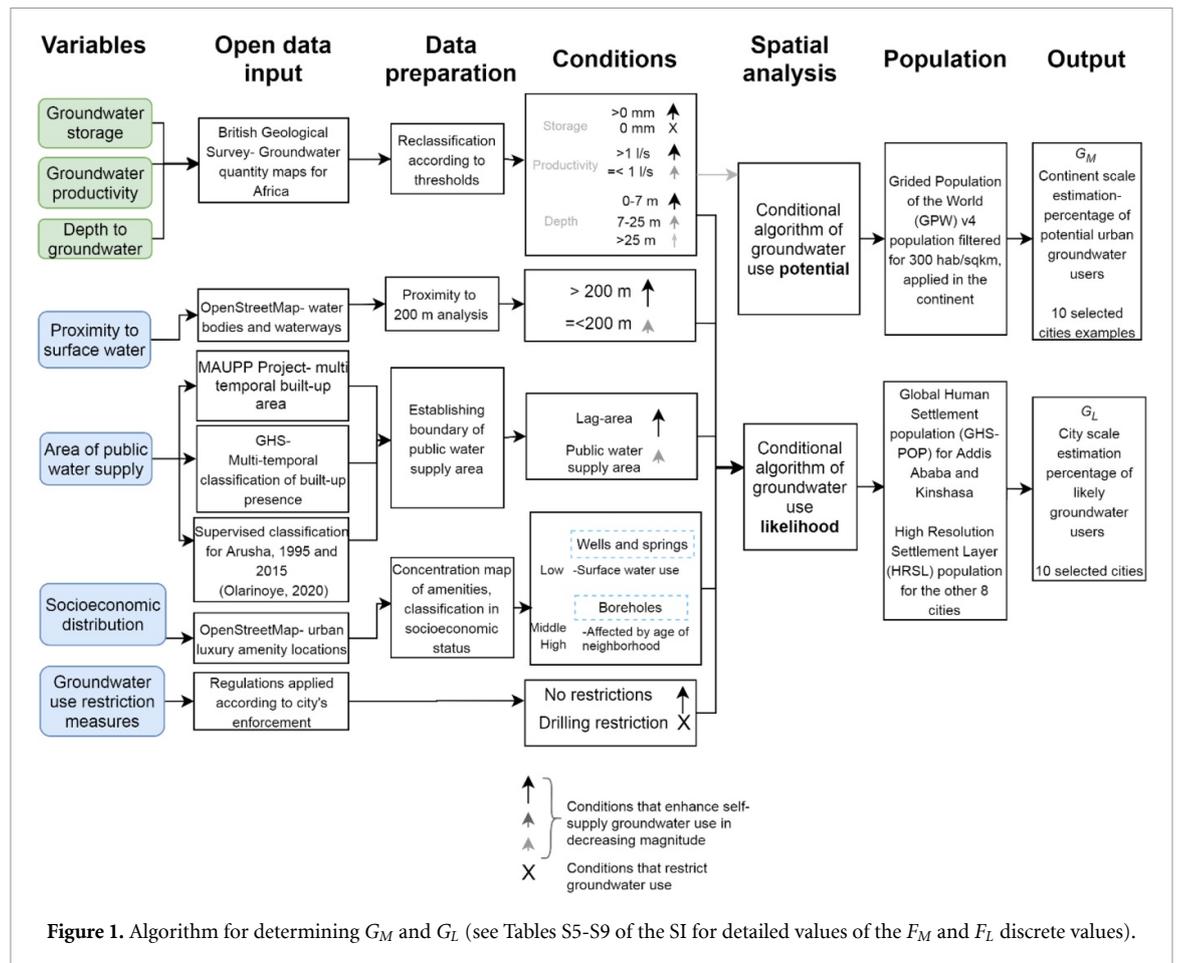
$G_L$  [inhabitants/km<sup>2</sup>] was defined as the *likely* UUGS in an area across the entire African continent.  $G_L$  was determined by:

$$G_L = F_L U \quad (2)$$

where  $F_L$  indicates the ratio or proportion of the population that are likely to use groundwater via self-supply. In this case  $F_L$  was determined by the parameters [groundwater storage], [depth to groundwater], [aquifer productivity factor], [proximity to surface water], [socio-economic status], and [lag-area of the public water supply] (figure 1). In addition, in the algorithm, we included the presence of imposed groundwater use restriction measures. This is to reflect the fact that in some cities in Africa, households are neither allowed to drill nor to abstract groundwater (Kampala), or there are prohibitively high customs duty on imports of drilling equipment (Addis Ababa) rendering drilling very expensive.

We used three sets of ranges of  $F_L$ : from 0–0.35 indicating a low likelihood, from 0–0.65 indicating an average likelihood, and from 0–0.95 (identical to  $F_M$ ) indicating a high likelihood of using groundwater through self-supply. Each range was made discrete by division into four values at 0, 33%, 67% and 100% of the maximum range value (see Tables S7–S9 (SI)).

When multiplied with  $U$ , these three sets of  $F_L$  values yielded  $G_L$  as arrays of population numbers per km<sup>2</sup>. In case of Addis Ababa and Kinshasa, we used GHS-POP, while HRSL was used for the other cities. Also in this case,  $G_L$  can be expressed as a percentage of the total population of a city, which we then



named  $G_L\%$ . Because not all data is available for each city in Africa, we determined  $G_L\%$  for cities with comprehensive data on groundwater use (see below). This enabled an assessment of the methodology to calculate  $G_L\%$  (see below).

The difference between  $G_M$  and  $G_L$  is the number of input parameters used and the number of sets of values of the parameter  $F$  (either  $F_M$  or  $F_L$ ). In the case of  $G_M$ , only hydro(geo)logical parameters were used, and therefore we consider  $G_M$  the maximum or potential UUGS. In addition, one set of  $F_M$  values ranging from 0–0.95 was used. For  $G_L$ , in addition to hydro(geo)logical parameters, the lag-area presence of a public supply network, socio-economic status, and—if applicable—imposed groundwater abstraction restrictions were taken into account. Furthermore, three sets of  $F_L$  values were used. Therefore, we consider  $G_L$  to more accurately indicate the urban population that actually depends on groundwater for one or more uses than  $G_M$ . We furthermore applied the following set of rules: 1) Only in case of groundwater depths > 25 m, the parameter aquifer productivity (< or >  $1 \text{ l s}^{-1}$ ) was applied. We assumed low productive aquifers would still be tapped at shallow depth, 2) Proximity to surface water only affected the low economic status. We assumed middle and high economic status did not use surface water, 3) Restriction measures applied to middle and high economic

status, but not to low economic status, and finally, 4) If groundwater was available it would be used, dependent on low, average or high likelihood conditions, except in case of restriction measures. Because the  $F$  parameter ranged between 0 and at most 0.95 (high likelihood conditions) instead of 1.0, this final assumption did not imply that in case of groundwater availability, the population was limited to using only groundwater. Still, a fraction  $1 - F$  of urban inhabitants could use other sources, although we did not specifically mention them (e.g. rainwater harvesting). Fig. S4 (SI) gives a worked example of the algorithm.

#### 2.4. Comparison with survey results

Comparison of the algorithm used (figure 1) with survey data was carried out only for  $G_L$ , since it was considered to be accurately calculating the UUGS. In order to validate our results, we compared  $G_L$  with the survey data from the 'Performance Monitoring and Accountability 2020 project' (PMA2020; Boyle *et al* 2019) for seven cities in SSA. PMA2020 uses innovative mobile technology to support low-cost, rapid-turnaround surveys monitoring key health and development indicators. Data are collected at household and health facility levels via mobile phones through a network of female data collectors. It uses a two-stage cluster design with residential area (urban vs. rural)

and sub-regions as strata, and standardized questionnaires to gather data about households that are comparable across program countries and consistent with existing national or regional surveys.

To our knowledge, the PMA2020 is one of the few survey instruments, which consistently collects information on the use and type of secondary water source for specific cities and makes the data readily available. We decided not to compare our results with the data from regional surveys, the basis for the earlier mentioned JMP. The JMP team has recommended that the 2018 version of the Multiple Indicator Cluster Surveys (<https://washdata.org/unicef-multiple-indicator-cluster-surveys-mics>) ask about the main source of drinking water used and the source of water used for other purposes, so we expect that more data sets on secondary source water will become available in the future. Furthermore, for Arusha we made use of fieldwork surveys carried out within our group (Komakech and de Bont 2018).

### 2.5. Sensitivity analysis

For the two proxies we developed we carried out a (modest) sensitivity analysis for the case of Kampala. For the proxy socioeconomic status, we changed the deciles that define the boundaries of high, middle and low socioeconomic status. For the proxy lag area of the public supply, we changed the (time dependent) urban boundary, thereby changing the areas served by the public supply and not served.

## 3. Results

### 3.1. Maximum urban population using groundwater obtained via self-supply ( $G_M$ )

Given the distribution of hydrogeological conditions and our definition of urban ( $>300$  inhabitants/km<sup>2</sup>), we estimated that 369 million people living in urban areas in mainland Africa could potentially use groundwater to meet their domestic needs (figure 2). This represents 79% of the total urban population of mainland Africa (470 million). The model shows that, because the resource is present, there is considerable potential to use groundwater in urban parts of Nigeria; around the lakes in Eastern Africa (e.g. Kenya, Uganda and Rwanda); in the Nile delta and around the Nile valley in Egypt; in Ethiopia, more scattered, in northern-eastern South Africa and Zimbabwe; and along the northern African coast, mainly in Algeria and Morocco.

### 3.2. Likely urban population using groundwater obtained via self-supply ( $G_L$ )

Based on availability of survey data, we selected seven cities for which we determined  $G_M\%$ - and  $G_L\%$  values (top 7 rows of table 1). The maps (figures S5-S25 in the SI) give a spatially distributed overview of input data per city.  $G_M\%$ -values ranged between 52 and 90%, and  $G_L\%$  values ( $F_L$  set) ranged between 5

and 76%. The average of the  $G_M\%$ -values in table 1 was 79% and the average of the  $G_L\%$ -values ( $F_L$  set) 31%, which indicated a difference of some 48 percentage points between the likely and the maximum population using groundwater obtained via self-supply. The differences between  $G_M\%$  and  $G_L\%$  were primarily due to the presence of a public supply network and a population with an average to high socio-economic status, who were—for the better part—assumed to be able to pay for a public supply connection. In the case of Kampala and Addis Ababa, the difference between  $G_M\%$ - and  $G_L\%$  was high (50% or more) due to a combination of favourable hydrogeological conditions for groundwater use ( $G_M\%$  is high: 75%–90%), while a piped network is covering a large part of the cities with household and yard connections, public standpipes and kiosks. Thus, there is less need to practice self-supply. As mentioned, in Kampala there are also restrictions to drill and in Addis Ababa, drilling equipment import restrictions make drilling expensive (*pers. comm. of one of the authors with the Ministry of Water, Irrigation, and Energy, and with the Addis Ababa Water and Sewerage Authority*).

Based on our time-dependent analysis of the urban population expansion, we observed that all cities in table 1 were rapidly increasing in size. When networked supply development lags behind, they develop important self-supply practices involving groundwater, if available. Per city in table 1, the difference between minimum and maximum  $G_L\%$  ranged from 17 percentage points in the case of Kampala (25%–8% = 17%) to 51 percentage points in the case of Lagos. These higher differences of 51 percentage points, 49 percentage points (Kano), 47 percentage points (Arusha) were primarily attributed to favourable hydrogeological conditions (groundwater storage, productivity, and depth to groundwater) on the one hand and low network supply coverages on the other. This enables self-supply. In contrast, low differences of 17 percentage points (Kampala) and 18 percentage points (Addis Ababa) were mainly caused by the above described high public coverages on the one hand and restrictive measures on the other hand.

### 3.3. Comparison with survey data

Survey data indicate that 3%–83% of the urban population use groundwater obtained via self-supply in the seven selected cities (table 1). When comparing  $G_L\%$ -values with the PMA survey data, we observed that for Arusha, Kampala, Kano, and Lagos,  $G_L\%$ -values were closest to the PMA survey data in case  $F_{L,max}$  values were used. For Addis Ababa and Nairobi  $G_L\%$ -values were closest to the PMA survey data if  $F_{L,min}$  values were used and for Kinshasa in case  $F_L$  values were used. From this we concluded that with the three sets of  $F_L$  values we used the bandwidth of likely UUGS in urban areas in continental Africa could be estimated. However, it was not possible to predict a more accurate 'likely UUGS' than a range of values, as presented

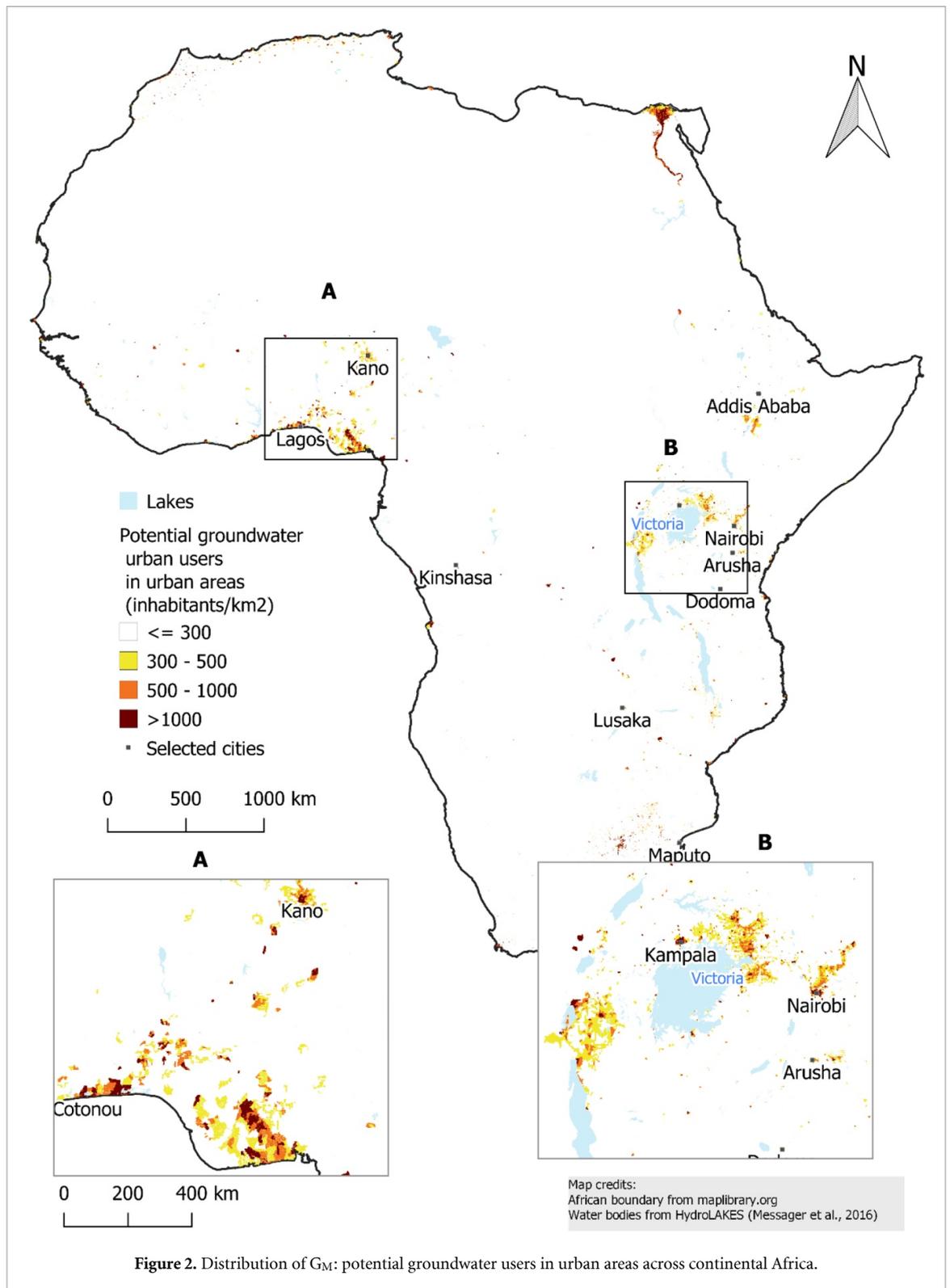


Figure 2. Distribution of  $G_M$ : potential groundwater users in urban areas across continental Africa.

in table 1. As an example, we calculated  $G_L\%$  for 3 cities without PMA survey data: Maputo, Dodoma, and Lusaka (lower 3 rows of table 1). So, in Maputo, the bandwidth of likely UUGS was 8%–32%, in Dodoma 21%–65%, and in Lusaka 16%–53%.

### 3.4. Sensitivity analysis

The difference in  $G_L\%$  when changing socioeconomic status, which was changed by adjusting decile

boundaries defining wealth, ranged from 1%–9% compared to the modelled values (table S10 (SI)). When changing the lag area, the difference in  $G_L\%$  ranged from 1%–3% compared to the modelled values (table S10). For the cases calculated, our geospatial model was more sensitive to changes in the socioeconomic distribution proxy than in the lag area. We attributed this to the greater dependence of low income areas on groundwater on the one hand and

**Table 1.** Maximum ( $G_M$ ) and likely ( $G_L$ ) UUGS determined in this study for 10 selected cities in Sub-Saharan Africa. For comparison actual UUGS (explained in the text) is given. All values are given as percentage of the total urban population. Actual UUGS is given as percentage of total urban population including 95% confidence interval (determined with Newcombe 1998).

City	$G_M\%$	$F_{L\_min}^*$	$G_L\%$		Actual UUGS (PMA)
			$F_L$	$F_{L\_max}$	
Arusha	90%	24%	48%	71%	65% $\pm$ 15%**
Kampala	75%	8%	17%	25%	25% $\pm$ 3%
Kano	71%	27%	52%	76%	83% $\pm$ 1%
Addis Ababa	90%	9%	18%	27%	3% $\pm$ 1%
Kinshasa	63%	7%	19%	29%	18% $\pm$ 1%
Lagos	89%	5%	36%	56%	61% $\pm$ 1%
Nairobi	77%	13%	30%	44%	6% $\pm$ 1%
Average	79%		31%		
Maputo	52%	8%	21%	32%	n.a.***
Dodoma	89%	21%	44%	65%	“
Lusaka	76%	16%	36%	53%	“

\* $F_{L\_min}$ : 0–0.35;  $F_L$ : 0–0.65;  $F_{L\_max}$ : 0–0.95;

\*\*based on Komakech and de Bont 2018;

\*\*\* n.a.: not available.

because low socioeconomic status pixels were more abundant in the more recent parts of the city, not affected by the lag area changes. From this modest sensitivity test, we concluded that changes in the two proxies we developed had effect on  $G_L\%$ , but this effect was limited, and our geospatial model appeared to be fairly robust.

#### 4. Discussion

We developed a spatially distributed GIS-based method for continental Africa (without islands) based on open data to estimate likelihood of self-supply groundwater use in urban areas. To arrive at a maximum number of potential urban self-supply groundwater users, we used hydrogeological data (groundwater storage, depth to groundwater and aquifer productivity) in combination with population density. To arrive at a likely number of urban self-supply groundwater users at city-scale, we used hydrogeological data, proxies for both piped water supply network coverage and socio-economic status, survey data and local or national restriction measures for groundwater use in combination with population density data. We demonstrate that in 2015 some 369 million urban inhabitants (~79% of the total urban population) of continental Africa could supply themselves with groundwater, since groundwater tables are not too deep (<7 m) and the aquifers are sufficiently productive. On a city-scale we demonstrate that our geospatial model is robust in the sense that changes in the proxies had an effect on  $G_L\%$ , but this effect was limited. Furthermore, we demonstrate that the calculated likely UUGS and the numbers based on PMA data coincide well, and we were able to determine a bandwidth, a range, of likely UUGS in urban areas in continental Africa. When comparing  $G_M\%$  and  $G_L\%$ ,

then the average difference is around 48 percentage points.

The differences between  $G_M\%$  and  $G_L\%$  were primarily due to the inclusion of three additional parameters in  $G_L\%$ : the two proxies (socio-economic status and public supply lag area) and the possibility to apply restriction measures. Furthermore, a number of rules were applied to determine  $G_L\%$ : (i) low productive aquifers would still be tapped at shallow depth, (ii) only (part of) the population with low economic status uses surface water, (iii) restriction measures did not apply to low economic status, and (iv) if groundwater was available, it would be used. From table 1, we concluded that the differences between  $G_M\%$  and  $G_L\%$  could be high, in the order of 50% or more for the following cases, which may be distinct or overlap: (i) in case of the presence of a piped supply network with high coverage, (ii) a population with average to high socio-economic status, who are -for the better part- assumed to be able to pay for a public supply connection, (iii) high coverage piped supply network and favourable hydrogeological conditions for groundwater use, so there is less need to practice self-supply despite the availability of groundwater. Finally, groundwater use restrictions further limit self-supply. Earlier, Grönwall *et al.* (2010) estimated that more than 30% of the urban population depends on wells, boreholes or springs as their principal source of drinking water. Based on our expanded method, and assuming that piped water supply network coverage in the cities examined is representative of the wider urban situation, we arrive at a slightly higher figure in the order of 32% (~150 million inhabitants).

The use of three sets of ranges of  $F_L$  indicating low ( $F_L = 0-0.12-0.23-0.35$ ), average ( $F_L = 0-0.21-0.44-0.65$ ), or high likelihood ( $F_L = 0-0.31-0.64-0.95$ ) requires attention. Assigning such range of  $F_L$

values to the terms low, average and high was essentially arbitrary in order to cover a wide, but realistic, range of self-supply likelihoods. From table 1, we concluded that 4 out of 7 cities were adequately modelled using the maximum likelihood set of values, 1 using the average set, and 2 using the minimum set of  $F_L$  values. Our conclusion is that determining the range was the best we could do. A preference for any of the sets of values used is not apparent. Conversely, without additional knowledge, we were unable to put a low, average or high groundwater self-supply likelihood 'label' on any of the cities we studied. In other words, our geospatial model did not capture the full range of variability in urban groundwater self-supply practices across continental Africa. We think the parameter 'groundwater awareness' or 'the culture of using groundwater' is missing in our model. In case of low likelihood set of  $F_L$  values, our own rule -if groundwater was available, it would be used- did not apply. We speculate that, for any particular city or country, regardless of restrictions, unless there is no culture of using groundwater, inhabitants of these cities would use self-supply groundwater.

Our approach has a number of important limitations. Firstly, it simplifies the spatial heterogeneity of the city and does not capture local particularities, such as the organization of private borehole/spring systems in specific neighbourhoods. Water access dynamics can change considerably from street to street (Smiley 2013). Our method is city-scale and does not offer street-to-street answers. In addition, the 5 km resolution of the Hydrogeological Map of Africa (Macdonald *et al* 2012), which we used as a basis for our work is rather coarse relative to the size of the cities we considered. As a result, complex local geology is not captured by the input data and is likely to affect model calculations.

Secondly, as indicated in the Methods section, we assumed that neighbourhoods developed in the same time have equal conditions of access to utility services. However, areas that developed in the same period can have important differences in access to piped water, based on the planned/unplanned origin of the settlement (Smiley 2013) as well as urban infill at a later point.

Thirdly, investigating groundwater use could also be addressed through a water balance approach, which estimates volumes of water going into and out of the urban aquifer complex, including abstractions for groundwater use. The water balance perspective gives a better insight into the environmental and hydrological dimension of groundwater use, by relating abstractions and recharge to define sustainable yields, or compare available water and demand to understand the potential of groundwater use. In the case of Kampala, according to Nyenje *et al.* (2010), spring discharge volume ( $10 \text{ mm y}^{-1}$ )—the main groundwater source—is less than 9% of the recharge ( $115 \text{ mm y}^{-1}$ ), which does not seem a lot. However,

data to assess the water balance at city scale of those cities mentioned in table 1 are not available. Of the data missing, most important is the spatially distributed effective recharge, which is determined by a combination of precipitation, actual evapotranspiration, land use, and soil composition.

Fourthly, the method employed was restricted to observations of the land. This means that dynamic elements like water tankers, who fetch water from one place to deliver it elsewhere, cannot be captured.

Fifthly, we only considered access to groundwater in terms of quantity and not the health and safety dimensions or groundwater quality aspects such as salinity. However, due to lack of information on the distribution of contaminants in aquifers (anthropogenic or natural), we did not include groundwater quality as a parameter for estimating groundwater usage likelihood. As cities grow, and since most sanitation occurs on-site, groundwater becomes polluted with faecal matter, which poses a health risk (Kulabako *et al* 2010, Lapworth *et al* 2017). Likewise, seawater encroachment due to increased groundwater abstraction in coastal or deltaic cities is a common problem, which we have not included. While self-supplied groundwater is often accessed and utilized for many different purposes, not all-domestic water need be of potable standard. The volumes of water needed for quenching thirst and for some food preparation purposes are small relative to other domestic needs (Grönwall and Danert 2020).

Sixthly, we did not consider dynamically changing groundwater levels, in particular in the face of climate change. In some cities, groundwater levels are declining. Groundwater levels may become too deep, shallow wells run dry, and disappear (e.g. . Mjemah *et al* 2009, Walraevens *et al* 2015).

Finally, the methodology is not capable of differentiating between hand-dug wells and springs, which is problematic as springs are more easily accessible, and usually free.

Our work offers several opportunities for application. It provides a basis for refining surveys at a local scale, as a way to analyse patterns of spatial inequalities of water access within the city, to estimate health risk, when coupled with (gridded) data on groundwater pollution or vulnerability to contamination, or in combination with water balance approaches as a first step in determining groundwater use volumes.

Our also study offers a new perspective on the body of research focused on continental Africa's urban groundwater use. Most of the available literature has focused on detailed descriptions of water access practices and surveys in specific peri-urban or informal settlements within cities of SSA (Smiley 2013, Nganyanyuka *et al* 2014, Grönwall 2016, Komakech and de Bont 2018), while only few study the spatial dimension of groundwater use at the scale

of the whole city (e.g. Pullan *et al* 2014, Yu *et al* 2019). Our work used a likelihood-of-use approach, and the outputs offer important considerations on the socio-hydrological dimension of groundwater use: the distribution and magnitude of people potentially relying on this resource.

The understanding of the magnitude and spatial scale of potential and actual groundwater use provides clear messages for the political leadership on urban domestic self-supply groundwater. A better understanding of the potential and likely use of urban domestic self-supply groundwater is essential to inform policy and practice, as well as influence public investment.

## 5. Conclusions

In 2015 some 369 million urban inhabitants (~79% of the total urban population) of continental Africa could supply themselves with groundwater. When including the proxies socioeconomic status and lag area of the public supply, both developed in this study, we calculated that in 2015 some 150 million urban inhabitants (~32% of the total urban population) of continental Africa were likely using groundwater obtained via self-supply. For 10 cities, the calculated likely UUGS and the numbers based on PMA data coincide well. Our geospatial model is robust in the sense that changes in the proxies had an effect on the likely UUGS ( $G_L\%$ ), but this effect was within limits. Our results offer an important outlook on the distribution and magnitude of off-grid people relying on groundwater. The understanding of the magnitude and spatial scale of potential and actual groundwater use can inform policy and practice, as well as influence public investment on urban domestic self-supply groundwater.

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## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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