Effects of water source accessibility and reliability improvements on water consumption in eastern Nairobi

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Under the commitments of the UN Sustainable Development targets, there is increasing pressure on water utility providers in developing countries to improve their levels of service to consumers, especially for the rapidly growing numbers of people with lower incomes who reside in urban informal settlements. However, pressure on water resources in many regions is simultaneously increasing owing to factors such as pollution, agricultural needs, and climate change. It is therefore important to assess the impacts of improving water services on city-wide water resources. This study examines consumption data from the East African city of Nairobi, collected from households of a variety of residential neighbourhoods. The study suggests that average per capita water consumption is closely related to water source choice (i.e. tap in the dwelling, yard tap, or water vendor kiosks). Within categories of water source type, variables such as household wealth, cost of water, and education do not have significant effects on per capita consumption. It is noted that increased accessibility of water causes the upper bound of consumption to rise, but not the lower. It may therefore be theorized that having a tap in a dwelling is necessary but not sufficient to increase per capita consumption. Within the sample examined, there is no statistically significant difference in per capita consumption between water source types other than a tap in a dwelling, and it is therefore suggested that providing a yard tap to those currently without any form of water connection may have negligible impact on city-wide water consumption.

Keywords: Kenya, water use model, water consumption, water accessibility, water source reliability

One of the targets of UN Sustainable Development Goal 6 is a commitment to ‘achieve universal and equitable access to safe and affordable drinking water for all,’ by 2030 (UN, 2015). The adoption of this target reflects the widespread recognition

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that access to safe drinking water is one of the cornerstones to sustainable development (UN, 2012). While substantial progress has been made in recent years – 91 per cent of the global population now use an improved drinking water source compared with 76 per cent in 1990 – as of 2015, 663 million people remained dependent on unimproved sources (JMP, 2015). Almost half of these individuals live in sub-Saharan Africa, where rapid population growth has posed a particular challenge to progress (JMP, 2015). It is also important to note that many of those with access to improved services still need to leave their house or compound to collect water, and some supplies remain unreliable, suffering from intermittent availability due to rationing, or seasonal variations in availability.

In Kenya, the total population with access to improved water sources has risen from 43 per cent in 1990 to 63 per cent in 2015, but this headline figure masks what has actually been a deterioration in access in urban areas from 92 per cent to 82 per cent over the same period (JMP, 2015). Trends such as this – driven largely by the enormous growth of informal settlements in major cities – are among those that will need to be reversed if the Sustainable Development Goals are to be achieved.

An important concern in considering how universal access can be achieved is the implications in terms of total water demand of improving access to services. Many urban utility providers already have to deal with constrained water resource supply, poor delivery infrastructure, and pressures on demand from rising living standards and growing economies, in addition to a plethora of other challenges. The very feasibility of providing universal access to improved water sources by 2030 for urban populations has therefore been up for debate, but the nature of the challenge is currently poorly understood.

A number of approaches to projecting future water demand have been outlined in the literature, including econometric techniques as reviewed by Nauges and Whittington (2010) and hydrologic-economic approaches as reviewed by Kirby et al. (2014). However, the former tend to depict water demand as a function of water prices, and the latter tend to focus on demand at river basin or country level. Neither approach is well suited to forecasting the impact of improved service levels on city-level water consumption.

Recognizing this gap, this paper sets out a simple model that enables future city- and sub-city-level water demand to be estimated based on projected population growth rates and user-defined water accessibility and reliability improvement scenarios. This is based upon the premise that water service level is largely defined by spatial accessibility and temporal availability, and neighbourhood subpopulations that share the same access characteristics typically have similar consumption traits. Water access improvements can consequently be simulated by moving subpopulations from one service category to another and updating their characteristic consumption figures to reflect this. This is done on a neighbourhood subpopulation level, and consumption is then aggregated to determine the effects on overall city water balance.

The model is applied to eastern Nairobi, an area that plays host to large, rapidly growing informal settlements, and where there are great inequalities in existing water access. Our findings suggest that improving both accessibility and reliability of supplies may not have such a significant impact on total water demand as might be expected. In particular, the model indicates that providing yard taps for households who currently have to leave the premises to collect water has only a marginal impact on total water demand, but such an improvement could have a significant impact on welfare at the household level. The research was conducted on behalf of Water and Sanitation for the Urban Poor (WSUP) with funding from the UK Department for International Development.

Methodology

Water use model

This research is based on the idea that water supply service levels in urban areas can be usefully described along two dimensions: accessibility and reliability. Accessibility describes the physical location of a water source: that is, whether the water source is a piped water supply located within the home (referred to as 'in the dwelling'), or a water source (piped or otherwise) located within the yard (referred to as 'in the yard'), whether water is delivered to the home by tanker or cart (referred to as 'delivered to the dwelling'), or whether water is physically carried to the home by the owner after being purchased from a kiosk or shop (referred to as 'carried to the dwelling'). Reliability describes the number of days per week that water is available and whether or not this can be predicted in advance. Service levels can be improved both by bringing sources closer to consumers – thereby increasing accessibility – and by increasing reliability. A representation of this concept and of the direction of improvements is given in Table 1.

For this study, a water use model was developed which predicts total domestic water demand based on current levels of service within a city, and predicts changes in total demand which may arise from selective improvements in service levels for targeted groups of consumers. The model is based on a workbook created in MS Excel 2013, with macros written in Visual Basic for Applications.

The model can be used at any spatial resolution, with the appropriate scale being determined by the availability of input data. Where reliable and accurate data sets are available, the model can be built on the basis of small geographical units, such as wards. If data is sparser, approximate values on a city scale can be obtained.

Table 1 Service levels

Water supply is…	*Predictable*		*Unpredictable*	
	Available > x days per week	*Available < x days per week*	*Available > x days per week*	*Available < x days per week*
In the dwelling	*Highest level of service*			
In the yard				*Increasing accessibility* ↑
Delivered to the dwelling				
Carried to the dwelling		←	*Increasing reliability*	*Lowest level of service*

Model set-up

The model requires typical per capita water consumption values for each service level, along with a corresponding estimate of energy usage for various delivery technologies. The user can also input a range of plausible leakage rates, ranging from 'high' (representing physical losses from the poorest functioning parts of the network) to 'low' (representing physical losses from the most efficiently functioning parts of the network). Population growth rates can be disaggregated for different geographical areas. This data can be estimated from secondary data or primary data collection.

For each geographical unit, the number of residents accessing water from each source is entered and the characteristic leakage rate and population growth rate selected. When all data are entered, the model collates the number of users in each service level and calculates the current (baseline) water and energy demand.

Scenario planning

Scenarios for improving service levels can then be simulated by selecting target population groups and moving these to another service level or leakage rate; for example, providing yard taps to all consumers who currently carry water to their houses, or receive deliveries of water to their houses. The resultant overall water and energy demand after the intervention is then calculated. Future demand is predicted using the population growth rates for both the baseline scenario and the intervention.

The spreadsheet is publicly available from http://www.wsup.com/wp-content/uploads/2013/05/Excel-Based-Modelling-Tool-a-tool-to-allow-others-to-perform-similar-analyses.xls.

Data collection

To obtain input data for the model, fieldwork was conducted in Nairobi, Kenya, for three weeks in April 2014. Both primary and secondary data points were collected. Published and unpublished literature on the water supply system in Nairobi was also reviewed. Kenyan national census data (Kenya National Bureau of Statistics, 2009) and data from the Demographic and Health Survey (Kenya National Bureau of Statistics and ICF Macro, 2010) was used to obtain information on the total number of residents with access at each service level and their geographical distribution. Secondary data was also used to identify neighbourhoods with different socio-economic characteristics and service levels to use as fieldwork locations. Data from the Global Water Operators' Partnership Alliance (GWOPA) and the French Institute for Research in Africa (IFRA), who conducted a survey of household water access in Nairobi aimed at mapping inequality in access to water and sanitation at a sub-city level and who interviewed more than 800 households, was used for this purpose (Ledant et al., 2011a, b).

To augment secondary sources, targeted primary data collection was carried out in eight neighbourhoods across eastern Nairobi. These neighbourhoods were purposively

Table 2 Neighbourhood characteristics

Neighbourhood name	*Residential typology*
Neighbourhood 1	Areas characterized by high-density, unplanned, low-quality housing
Neighbourhood 2	
Neighbourhood 3	
Neighbourhood 4	Area characterized by low-density, low-quality housing
Neighbourhood 5	Area characterized by collective housing with open access
Neighbourhood 6	Area characterized by high-density, low-quality, planned housing
Neighbourhood 7	Area characterized by high-density multistorey buildings
Neighbourhood 8	Area characterized by dense, individual housing

sampled to give a cross-section of settlement types and service levels. Further details on the characteristics of these neighbourhoods are given in Table 2.

Data was collected from 191 households using questionnaires written in English and administered by enumerators fluent in English and Swahili. A structured random sampling method to select households within each neighbourhood was initially planned. However, poorly defined streets, inaccurate maps, and unclear definitions of settlements made it challenging to apply structured sampling methods. Therefore, to balance time constraints with the representativeness of the sample, a random arbitrary sampling method was used, while trying to give even coverage across the settlements. Further primary data collection methods included two focus group discussions, 15 water point observations, and six key informant interviews. The primary aim of the fieldwork was to gain more detailed information on water consumption by users of different water source types and to examine the factors influencing water consumption levels.

Water consumption for households who collect water from a source outside the home was estimated by establishing the size of containers used and the number of times they are filled per day. This was cross-checked and triangulated with expenditure on water, and daily or weekly water usage by activity. For those with taps in the dwelling and yard taps, consumption was calculated by estimating the size of storage containers and the number of times they are filled per day or week. Additionally, consumption values for these groups were back-calculated using their average monthly water bills and the Nairobi City Water and Sewerage Company (NCWSC) tariff, and checked against stated consumption values and water usage by activity.

Household wealth has been proven to be a more robust indicator of financial stability than income (Rutstein and Johnson, 2004), which is notably difficult to assess in developing countries (Deaton, 1997). Therefore, in this study, a wealth index score was included as a variable and assessed using proxies of asset ownership. This method involves asking respondents to identify assets they own from a list, recording the number of people sleeping per room, and observing the construction materials of the house. The collected variables were then weighed and aggregated to form one wealth score using principal component analysis, as suggested by Rutstein and Johnson (2004). As the relative value of assets can be very different in each country, the list of assets used in the questionnaire was derived from the most recent Demographic and Health Survey in Kenya (Kenya National Bureau of Statistics and ICF Macro, 2010). Further details on the fieldwork methodology is given by Purshouse et al. (2015) in the final report of the Nairobi case study.

Results and discussion

Multidimensional analysis of the drivers of household water use in Nairobi

After data cleaning and validation, the overall water use per capita for each respondent in the household survey was calculated. Table 3 shows the average consumption of water by source access category, along with the number of respondents in each category. In the surveyed sample, 86 per cent of respondents claimed that their water supply was predictable. The field team had concerns as to whether or not the question was understood correctly by the remaining 14 per cent. The two categories of predictability in Table 1 were therefore collapsed. For users who carry water to their dwelling, get water delivered to their dwelling, or have a tap in their dwelling there was no statistically significant difference in mean consumption against availability (t-test, $p = .161$, $p = .923$ and $p = .092$, respectively). Therefore, no distinction between consumption values on the basis of availability has been made for these water access types. For users of yard taps, there was a statistically significant difference in mean consumption on the basis of availability (t-test, $p = .042$); therefore this group has been disaggregated accordingly. The mean distance to the water source within the 'carried to dwelling' category was 36.25 m, with a standard deviation of 52.52 m.

The histograms of water consumption for the four source categories in Figure 1 show that the distribution for users carrying water home is strongly clustered around the mean, while the distributions are wider for sources with higher accessibility. This is confirmed by the significantly higher standard deviation of water consumption for users of private taps compared with users who carry water to their homes, at 52.3 litres per capita per day (lpcd) and 12.2 lpcd, respectively. The histograms also show that the upper bound of the distribution changes with increased accessibility, but not the lower bound. This suggests that having a household connection is necessary, but not sufficient to increase domestic water consumption. Further qualitative surveys may be necessary to ascertain the reasons for this.

Table 3 Average consumption values and number of respondents by source

Water access source		*Mean (lpcd)*	*Median (lpcd)*	*Standard deviation (lpcd)*	*N in sample*
Carried to dwelling		27.8	25.0	12.2	55
Delivered to dwelling		43.5	45.7	22.4	11
Tap in yard	≤ 4 days per week	33.2	28.6	19.7	21
	> 4 days per week	50.9	58.6	21.5	10
Tap in dwelling		69.0	60.0	52.3	27

Note: lpcd = litres per capita per day

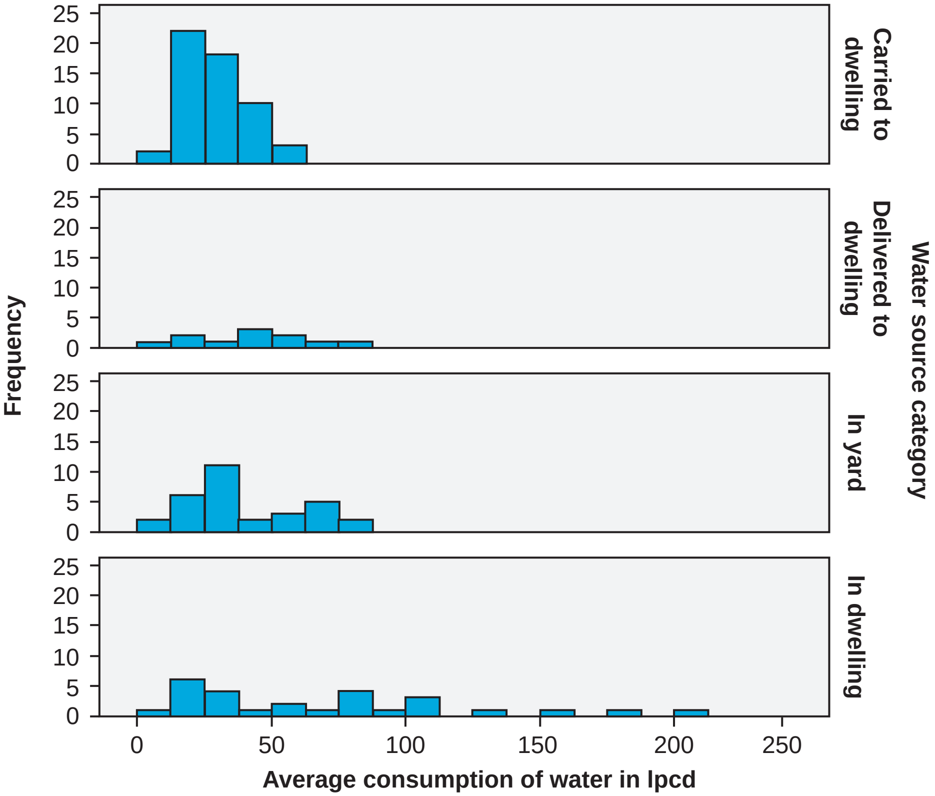

Figure 1 Histograms of water consumption by water source

After this data characterization and inspection, the factors that influence household water demand in Nairobi were analysed by correlating the collected variables. The strongest correlations (all significant at a $p \leq 0.001$ level) were found between wealth score and water source category ($r = .655$), wealth score and neighbourhood category ($r = .673$), and neighbourhood category and water source category ($r = .583$). Average water consumption is correlated to water source category ($r = .443$), wealth score ($r = .362$), and neighbourhood category ($r = .366$).

This suggests that increased household wealth leads to higher water consumption, which is in line with the results of Grafton et al. (2011) and Dias et al. (2014), who find that income can be used to predict household water demand. However, in our sample, a partial correlation of wealth score and average water consumption while controlling for the water source category was found not to be significant ($r = .107$, $p = .239$). Therefore, within one particular water source category, higher wealth is not associated with higher water consumption. Conversely, the partial correlation of water source category and average consumption is still significant after controlling for wealth score (relationship prior to controlling: $r = .443$, $p \leq 0.001$; relationship after controlling: $r = .292$, $p = .001$).

In summary, this study indicates that wealth and neighbourhood characteristics can strongly influence the type of water source used at household level. After a water source has been established, this can then become the most important factor determining the amount of water a household consumes, as shown in Figure 2.

Modelling the impact of improving service levels in Nairobi

The spreadsheet model described above was used to assess the impacts that improvements in service levels have on the city-wide water demand. Five scenarios were defined and impacts of interventions modelled over a period of 20 years.

Secondary sources suggest that in Nairobi there is an east-west divide in average water consumption. Ledant et al. (2011b) found that users in the west consume 129 to 288 lpcd, compared with values of around 30 lpcd in the east. The significantly higher consumption in the western part of town is likely caused by higher wealth, which typically leads to higher domestic use – for example, for gardening – as well as higher household connection coverage in the west (Ledant et al., 2011b). As this study is primarily concerned with improvements to services in informal areas where many users currently do not have taps in their dwellings, the model was constructed to include only the eastern part of Nairobi. Residents in the west were

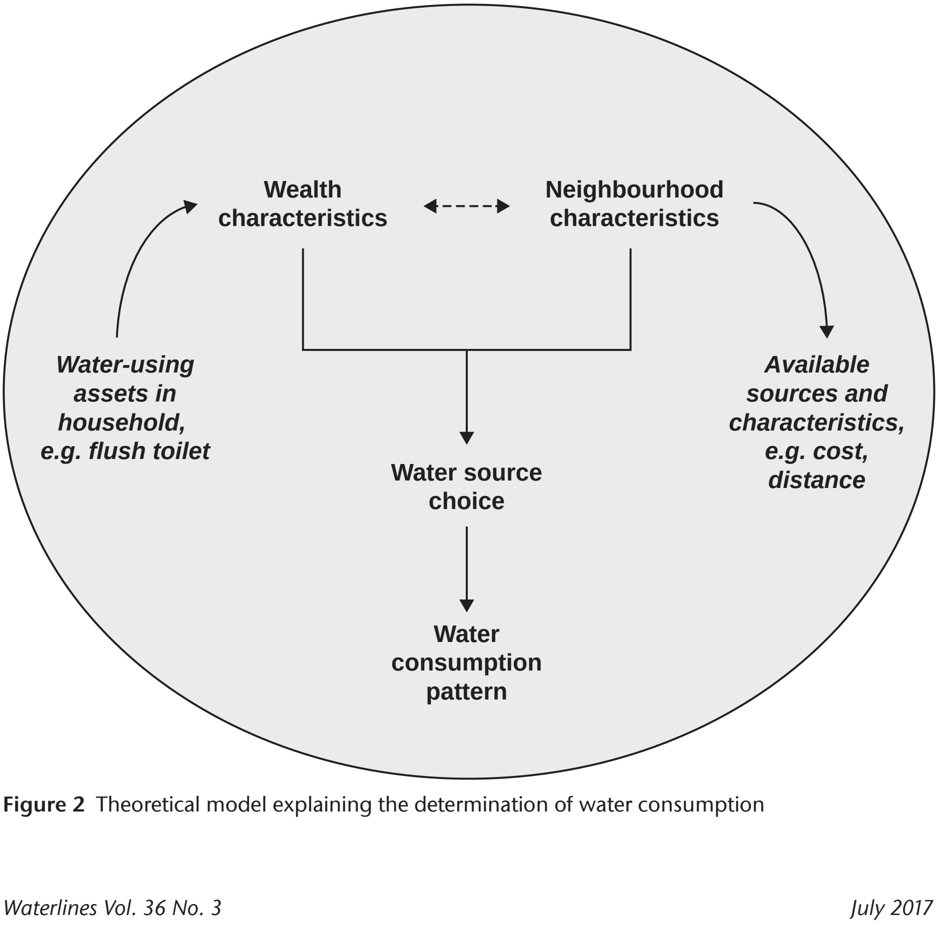

Figure 2 Theoretical model explaining the determination of water consumption

included in the estimation of the current baseline consumption, while improvements to service were modelled only for the population in eastern Nairobi.

The model estimates a baseline total domestic consumption of 120,574 megalitres (Ml) per year, including physical losses. The total system input volume according to a water balance by the Nairobi City Water and Sewerage Company shared with the research team is 199,432 Ml per year. The percentage of water supplied to commercial and industrial users is 32 per cent (IBNet, 2015), which leaves around 135,500 Ml per year for domestic consumption. The model therefore predicts baseline total demand to within 15 per cent of the actual water production. There are several possible explanations for the difference of ~15,000 Ml between the model result and the value from the water balance. The percentage of water used for commercial and industrial purposes could be higher than the reported 32 per cent, thereby reducing the amount of water for domestic consumption. Physical losses are notably hard to assess precisely (Kingdom et al., 2006) and could be higher than the 18 per cent assumed in the simulation. Also, the model assumes that all users of one accessibility category consume the same amount of water per day. In reality, some households may be using significantly higher quantities, which would lead to an underestimation of total water demand. A more detailed study with additional primary data collection would be needed to identify which of these factors is actually operating and to improve the accuracy of the estimates. Nonetheless, the model predicts total demand with a level of accuracy that is considered adequate for a preliminary assessment of the impacts of changing service levels.

The most striking result from the model is that simple improvements for those with the lowest service levels do not greatly increase overall water demand. If all residents in eastern Nairobi without any form of tap were provided with yard taps, supplying water for four days a week or fewer, city-wide water demand would only increase by 0.6 per cent (NB: the percentage increase in city-wide water demand is less than the increase in individual demand because residents without any form of tap make up only a part of the population of eastern Nairobi). This increase rises to 3 per cent if yard taps are provided with a water supply for more than four days a week. Overall, this would represent a very small impact on water resources, but a major improvement in service for more than 350,000 residents as they would no longer have to experience the physical strain of carrying water to their homes, and time spent collecting water would be free for other activities. Therefore, utilities do not necessarily need to expect a substantial increase in water demand if they improve services for the poorest. Additionally, the model indicates that this change would only have a minor impact on overall energy demands for domestic water production.

By contrast, giving taps inside their dwellings to all residents in the eastern part of the city increases the overall water demand by 15 per cent. This is a significant increase, and would need to be balanced against the availability of bulk water. However, this scenario also means that more than 1.5 million users would gain access to a water connection in their own home, which could significantly improve their quality of life. These users would also become paying customers, which could provide a way to increase cost recovery for the utility company. Reducing physical losses in the process of extending coverage would help reduce the impact of additional water demand, while the reduction of commercial losses would make the improvements more financially viable.

Limitations of the approach

Using a combination of primary and secondary data for Nairobi, we show that the water use model is a tool that can easily be used for predicting overall water and energy demand, and for modelling changes associated with altering service levels in selected geographic areas. This process is straightforward, but the accuracy of the modelled results is highly dependent on the accuracy and scale of data on household consumption patterns. The model is highly adaptable and can be constructed on any scale, depending on data availability.

In its current form, the model operates on a number of basic assumptions that introduce certain limitations:

1. Users with similar levels of service (access categories and reliability) are assumed to have homogeneous per capita water consumption; it is not currently possible to include geographical variations in consumption even though these appear to be significant in the case of Nairobi. Uncertainty around household consumption could be accommodated by using Monte Carlo simulations within the spreadsheet to account for the variability of water use within one category.
2. Consumers moved to a new service level are assumed to behave in the same way as those who experienced that service level at baseline. However Briand et al. (2010) demonstrated that this may not always be the case.
3. Finally, the model produces a steady-state estimate of final water and energy demand after an intervention to improve service levels. It does not deal with the practical problems surrounding these improvements such as investment needs, legal issues with land tenure in informal housing areas, time needed for construction, or political will to actually improve services.

Nonetheless, the model shows promise and further trials could confirm validity, while its functionality could easily be extended to include greater heterogeneity in population, geography, and consumption behaviours. It could also be readily extended to work on an online platform. This would allow the creation of a database of input data from cities where the model was used and would therefore allow the tool to suggest values for missing input data, drawing on the data from cities in the same region, gross domestic product range, or climate zone. The model could also be extended to work with geographical information systems. This would allow the inclusion of spatial data on water use and the creation of graphical outputs, such as maps showing the increase in water demand by district.

The main limitation of fieldwork for the Nairobi case study was the small sample size and relatively short time frame for data collection. In total, 191 household surveys were conducted, which is not statistically representative of the entire city. Therefore, results should be seen as indicative and could be validated by a more rigorous study with large sample sizes. However, they are still of value to show trends and pattern within the data and to create a theoretical model of the determination of water demand in Nairobi.

Conclusion

This paper described the creation of a novel tool to model the impact of improvements in service levels on city-wide water demand. The results of our fieldwork suggest that the overall water consumption of a household is most strongly linked to their choice of water source, which in turn is correlated with wealth and neighbourhood characteristics. When applied to the case of Nairobi, the model suggests that improvements in service levels for significant parts of the city may not have as large an impact on overall water demand as might be expected. The model predicted that improving services in eastern Nairobi by providing yard taps to users who currently carry water or have water delivered to their dwelling increases city-wide water consumption by only 3 per cent. This is a small increase but could mean a major improvement in the quality of life for these residents thanks to the added convenience, and savings of time and physical exertion. Providing taps inside the dwellings of all residents in the eastern part of the city is predicted to increase total water demand by 15 per cent, which might require additional bulk water supplies to be sourced for the network. These results have significant implications for the cities in the global South, in light of the SDG call for universal access to well-managed water services that provide accessible and reliable facilities. While improvements in accessibility represent a significant improvement in levels of service for households, their implications for total water demand at city level may be less significant than policymakers may expect.

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