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Key Points:

- Uniform price tariffs perform as well as or better than increasing block tariff alternatives relative to several metrics of tariff performance
- To promote economic development and address water scarcity, economic efficiency should be a primary objective of tariff reform
- Revising tariffs to improve cost recovery is politically difficult because customers perceive increased water bills as welfare losses

Supporting Information:

Supporting Information may be found in the online version of this article.

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Assessing the Performance of Water and Sanitation Tariffs: The Case of Nairobi, Kenya

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Abstract Policymakers and utility managers can use a variety of tariff structures to calculate customers' bills for water and sanitation services, ranging from a simple fixed monthly fee to complicated multi-part tariffs with seasonal pricing based on metered water use. This study examines the performance of several alternative tariff structures for water and wastewater services in Nairobi, Kenya using a dynamic tariff simulation model applied to a complete set of billing records from Nairobi City Water and Sewer Company. Simulations show that a uniform volumetric price tariff structure performs as well as or better than several increasing block tariff (IBT) structures across the six performance metrics considered (customer welfare, social welfare, cost recovery, the subsidy delivered through the tariff, subsidy incidence, and water conservation). These findings are robust to changes in the level of cost recovery. This finding challenges the wisdom of the widespread use of IBTs in low- and middle-income countries and current perceptions of best practice in tariff design.

1. Introduction

Water utilities in developing countries charge their customers far below the total average costs of the services they provide (Andres et al., 2019; Danilenko et al., 2014). Direct subsidies from higher levels of government and international donors are rarely sufficient to make up a water utilities revenue shortfall. Water utilities in developing countries are thus under pressure to increase water to tariffs (user fees) to generate the revenue needed to repair and replace existing infrastructure as it ages, invest in infrastructure to improve service quality, and increase capacity to meet the needs of unconnected households and rising populations. In cities where increasing water withdrawals and climate-driven hydrological variability contribute to water scarcity, raising tariffs is also essential to promote water conservation and fund more climate-resilient infrastructure.

Despite the need to increase tariffs, water utilities in developing countries face political pressure from both customers and higher-levels of government to keep prices low to minimize social unrest and ensure that water and sanitation services are affordable to poor households. In some cases, they may feel political pressure to meet the United Nations' Sustainable Development Goal of universal access to safe and affordable water and sanitation services (United Nations General Assembly, 2015).

To address these financial, hydrological, and political pressures on tariffs, water utilities in developing countries can change both the average price charged customers and the tariff structure itself, that is, the procedure used to calculate different customers' water bills. However, policymakers and water utility managers typically want to know what will happen to various performance metrics before making such changes in the tariff. Models are needed to make such forecasts.

Water utilities in developing countries operate in different contexts and have different concerns than utilities in industrialized countries. As a result, models used to forecast the implications of tariff reform in developing countries must be attentive to these differences. There are three ways in which utilities in developing and industrialized countries differ that are particularly relevant for modeling the implications of tariff reform.

First, water utilities in developing countries need to plan for multi-year tariff reforms because it is politically infeasible to immediately raise prices to cost recovery levels by a single, one-time adjustment. In contrast, prices for municipal water and sanitation services are closer to cost recovery levels in industrialized countries, and they are typically adjusted for inflation and other factors frequently (e.g., annually).

Second, population and economic growth are much faster in most cities in developing countries than in industrialized countries. One of the main benefits of tariff increases in developing countries is the postponement of capacity expansion resulting from decreased water use and the resulting cost savings. This feedback relationship between tariffs and the costs of capacity expansion is important for assessing the performance of tariff reform programs in developing countries. It is rarely an important issue in cities in industrialized countries because economic and population growth are typically much lower, tariffs are adjusted more frequently, and one-time development charges are more commonly used to fund capacity expansion.

Third, substantial portions of an urban population may not be connected to the piped water and sewer network in developing countries. Water utility managers are concerned that tariff increases may make piped water and sanitation services unaffordable and hinder progress toward getting unconnected households onto piped networks. This is rarely a concern in industrialized countries, where it is taken for granted that 100% of households in a city have access to piped water and sewer services.

This article presents a simulation model that water utilities in developing countries can use to forecast the consequences of a multi-year tariff reform program. This simulation modeling framework enables the user to examine the effects of a variety of tariff structures that could be deployed in a tariff reform program, ranging from a simple fixed monthly fee to more complicated multi-part tariffs with seasonal pricing based on customers' metered water use. The consequences of the tariff reform program are assessed in terms of six performance metrics: (a) cost recovery; (b) change in customer welfare; (c) economic efficiency (changes in social welfare); (d) total subsidy delivered through the tariff; (e) the distribution of the subsidy in different income groups (subsidy incidence); and (f) water conservation (changes in the total quantity of water produced by the utility). The simulation model is applied to Nairobi, Kenya, a rapidly growing city with conditions similar to those in many large cities in low- and middle-income countries, to illustrate how it can be used to analyze a specific case. In the application, the performance metric of cost recovery is incorporated in the simulation model as a constraint, and different cost recovery levels are simulated.

The study makes three main contributions. First, the simulation model presented here is designed to address the problems faced in cities of the Global South and applied to the case of Nairobi, a city facing similar challenges to cities in developing countries across the globe. There are relatively few studies on the effects of water price increases in developing countries. Thus, this article adds to a small, but important literature on the modeling and assessment of tariff reform in developing countries.

Second, five tariff structures are simulated in the Nairobi case presented in this study. These tariff structures were selected to compare the performance of increasing block tariffs (IBTs) (the tariff structure implemented by the vast majority of utilities in developing countries) and uniform price (UP) tariffs, which may send a clearer price signal to customers). The consequences of each of the five tariff structures are compared to the performance of the status quo tariff in terms of six policy-relevant metrics of tariff performance. Most existing studies examine only one or two tariff structures and assess the consequences of price changes in terms of a small set of metrics of tariff performance. Thus, this study adds to the growing body of the literature on the use of IBTs in developing countries and provides a more holistic assessment of tariff performance.

Finally, the simulation model described in this study and applied to Nairobi examines the phase-in of tariff reforms over a 5-year planning period in annual time steps. This longer time horizon allows for a more realistic, gradual increase in water tariffs, and permits the analyst to incorporate increases in population and economic growth in the counterfactual baseline in which tariffs remained unchanged over the 5-year projection period. Most previous analyses of tariff changes model just two periods: before and after the tariff change. The approach adopted in this study allows a direct comparison of (a) what would happen if the tariff reforms were implemented over time and (b) what would happen in the evolving, dynamic baseline in which the tariff reform is not implemented. This comparison can be an effective way of communicating to policymakers both the changes that would result from implementing different tariff reform programs and the implications of continuing with the status quo approach.

2. Background and Literature

A water tariff is a set of rules a utility uses to calculate how much customers need to pay regularly (usually monthly) in exchange for a specified level of service. Utilities can use a variety of tariff structures to charge customers for water and sanitation services. Tariffs can range from a simple fixed charge that does not vary with customer water use to more complicated multi-part tariffs with both a fixed and volumetric charge. Tariffs used to calculate the volumetric portion of customers' water and wastewater bills include IBTs, decreasing block tariffs, and UP tariffs. Tariffs can also be constant throughout the year or vary seasonally. Different tariffs can be used to calculate the water bill of different types of customers (e.g., residential and industrial) and types of households (e.g., for different size households or households with different incomes or types of property).

Professional organizations, such as the American Water Works Association (AWWA, 2017) provide detailed guidance on best professional practice in tariff design. However, this guidance is based on experience in industrialized countries. Because prices in industrialized countries are often close to the full financial cost of service delivery and because tariffs are updated regularly, little attention has been paid to forecasting how status quo conditions may change in the future in the absence of tariff reforms or to simulating the performance of different tariff reform programs.

There are many choices an analyst must make when modeling the consequences of alternative tariffs, including the specification of baseline conditions, the approach to forecasting customer water use, how a utility's costs change with water use, assumptions about the desired level of cost recovery, and the number and specification of performance metrics used to evaluate the tariff performance. Commercial tariff consultants typically use representative customer types and frequency distributions of the water use of the utilities' customers to forecast the effects of different tariffs on utilities' income and balance sheets. The precise calculations used in these models are often proprietary and not available to the public. Typically, it is unclear what these proprietary consultant models assume about how customers' water use responds to tariff increases or how baseline conditions would change in the absence of tariff reforms. This may not be a critical issue in industrialized countries where prices are at or near full cost recovery, price increases are typically small, and baseline conditions are relatively stable, but is essential in many low- and middle-income countries where substantial price increases are required to achieve full cost recovery and baseline conditions are often more dynamic.

Commercial tariff studies in industrialized countries focus primarily on meeting utilities' financial cost recovery objectives. They may consider the effect of price increases on the water use and bills of different types of representative customers (e.g., customer class, water use, and service level). While commercial tariff studies are often guided by the principle of cost of service equity, they typically do not consider economic efficiency or the distributional consequences (i.e., social equity) of tariff alternatives.

Alongside commercial consulting practice, there is a broad academic literature on the pricing of municipal water and sanitation services. In particular, there is a rich theoretical literature on pricing utility and water and sanitation services (e.g., Berg & Tschirhart, 1989; Griffin, 2001; Hanemann, 1997; Kahn, 1988) and an extensive literature on estimating the demand for municipal water services (Dalhuisen et al., 2003; Espey et al., 1997; Reynaud & Romano, 2018; Worthington & Hoffman, 2008). Relatively less attention, however, has been paid to assessing the performance of alternative tariffs. For example, only approximately one-third (14 out of 44) of studies identified in a recent systematic review of the literature on the design and evaluation of water tariffs focused explicitly on comparing the performance of alternative tariffs (Fuente, 2019). Only four of these studies compared the performance of alternative tariffs in a low- or middle-income country (Briand, 2006; Cueva & Lauria, 2001; Groom et al., 2008; Klassert et al., 2018).

Overall, there is considerable heterogeneity in how studies in the academic literature model and assess tariff performance. The modeling approaches used in the academic literature range from relatively simple models that forecast changes in water use based on a single parameter (typically average price) in a single time step to models that use systems of equations in a dynamic context to assess the performance of various tariffs over multiple periods. The former includes studies that empirically estimate the demand for municipal water services and then use parameters estimated in the demand models (e.g., the price elasticity of demand) to forecast customer water use under one or more alternative tariffs (Diakite et al., 2009; Garcia-Valinas, 2005; Renzetti, 1992b). The latter includes computable general equilibrium models (Briand, 2006), agent-based models (Rosenberg, 2010), and system dynamic models (Ahmad & Prashar, 2010; Sahin et al., 2017). Studies in the literature use either customer account (household) level data or utility-level data as their unit of analysis. Fuente (2019) found that the majority (60%) of studies in the literature used utility-level data to simulate tariff performance.

Policymakers and utility managers often want to know how changes in the tariff will affect a range of financial, social, and economic outcomes (i.e., metrics of tariff performance). Unlike commercial tariff studies, economic efficiency is prominently featured in the academic literature on tariffs. The majority of studies in the academic literature focus on changes in customer welfare and address economic efficiency by either measuring changes in customer welfare associated with a transition to a new tariff or use the concept of economic efficiency to derive a tariff that maximizes customer welfare.

In contrast to commercial consulting practice, cost recovery is typically not a primary focus of studies in the academic literature and is generally treated as a constraint in a simulation or optimization model. Because the literature is dominated by studies in industrialized countries where tariffs are often sufficient to meet the financial costs of service delivery, most studies in the literature examine the performance of alternative tariffs at utilities' current level of cost recovery. Exceptions to this include Cueva and Lauria (2001) and Rosenburg (2010), who explicitly compare the level of cost recovery achieved by different tariffs, and Nauges and Whittington (2017), who examine the performance of nine tariff alternatives at two different levels of cost recovery. Cost recovery is an important performance metric for policymakers in low- and middle-income countries and needs to be included in tariff models used in these contexts.

In addition to economic efficiency and cost recovery, studies in the academic literature consider additional performance metrics, including revenue stability, social equity, affordability, maintenance of reservoir levels, and water conservation. Despite the range of performance metrics considered in the academic literature, individual studies typically consider only one or two metrics of tariff performance (Fuente, 2019). This is particularly true of studies that focus on economic efficiency (Baerenklau et al., 2014; Briand, 2006; Garcia & Reynaud, 2004) or subsidy incidence (Renzetti et al., 2014; Whittington et al., 2015). Overall, studies in the literature on the design and evaluation of water tariffs examine only a small number of performance metrics, have different primary aims (e.g., estimating future water use vs. simulating tariff performance), and focus primarily on water pricing in industrialized countries. The following section describes a practical model designed to assist water utilities in developing countries that want to evaluate the consequences of a long-term tariff reform program.

3. A Simulation Model for Understanding the Consequences of Tariff Reforms

3.1. Description of the Simulation Model

Figure 1 presents a schematic of this multi-year simulation model. The model begins in year 0 with the utility's existing set of customers and their current water use, an existing tariff structure, and utility revenues. The model simulates conditions with and without a tariff reform program, which allows a comparison of the six performance metrics in the two cases and thus the changes due to the tariff reform program. The model uses annual time steps and simulates conditions for a specified planning period. The model can simulate a change in tariff structure and a one-time tariff increase, or it can simulate a change in tariff structure and a multi-year phase-in of annual tariff increases with the new tariff structure. This combination of a (possible) change in tariff structure and any associated annual tariff increases is termed a “tariff reform program.”

In the baseline simulation without a tariff reform program (“dynamic baseline”), existing conditions may change due to population growth, economic growth, and changes in weather and climate. In the “dynamic baseline,” the utility may be connecting unconnected households to the piped water network and households with water connections to a sewer network at exogenously specified annual rates.

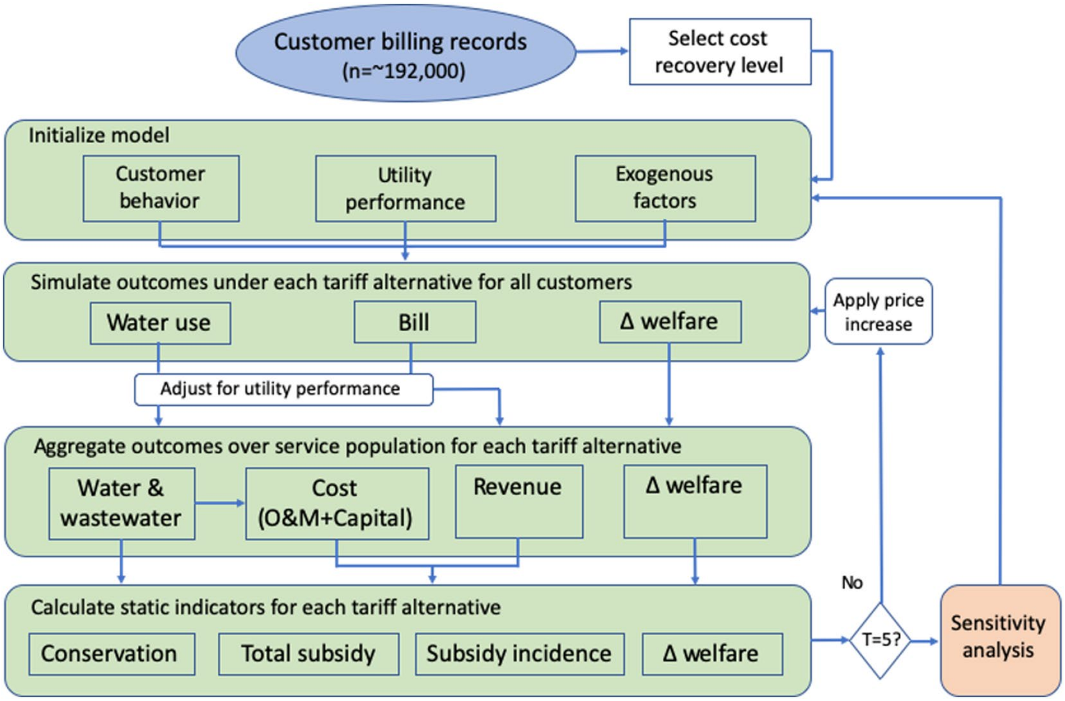

Figure 1. Schematic representation of the tariff simulation model.

The model can be used to simulate and compare a specified number of different tariff reform programs. For example, the model can simulate the consequences of different tariff structures, such as a uniform volumetric tariff with no fixed charge, a uniform volumetric tariff with a positive fixed charge, a uniform volumetric tariff with a negative fixed charge (i.e., a rebate), and various block tariff structures (increasing or decreasing) with and without fixed charges. The model can thus simulate how different tariff structures perform relative to various performance metrics as a utility moves along the specified reform path.

The total quantity of water used by customers and the total quantity of wastewater produced in a given year are determined by the size of the service population, the composition of the service population (i.e., the fraction of customers with water service only and the fraction with both water and wastewater service), the tariff utilized to calculate customers' water bills (either in the dynamic baseline or in the simulation with the tariff reform program), weather and climate conditions, and the wealth and other attributes of the service population.

The water use of customers in the simulation model is specified in the initial conditions for year 0. The model presented here simulates the water use of all individual customers in the service population. Utilities serve several customer types, including residential customers, commercial and industrial customers, bulk customers, and kiosks. The model could be adapted to use a representative customer for each customer type and an assumed distribution of water use assigned to each customer type. Water use in subsequent periods is modeled as a function of the water use in the prior period, customers' price and income elasticities of demand, the price customers are charged by the utility, and an exogenous change in income (Equation 1). Though not considered here, simulations that examine long planning periods could include exogenous changes in climate as well as information about forecast changes in technology.

$$\mathrm{WUSE}_{ij,t+1} = \mathrm{WUSE}_{ij,t} * \left[1 + \left(\beta_{ij,t} * \Delta P_{ij,t} + \varepsilon_{ij,Y} * \Delta Y_{ij,t+1}\right)\right], \tag{1}$$

where, $\mathrm{WUSE}_{ij,t+1}$ is the annual water use for customer i of type j in year $t+1$; $\mathrm{WUSE}_{ij,t}$ is the annual water use for customer i of type j in year t; $\beta_{ij,t}$ is the price elasticity of demand for customer i of type j in year t; $\Delta P_{ij,t}$ is the percent change in average (marginal) price from year t to $t-1$ for customer i of type j; $\varepsilon_{ij,Y}$ is the income elasticity of demand for customer i of type j; and $\Delta Y_{ij,t+1}$ is the exogenous percent change in income for customer i of type j from year t to $t+1$.

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For decades economists have studied the extent to which customers respond to marginal, average, or some other price signal for different goods and services (see Nordin, 1976; Taylor, 1975; for income taxes, see Chetty et al., 2011; Saez, 1999, 2003, 2010; for electricity prices, see Borenstein, 2009; Ito, 2014; and for water see Binet et al., 2013; Cook & Brent, 2021; Foster & Beattie, 1981; Howe & Linaweaver, 1967; Ito, 2013; Nataraj & Hanemann, 2011; Ruijs et al., 2008). Factors that influence whether customers respond to marginal price, average price, or some other price signal include the tariff structure, salience of customers' water bills, individual customer characteristics, water use, billing frequency, and payment method (e.g., automatic withdrawal, payment center, and mobile money). In many low- and middle-income countries, customers may not be well-informed about the marginal price they face. In this specification of the tariff simulation model, it is assumed that customers respond to changes in the average price rather than the marginal price. An analyst could modify this assumption if local conditions suggested that customers were responding to the marginal price.

The total quantity of water the utility must produce in each year of the planning period is a function of customers' water use and the utilities level of non-revenue water, which is defined here as water that is produced, but not delivered to customers due to leaks, system flushing, etc. (Equation 2).

$$Q_{w,t} = \frac{\left[\sum_{j=1}^{J}\sum_{i=1}^{N_{j,t}}\left(\mathrm{WUSE}_{ij,t}\right)\right]}{\left(1 - \mathrm{NRW}_t\right)}, \tag{2}$$

where, $Q_{w,t}$ is the quantity of water that must be produced by the utility in year t; J is the number of customer types; $N_{j,t}$ is the total number of customers of type j in year t; and NRW_t is the portion of $Q_{w,t}$ that is, non-revenue water in year t.

The total quantity of wastewater the utility must treat in each year of the planning period is a function of customer water use, the fraction of customers with a wastewater connection, and the fraction of household water use that enters the sewer network (i.e., indoor water use; Equation 3).

$$Q_{\mathrm{ww},t} = \left[\sum_{j=1}^{J}\sum_{i=1}^{N_{j,t}}\left(\mathrm{WUSE}_{ij,t}\cdot f_{j,\mathrm{ww}}\cdot \mathrm{Iww}_{ij,t}\right)\right], \tag{3}$$

where, $Q_{\mathrm{ww},t}$ is the quantity of wastewater that must be treated by the utility in year t; $f_{j,\mathrm{ww}}$ is the fraction of water used by customers of type j that enters the wastewater collection system; and $\mathrm{Iww}_{ij,t} = 1$ if customer i of type j has a wastewater connection at time t; 0 otherwise.

A customer's average monthly bill and thus annual bill in period t is a function of their water use, customer type, service, and the tariff used to calculate their monthly bill in period t (Equation 4).

$$\mathrm{BILL}_{ij,t} = f\left(\mathrm{WUSE}_{ij,t}, J, \mathrm{Iww}_{ij,t}\right), \tag{4}$$

where, $\mathrm{BILL}_{ij,t}$ is the annual bill for customer i of type j in year t.

The utility's annual revenue is the sum of all customers' bills multiplied by the utility's collection efficiency—that is, the percent of total billings the utility collects as revenue (Equation 5)

$$\mathrm{REV}_t = \left[\sum_{j=1}^{J}\sum_{i=1}^{N_{j,t}}\mathrm{BILL}_{ij,t}\right]\cdot \mathrm{CE}_t, \tag{5}$$

where, REV_t is the utility's revenue in year t and CE_t is the utility's collection efficiency in year t.

The utility's collection efficiency (CE_t) can be assumed to remain constant over the planning period or may be allowed to vary over time. A time-varying collection efficiency might be appropriate if a utility is undertaking an aggressive program of utility reform.

A water utility needs financial resources to pay for three broad categories of costs: (a) routine operations and maintenance costs (O&M costs), (b) repair and replacement of the existing capital stock, and (c) expansion of the water and wastewater network to meet the increased demand for these services (expansion costs). Any costs of debt service are subsumed in categories b and c. Although most utilities in low- and middle-income countries are public or quasi-public entities, any privately owned utilities would also require a return on capital, which may be paid to shareholders as dividends or retained as profits (Equation 6).

$$C_t = f\left(\text{OPEX}_{\text{w},t}, \text{OPEX}_{\text{ww},t}, R \,\&\, R_{\text{w},t}, R \,\&\, R_{\text{ww},t}, \text{EXP}_{\text{w},t}, \text{EXP}_{\text{ww},t}, \kappa_{\text{w}}, \kappa_{\text{ww}}\right), \tag{6}$$

where C_t is the utility's total cost in year t; $\text{OPEX}_{\text{w},t}$ is the operating expenses for water services in year t, which are functions of the input prices for these services in year t; $\text{OPEX}_{\text{ww},t}$ is the operating expenses for wastewater services in year t, which are functions of the input prices for these services in year t; $R\&R_{\text{w},t}$ are the repair and replacement expenses for the existing water network in year t; $R\&R_{\text{ww},t}$ are the repair and replacement expenses for the existing wastewater network in year t; $\text{EXP}_{\text{w},t}$ is the capital costs associated with the expansion of the existing water network in year t; $\text{EXP}_{\text{ww},t}$ is the capital costs associated with the expansion of the existing wastewater network in year t; κ_{w} is the cost elasticity of scale associated with water service delivery; and κ_{ww} is the cost elasticity of scale associated with wastewater service delivery.

The simulation model does not incorporate the lumpiness of capital projects and the need to build in advance of demand for services. It is simply assumed that if the aggregate quantity of water the utility must produce or the quantity of wastewater that requires treatment exceeds existing capacity, the new capacity is available and remains in service for the duration of the planning period. This is a simplifying assumption, and future extensions to the model could incorporate forward-looking capital expansion planning.

3.2. Evaluating the Consequences of Tariff Reform Programs

The consequences of the alternative tariff reform programs can be evaluated using all or a subset of the following six performance metrics: (a) cost recovery, (b) changes in customer welfare, (c) changes in social welfare, (d) the total subsidy delivered through the tariff, (e) the distribution of subsidies among different income groups (subsidy incidence), and (f) water conservation (changes in the total quantity of water used by customers). Other possible performance metrics include total revenue, revenue stability, and affordability (if the analyst has information on customers' income). (See Berg & Tschirhart, 1989; Bonbright, 1961; Hanemann, 1997; Whittington, 2011 for a detailed overview of the various objectives of tariff setting). In commercial consulting practice, it is also common to present the percent increase in bills for different types of customers, and it is a simple matter to provide this information based on the results of the simulation model if desired.

Economists typically argue that tariffs should be set to maximize social welfare. However, regulators and utilities often do not consider economic efficiency when designing and approving tariffs for water and sanitation services. The performance metrics included in the simulation model were selected for two reasons. First, these metrics represent issues that often matter to a range of stakeholders whose perspectives are considered in tariff design (e.g., policymakers, utility managers, customers, and civil society). Second, the inclusion of performance metrics beyond economic efficiency can facilitate a useful discussion about the explicit trade-offs between different metrics of tariff performance.

The simulation model examines the percent of total costs recovered from revenue at the end of the specified planning period (Equation 7).

$$\text{CR}_T^{\gamma} = \frac{\text{REV}_T^{\gamma}}{C_T^{\gamma}} \cdot 100, \tag{7}$$

where CR_T^{γ} is the percent cost recovery at the end of the planning period (T) under tariff γ; REV_T^{γ} is the total revenue at the end of the planning period (T) under tariff γ; and C_T^{γ} is the total cost at the end of the planning period (T) under tariff γ.

The change in customer welfare is approximated as the change in consumer surplus associated with the shift to each of the tariff alternatives relative to the status quo tariff. Following Nauges and Whittington (2017), the annual change in consumer surplus for each customer in year t is calculated as

$$\Delta\text{CS}_{ij,t}^{\gamma} = -\left(\frac{Q_{ij,t}}{P_{ij,t}^{\beta_{ij,t}}\left(1+\beta_{ij,t}\right)}\right)\left(P_{ij,t}^{\gamma\left(1+\beta_{ij,t}\right)} - P_{ij,t}^{\left(1+\beta_{ij,t}\right)}\right) \tag{8}$$

where $\Delta\text{CS}_{ij,t}^{\gamma}$ is the change in consumer surplus for customer i of type j under tariff alternative γ in year t; $Q_{ij,t}$ is the quantity of water customer i of type j would use under the status quo tariff in year t; $P_{ij,t}$ is the

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average price faced by customer i of type j at time t under the status quo tariff in year t; $P^{\gamma}_{ij,t}$ is the average price faced by customer i of type j under tariff alternative γ in year t.

The net present value of the change in consumer surplus is calculated by summing over the customer base for each year and discounting the stream of surplus changes using an assumed real (i.e., net of inflation) discount rate (Equation 9).

$$\Delta \text{CS}^{\gamma}_{\text{NPV}} = \sum_{t=1}^{t=T} \left[\frac{\sum_{j=1}^{J} \sum_{i=1}^{N_{j,t}} \left[\Delta \text{CS}^{\gamma}_{ij,t} \right]}{(1+\delta)^{t}} \right], \tag{9}$$

where δ is the real discount rate.

Utilities serve both residential and non-residential (commercial, industrial, etc.) customers. Non-residential customers are assumed to be producers that select their use of inputs, including water, to minimize the cost of producing a certain level of output (Renzetti, 1992a; Reynaud, 2003). Because information on non-residential customers' use of other inputs is not available, it is assumed that their water demands are separable from other input demands (Garcia & Reynaud, 2004; Renzetti, 1992a, 1992b; Reynaud, 2003).

As noted by Renzetti (1992b), a change in the water tariff can affect residential customers through two distinct channels. A change in tariff will affect residential customers directly through the difference in price they face for water and sanitation services (Equation 7). A change in tariff may also affect residential customers indirectly via the impact of price changes on non-residential customers' outputs. This second effect is not included in our estimates of the change in customer welfare.

Customers are assumed to respond to changes in average rather than marginal price. If customers respond to changes in marginal price, Equation 7 will not accurately measure the change in consumer surplus under IBTs (Nauges & Whittington, 2017). Supporting Information S1 discusses this issue in more detail and describes how changes in consumer surplus are calculated if customers respond to marginal price.

Most utilities in low- and middle-income countries do not generate sufficient revenue to cover the cost of providing piped water and sanitation services. Indeed, many utilities struggle to cover operations and maintenance costs (Danilenko et al., 2014). When revenues do not cover the cost of service delivery, customers enjoy considerable welfare gains associated with highly subsidized water relative to full cost recovery prices. As prices rise, customers experience a decrease in welfare, but social welfare increases as the magnitude of subsidies delivered through the tariff decreases, and welfare losses associated with inefficient water use decrease. The change in social welfare is approximated as the difference between the change in the magnitude of the subsidies associated with a shift to a new tariff and the change in customer welfare that accompanies this transition. This approximation is a lower bound on the welfare effects because it does not include the welfare effects associated with financing this subsidy (e.g., the opportunity cost of capital or taxes used to finance the subsidy) or the scarcity value of water.

The annual subsidy delivered through each tariff alternative is defined as the difference between the utility's revenue and the cost of providing services. The subsidies delivered through the tariff alternatives each year are calculated, and the net present value of the stream of subsidies over the simulation period is determined.

Subsidy incidence in the simulation model is defined as the share of subsidies delivered to low-income customers (Equation 10).

$$S_t = \frac{\sum_{j=1}^{J} \left(\sum_{i=1}^{N_{j,t}} \left(\text{WUSE}_{ij,t} \cdot \text{COST}_{ij,t} - \text{BILL}_{ij,t} \right) \cdot L_i \right)}{\sum_{j=1}^{J} \left(\sum_{i=1}^{N_{j,t}} \left(\text{WUSE}_{ij,t} \cdot \text{COST}_{ij,t} - \text{BILL}_{ij,t} \right) \right)}, \tag{10}$$

where S_t is the share of subsidies delivered to residential customers in low-income areas in year t; $\text{COST}_{ij,t}$ is the average cost of serving customer i of type j in year t; and $L_i = 1$, if customer i is a low-income residential customer and 0 otherwise.

To the extent that tariffs send the correct signal to customers to reduce water use until the marginal benefits of use equal the social marginal cost of supplying the service, the benefits of water conservation are subsumed in the economic efficiency performance metric. However, policymakers often express concern about water conservation *per se*. In the simulation model, the water conservation performance metric is defined as the percent change in total water use under each tariff alternative at the end of the planning period relative to total water use simulated in the dynamic baseline (i.e., total water use under the current tariff at status quo levels of cost recovery).

$$\mathrm{CONS}_T^{\gamma} = \frac{Q_{w,T}^{\gamma} - Q_{w,T}^{SQ}}{Q_{w,T}^{SQ}} \cdot 100, \tag{11}$$

where CONS_T^{γ} is the percent water conservation in the final year (T) of the planning period under tariff alternative γ; $Q_{w,T}^{\gamma}$ is the the quantity of water that must be produced by the utility under tariff alternative γ in the final year (T) of the planning period; and $Q_{w,T}^{SQ}$ is the quantity of water that must be produced by the utility under the current tariff at status quo levels of cost recovery in the final year (T) of the planning period.

The model is initiated by calculating the outcomes (water use, revenue, costs, etc.) and six performance metrics described above assuming the existing (status quo) tariff remains in effect over the planning period. This is the dynamic baseline (counterfactual) against which alternative tariffs are compared. The simulation model can be used to search for an improved tariff reform program or to examine a specific set of tariff alternatives. This paper does the latter. The following section describes the application of the simulation model to Nairobi, including how the model is solved.

4. Application to Nairobi, Kenya

The simulation model described above is applied to the case of Nairobi, Kenya, a rapidly growing city with conditions similar to those of many large cities in low- and middle-income countries. The performance of five alternative tariffs is evaluated relative to the status quo tariff for three levels of cost recovery. The performance metric for cost recovery is treated as a constraint on the model solution. The results for the other five performance metrics are presented for three cost-recovery targets (36%, 68%, and 100%) at the end of the planning period.

The model can accommodate different planning periods to meet the needs of the analyst. A 5-year planning horizon is used in the application to Nairobi because it reflects a period over which utilities in low- and middle-income countries often engage in tariff revisions and might consider transitioning to full cost recovery. As described below, the model is solved by selecting values for the fixed charge, volumetric price(s), sewer surcharge, and annual price increases that meet the designated cost recovery targets.

Like many utilities in the Global South, Nairobi City Water and Sewer Company (NCWSC) struggles to provide continuous water supply to its customers. Nairobi's main water supply comes from sources in the Thana river basin. Water is collected via a series of diversions, tunnels, and reservoirs. The city's main water supplies come from the Sasuma Dam Reservoir, the Ndakanini Dam Reservoir, and the Ruiru Dam Reservoir, located between 25 and 60 km from the city. Finished (treated) water is transported from three treatment plants to the city via a series of pipelines. The largest treatment plant is located in Ngethu, ~30 km from Nairobi. To better meet existing demand and accommodate projected population growth, the city began construction in 2019 on the first phase of a major water supply expansion project (the Northern Collector), which is expected to be completed by 2022.

4.1. Customer Water Use

The Nairobi simulation model uses information on customer water use from a complete set of 21 months of NCWSC's billing records. The billing data cover the period from August 2012 to May 2014 and contain information on the water use of NCWSC's ~200,000 customer accounts. Customers' average monthly water use over this period is calculated from actual meter readings in the billing data. These calculations define the initial conditions for customer water use in year 0 of the tariff simulation (see Fuente et al., 2016 for additional information on the customer billing data).

Local estimates of the price elasticity of demand for piped water services in Nairobi are not available. Thus, estimates of the price elasticity of demand from the literature are used in the Nairobi model. Residential customers who use above 5 m^3/mo. are assumed to have a price elasticity of demand of −0.2 (Arbués et al., 2003; Dalhuisen et al., 2003; Espey et al., 1997; Nauges & Whittington, 2010). (See Supporting Information S2

Table 1
Summary of the Tariff Alternatives

Tariff alternative	Tariff type	No. of blocks	Lifeline block (m^3/ac./month)
IBT4 (baseline)	IBT	4	10
IBT3	IBT	3	6
IBT2-5	IBT	2	5
IBT2-10	IBT	2	10
UP	Uniform price	n.a.	n.a.
UP + R	Uniform price w/rebate	n.a.	n.a.

Note. IBT, increasing block tariff; UP, uniform price.

for a summary of the parameters used in the simulations.) Recognizing that some portion of a customer's water use may be insensitive to price changes (Dharmaratna & Harris, 2012; Garcia-Valiñas et al., 2014; Gaudin et al., 2001; Martínez-Espiñeira & Nauges, 2004), residential customers who use less than 5 m^3/mo. are assumed to have a price elasticity of 0.

There are relatively few studies on the demand for water among non-residential customers (e.g., commercial, industrial, and bulk customers). However, the literature suggests that non-residential customers in industrialized countries are typically more responsive than residential customers to price changes (Flyr et al., 2019; Garcia & Reynaud, 2004; Renzetti, 1992a, 1992b; Reynaud, 2003; Worthington, 2010). Thus, the price elasticity of demand for non-residential customers is assumed to be −0.3. Equation 1 recognizes the possibility that customer water use may be responsive to changes in income. Information on the baseline income of customers was not available. Thus, changes in income are not included in the Nairobi application.

4.2. Water Production and Wastewater Treatment

In the Nairobi model application, the customer base is assumed to increase by 5% per year. This reflects population growth in the city, which is ~4% per year, and NCWSC's efforts to connect new customers to the network. The fraction of customers with a connection to the piped sewer network is assumed to remain the same as the customer base grows.

The utility's level of non-revenue water (shown in Equation 2) is assumed to be 35%, the most recent figure reported by NCWSC (WASREB, 2019). The level of non-revenue water is assumed to remain constant over the simulation period. The fraction of water delivered to customers with a connection to the piped sewer network that is, returned to the wastewater network (shown in Equation 3) is assumed to be 85%.

4.3. Revenue and Costs

NCWSC's annual revenue is a function of customers' bills in a particular year and the utilities collection efficiency (Equation 4). NCWSC's collection efficiency is assumed to be 95% and remains constant throughout the planning period. This number is consistent with figures reported by Kenya's national water regulator (WASREB, 2019).

The full cost of water and wastewater services includes the O&M and capital costs required to provide these services without running down the capital stock. The full cost of water and wastewater service in Nairobi is assumed to be 0.94 and 0.98 USD/m^3, respectively (see Fuente et al., 2016 for a derivation of these costs).

4.4. Metrics of Tariff Performance

Information on customer socioeconomic status is required to estimate the share of subsidies delivered to low-income customers. Like many utilities, however, NCWSC does not have socioeconomic or demographic information about its customers. In the absence of household-level data on income or socioeconomic status, the GIS location of customer accounts is used to identify which accounts are located in low-income areas. Information on the location and extent of low-income areas in Nairobi was obtained from the MajiData project of Kenya's Ministry of Water and Irrigation and Water Services Trust Fund.

4.5. Tariff Alternatives, Modeling Assumptions, and the Path to Full Cost Recovery

The application of the simulation model to Nairobi compares five tariff alternatives relative to a status quo tariff (Table 1), which is defined as the tariff in place during the period represented by the billing data used in the simulation model. This status quo tariff is an IBT with four usage blocks (IBT4): 0–10, 11–30, 31–60 m^3/mo. and greater than 60 m^3/mo. (Table 1). The five tariff alternatives simulated include an IBT with three usage blocks and a lifeline (first) block of 10 m^3/mo. per account (IBT3); an IBT with two usage blocks and a lifeline (first) block of 5 m^3/mo. per account (IBT2-5); an IBT with two usage blocks and a lifeline (first) block of 10 m^3/mo. per account (IBT2-10); a UP traiff; and a UP traiff with a fixed charge or rebate (UP + R), in which the uniform volumetric price is set equal to the long-run marginal cost of service delivery.

The IBT3 tariff alternative represents the tariff that NCWSC asked the regulator to approve in its most recent tariff review in 2015 (A modified version of the tariff was approved in 2016.) The IBT2-5 and IBT2-10 tariff alternatives provide an opportunity to examine how reducing the number of blocks and the size of the lifeline block affects tariff performance. The UP tariff offers the opportunity to compare how a simple UP tariff performs relative to IBTs. The UP + R tariff alternative examines the performance of a tariff promoted by some economists to simultaneously achieve economic efficiency and cost recovery when marginal costs diverge from average costs (Boland & Whittington, 2000; Coase, 1946; Saunders et al., 1977).

The tariff alternatives are assumed to share several common features. The monthly meter rent is assumed to be constant across all tariff alternatives (0.68 USD/mo. at baseline), and the volumetric price applied to bulk and kiosk customers is assumed to be the same across tariff alternatives for a given level of cost recovery. Except for the UP + R tariff alternative, the sewerage surcharge is assumed to be 75% for all tariffs, the same surcharge currently assessed by NCWSC. Under the UP + R tariff alternative, the volumetric rate for sewer service is set equal to the long-run marginal cost of sewer service. The effect of this assumption is examined via sensitivity analysis and presented in Supporting Information S3.

The volumetric prices for each tariff alternative are set to ensure that each tariff achieves the same level of cost recovery in each of the three cost recovery scenarios considered. For the IBT tariff alternatives, there are many combinations of volumetric prices in each block of the IBT that could achieve a particular level of cost recovery. The volumetric prices for each tariff alternative in our simulation were determined using the following procedure. The price in the lifeline block of the IBT tariff alternatives is the same in each cost recovery scenario. For example, in the status quo cost recovery scenario (36%), the volumetric price in the lifeline block is 0.22 USD/m^3 in all IBT tariff alternatives. This was the volumetric price in place during the period represented in the billing data used in the simulation. In the IBT3 tariff scenario, the prices in the second and third usage blocks are set to ensure the volumetric prices in each block are proportionate to the volumetric prices in each block at the status quo level of cost recovery. The volumetric prices for the upper block in the IBT2-5 and IBT2-10 tariff alternatives are set to meet the target level of cost recovery in each cost recovery scenario.

Under the UP + R tariff alternative, the volumetric price for water and sewerage service is set equal to the long-run marginal cost of service delivery. Information on the long-run marginal cost of service delivery in Nairobi is not available and is thus assumed to be equal to the average O&M and capital costs for water and sewerage service in Nairobi. A positive fixed charge or a rebate is calculated to meet the appropriate cost recovery level. For example, if revenue exceeds the amount necessary to achieve a particular level of cost recovery, customers receive a rebate. Conversely, when revenue is not sufficient to meet a specific level of cost recovery, customers are assessed a positive fixed charge. The fixed charge or rebate is assumed to be applied in a lump sum manner—that is, the fixed charge or rebate allocated to each customer is calculated by dividing the amount needed to achieve the target level of cost recovery by the total number of customer accounts. Due to the lump sum nature of the transfer, the fixed charge or rebate is not included in the calculation of customers' average price. If customers respond to average price and include the fixed charge or rebate in their calculation of average price, the UP + R tariff alternative resembles the UP tariff alternative with the exception of the wastewater surcharge.

For the intermediate (68%) and full (100%) cost recovery scenarios, the volumetric prices in the tariff alternatives are set as described above, but the meter rent and volumetric prices in each tariff alternative are increased by a fixed percent (in real terms) every year to reach the target level of cost recovery in the final year of the planning horizon. This is not the only tariff trajectory NCWSC could take to achieve a particular level of cost recovery. For example, an analyst could opt to leave the meter rent at status quo levels and set the required annual increase in volumetric prices to meet the specified level of cost recovery. Similarly, price

Table 2
Summary Statistics From the Nairobi City Water and Sewer Company Customer Base

	Unit	Residential	Non-residential	Kiosk	Bulk
Water use					
% Total	%	57%	35%	3%	4%
Mean (SD)	m^3/month	31 (194)	347 (1,927)	192 (942)	11,301 (47,609)
Accounts	%	94%	5%	1%	<1%
Total revenue	%	56%	41%	1%	2%

increases could be phased in earlier or later in the planning period, rather than at a constant rate throughout, to meet a particular cost recovery level.

4.6. Data

The NCWSC billing data used in the simulations contain ~200,000 accounts. Residential customers constitute nearly 95% of customer accounts in NCWSC's billing records and account for ~60% of water sold (Table 2). Although non-residential customers represent a small share (5%) of the total number of accounts, they account for 35% of total water use and 40% of total revenue under the baseline tariff. Mean water use among residential customers is 31 m^3/mo. compared to 347 m^3/mo. among non-residential customers. The relatively high mean water use among residential customers reflects the fact that residential customer accounts include single-family homes, households that may share a connection or sell water to neighbors and tenants, and multi-unit dwellings that share a meter. Over 70% of customer accounts receive both water and sewer service. Under the baseline tariff, residential customers with only water service pay an average price of 0.57 USD/m^3. Residential customers with both water and wastewater service pay an average of 0.80 USD/m^3 for both services, which reflects the 75% surcharge NCWSC assesses for wastewater service.

5. Results

Under the status quo tariff, NCWSC achieves a simulated 36% level of cost recovery in Year 5 of the planning period and the amount of water sold increases from 9.7 million to 12.4 million m^3/mo. of water per month. Revenue grows from 6.6 million USD/mo. in year 0–8.5 million USD/mo. in year 5, while costs increase from 18.4 million to 23.5 million USD/month (Figure 2). As a result, the subsidy delivered through the tariff increases throughout the simulation period, and NCWSC's average monthly financial loss increases from 11.8 million USD in year 0–15 million USD in year 5. Under the status quo tariff, residential customers in low-income areas receive 13% of the total subsidy delivered through the tariff, which is proportional to their share of water use but less than the share of total accounts they represent (20%). Thus, the subsidy delivered through status quo tariff is regressive.

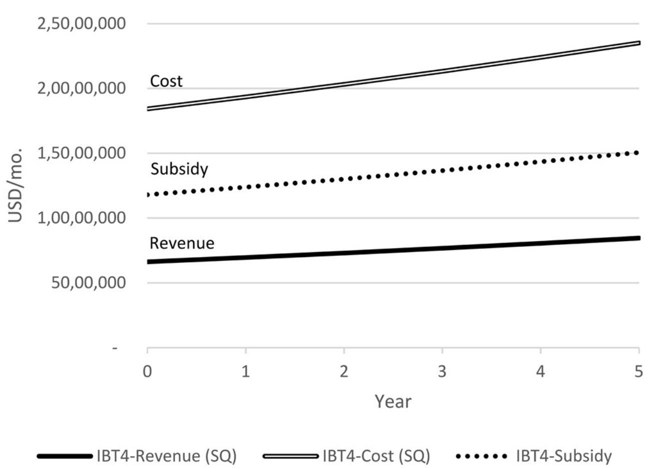

Figure 2. Annual average monthly revenue, cost, and subsidy under the baseline tariff at status quo cost recovery.

5.1. Results for Different Tariff Alternative Assuming Status Quo Cost Recovery (36%)

When implementing tariff reforms, a utility may opt to change the tariff structure and maintain its current level of cost recovery. Table 3 summarizes the fixed charge and volumetric prices under each tariff alternative that allow the utility to maintain the status quo level of cost recovery. Table 4 summarizes the performance of the tariff alternatives (Figures are reported on an average monthly basis, rather than an annual basis.) With the exception of the UP + R tariff alternative, the alternative tariffs result in 0%–2% reductions in water use relative to the baseline tariff. Customers face higher prices under the UP + R tariff, which produces a 28% reduction in water use relative to the baseline tariff. This simulated

Table 3
Summary of Tariff Alternatives Simulated Under Base Case Assumptions (t = 5)

		Cost recovery scenario		
		36%	68%	100%
Common components		*t* = 5	*t* = 5	*t* = 5
Meter rent	USD/month	0.68	1.31	1.95
Sewer surcharge[a]	%	75%	75%	75%
Annual price increase	%	0%	14%	24%
4-Block IBT (IBT4—status quo)				
0–10	USD/m^3	0.22	0.22	0.22
11–30	USD/m^3	0.45	0.45	0.45
31–60	USD/m^3	0.5	0.5	0.5
>60	USD/m^3	0.63	0.63	0.63
Kiosk	USD/m^3	0.17	0.17	0.17
Bulk	USD/m^3	0.30	0.30	0.30
3-Block IBT (IBT3)				
Block 1 upper bound	m^3/month	6	6	6
Block 2 upper bound	m^3/month	60	60	60
P Block 1	USD/m^3	0.22	0.43	0.64
P Block 2	USD/m^3	0.37	0.72	1.07
P Block 3	USD/m^3	0.60	1.15	1.72
Kiosk	USD/m^3	0.17	0.33	0.49
Bulk	USD/m^3	0.30	0.58	0.86
2-Block IBT: 10 m^3/month block 1 (IBT2-10)				
Size of lifeline block	m^3/month	10	10	10
Price in lifeline block	USD/m^3	0.22	0.42	0.63
Price in UB	USD/m^3	0.51	0.96	1.41
Kiosk	USD/m^3	0.17	0.33	0.49
Bulk	USD/m^3	0.30	0.58	0.86
2-Block IBT: 5 m^3/month block 1 (IBT2-5)				
Size of lifeline block	m^3/month	5	5	5
Price in lifeline block	USD/m^3	0.22	0.42	0.63
Price in upper block	USD/m^3	0.48	0.90	1.34
Kiosk	USD/m^3	0.17	0.33	0.49
Bulk	USD/m^3	0.30	0.58	0.86
Uniform price (UP)				
Volumetric price	USD/m^3	0.47	0.90	1.32
Uniform price w/rebate (UP + R)				
Volumetric price (water only)	USD/m^3	0.94	0.94	0.94
Volumetric price (water + wastewater)	USD/m^3	1.93	1.93	1.93
Volumetric price (wastewater only)	USD/m^3	0.98	0.98	0.98
Rebate (+)/fixed chard (−)	USD/ac/month	27.00	5.00	−17.00

Note. IBT, increasing block tariff; UP, uniform price.
[a]Except the UP + R tariff.

Table 4
Summary of Status Quo Cost Recovery Simulation Results

		Status quo cost recovery (36%)					
Performance metric	Units	Status quo	IBT3	IBT2-10	IBT2-5	UP	UP + R
Water use ($t = 5$)	m^3/month	12,383,647	12,380,255	12,337,642	12,301,990	12,088,538	8,920,168
% Change	%	n.a.	0%	0%	−1%	−2%	−28%
Subsidy (NPV[a])	USD/month	−51,421,219	−51,619,459	−51,315,742	−50,901,736	−50,217,540	−40,152,355
% Change	%	n.a.	0%	0%	−1%	−2%	−22%
Subsidy incidence ($t = 5$)	%	13%	13%	13%	13%	12%	20%
Change in customer welfare (NPV[a])	USD/month	22,652,996	23,218,485	23,095,269	23,079,387	23,755,317	25,094,628
% Status quo[b]	%	n.a.	2%	2%	2%	5%	11%
Net loss (NPV[a])	USD/month	−28,768,223	−28,400,974	−28,220,472	−27,822,349	−26,462,223	−15,057,727
% Status quo[b]	%	n.a.	−1%	−2%	−3%	−8%	−48%
		Intermediate cost recovery (68%)					
Performance metric	Units	Status quo	IBT3	IBT2-10	IBT2-5	UP	UP + R
Water use ($t = 5$)	m^3/month	12,383,647	10,853,253	10,815,253	10,820,741	10,641,138	8,917,517
% Change	%	n.a.	−12%	−13%	−13%	−14%	−28%
Subsidy (NPV[a])	USD/month	−51,421,219	−36,191,416	−35,628,057	−35,904,667	−35,733,893	−30,337,416
% Change	%	n.a.	−30%	−31%	−30%	−31%	−41%
Subsidy incidence ($t = 5$)	%	13%	15%	14%	13%	12%	20%
Change in customer welfare (NPV[a])	USD/month	22,652,996	12,145,786	11,823,479	12,365,880	13,491,286	15,285,951
% Status quo[b]	%	n.a.	−46%	−48%	−45%	−40%	−33%
Net loss (NPV[a])	USD/month	−28,768,223	−24,045,630	−23,804,578	−23,538,787	−22,242,607	−15,051,465
% Status quo[b]	%	n.a.	−16%	−17%	−18%	−23%	−48%
		Full cost recovery (100%)					
Performance metric	Units	Status quo	IBT3	IBT2-10	IBT2-5	UP	UP + R
Water use ($t = 5$)	m^3/month	12,383,647	9,898,537	9,918,740	9,896,447	9,753,071	8,915,385
% Change	%	n.a.	−20%	−20%	−20%	−21%	−28%
Subsidy (NPV[a])	USD/month	−51,421,219	−24,589,845	−24,690,292	−24,532,503	−24,981,270	−21,788,999
% Change	%	n.a.	−52%	−52%	−52%	−51%	−58%
Subsidy incidence ($t = 5$)	%	13%	n.a.	n.a.	n.a.	n.a.	n.a.
Change in customer welfare (NPV[a])	USD/month	22,652,996	3,079,043	3,292,752	3,551,124	5,211,214	6,741,784
% Status quo[b]	%	n.a.	−86%	−85%	−84%	−77%	−70%
Net loss (NPV[a])	USD/month	−28,768,223	−21,510,802	−21,397,540	−20,981,379	−19,770,056	−15,047,216
% Status quo[b]	%	n.a.	−25%	−26%	−27%	−31%	−48%

Note. IBT, increasing block tariff; UP, uniform price.
[a]All NPV calculations use a 5% discount rate. [b]Percent change measured relative to customer welfare and net loss under the status quo tariff relative to efficient prices.

reduction in water use is driven by the fact that the volumetric price for water service under the UP + R tariff is four times larger than the volumetric price in the first block of the baseline tariff and one and half times larger than the price in the highest block of the baseline tariff (Table 3). The magnitude of the simulated reduction in water use under the UP + R tariff must be viewed with caution because the elasticities used in the simulation model represent customers' response to small changes in price.

All customers are subsidized at status quo levels of cost recovery. Under the baseline tariff, the IBT, and the UP tariff alternatives, customers are subsidized via prices that do not reflect the full cost of service delivery. Under the UP + R, customers are subsidized via a rebate. At the status quo level of cost recovery, customers would receive a rebate of 27 USD/month under the UP + R tariff alternative. Overall, the magnitude of the subsidy delivered through the tariff is quite large, ~150% of the total revenue received by the utility. The IBT and UP tariff alternatives result in 0%–2% reductions in the net present value of subsidies delivered through the tariff over the simulation period. In contrast, the UP + R tariff alternative results in a 22% reduction in the net present value of the subsidies delivered through the tariff, which reflects the simulated decrease in water use under this tariff.

The IBT and UP tariff alternatives perform similarly to the baseline tariff with respect to subsidy incidence, delivering 12%–13% of the total subsidies to residential customers in low-income areas. This reflects the fact that water use and income are not highly correlated in Nairobi (Fuente et al., 2016). Only the UP + R shows a marked improvement in subsidy incidence relative to the baseline tariff, delivering 20% of the subsidies to customers in low-income areas. This improvement in subsidy targeting occurs because all accounts receive the same rebate under the UP + R tariff. While the UP + R tariff performs better than the other tariff alternatives with respect to subsidy incidence, subsidies remain poorly targeted because nearly 80% of the subsidies do not reach low-income customers. This finding is consistent with other research showing that a water tariff is an ineffective means of delivering subsidies to low-income customers (Fuente et al., 2016; Komives et al., 2005; Nauges & Whittington, 2017; Whittington et al., 2015) (Though the magnitude of the subsidy delivered through the tariff changes in subsequent cost recovery scenarios, the share of subsidies reaching low-income customers remains constant for each tariff alternative. Thus, it is not discussed further below.)

Average prices are far below the long-run marginal cost of service delivery at the status quo level of cost recovery. At such low prices, customers enjoy considerable welfare gains relative to prices that reflect the full cost of service delivery. Under the baseline tariff, the consumer surplus for residential customers relative to efficient prices is estimated to be ~6.6 million USD/month in 5 years of the simulation. Under the three IBT tariff alternatives, customers experience a small (2%) increase in welfare relative to the baseline tariff. Customers experience larger welfare gains under the UP (5%) and UP + R (11%) tariff alternatives. Though customers experience a reduction in welfare associated with a higher volumetric price and reduced water use under the UP + R tariff alternative, this loss in welfare is offset by the rebate provided under this tariff.

All of the tariff alternatives result in net losses to society at status quo levels of cost recovery because the magnitude of the subsidy delivered through the tariff is larger than the welfare gains customers experience from the low volumetric prices at this level of cost recovery. However, all of the tariff alternatives considered reduce net losses to society relative to the baseline tariff. The IBT tariff alternatives reduce net losses by 1%–3%, and the UP tariff alternative produces a simulated 8% reduction in losses. Under the UP + R tariff alternative, the combination of decreased overall subsidy and increase in consumer surplus yields a 48% decrease in losses relative to the baseline tariff.

5.2. Results for Different Tariff Alternative Assuming Intermediate (68%) Cost Recovery

At status quo levels of cost recovery, customers experience considerable welfare gains relative to efficient pricing. However, this results in substantial losses to society, highlighting potential gains that can be achieved by getting utilities on the path to cost recovery. The intermediate level of cost recovery (68%) scenario represents the mid-point between status quo and full cost recovery. To reach the intermediate level of cost recovery by year 5 of the planning period, the simulations indicate NCWSC would need to increases prices 14% annually (Table 3). With these price increases, meter rent increases from 0.68 to 1.31 USD/month. Prices in the lifeline block of the IBT tariff alternatives increase from 0.22 to 0.42, and the volumetric price in the UP tariff alternative increases from 0.47 to 0.90. At the intermediate level of cost recovery, the rebate provided to customers in the final year of the simulation under the UP + R tariff decreases from 27 to 5 USD/month per account.

At intermediate cost recovery, the performance of the tariff alternatives relative to one another is similar to what was observed at status quo levels of cost recovery (Table 4). As prices increase to improve cost recovery, the IBT and UP tariff alternatives produce similar decreases in the overall water use (12%–14%) relative to the baseline tariff. The UP + R tariff produces the same simulated reduction (28%) in water use as the status quo level of cost recovery because the volumetric price does not change under the UP + R tariff.

The increase in prices required to meet the intermediate level cost recovery, and the simulated decrease in water use that accompanies this increase, result in a reduction in customer welfare relative to the dynamic baseline (i.e., the baseline tariff at status quo levels of cost recovery). In particular, under the IBT tariff alternatives, customers experience nearly 50% reductions in the net present value in welfare relative to the dynamic baseline. Customers are slightly better off under the UP tariff alternative, which results in a 40% reduction in customer welfare over the planning period. The UP + R tariff alternative produces the smallest reduction (33%) in welfare for customers. This smaller reduction in welfare occurs because the welfare losses associated with decreased water use are partially offset by the rebate they receive under the UP + R tariff at the intermediate level of cost recovery.

Although customers experience welfare losses as prices rise to improve cost recovery, subsidies are substantially reduced relative to the dynamic baseline. The IBT and UP tariff alternatives result in a 30%–31% reduction in the net present value of subsidies over the planning period. As observed at status quo levels of cost recovery, the UP + R tariff alternative results in the largest (41%) reduction in subsidies.

On balance, the decrease in customer welfare and reduction in subsidies at an intermediate level of cost recovery results in considerable reductions in the net losses to society. In particular, the IBT tariff alternatives result in a 16%–18% reduction in net losses. The UP and UP + R tariff alternatives yield 23% and 48% reductions in losses, respectively.

5.3. Results for Different Tariff Alternatives Assuming Full (100%) Cost Recovery

Though customers experience welfare gains relative to efficient pricing at intermediate levels of cost recovery, considerable subsidies continue to be required when the utility does not generate sufficient funds to cover the cost of providing water and sanitation services. The full cost recovery scenario simulates a situation in which NCWSC commits to an aggressive effort to achieve full cost recovery by the end of the planning period. To reach full cost recovery by the end of the simulation period, the utility would need to increase prices 24% annually (Table 3). Under these price increases, the price in the lifeline block of the IBT tariff alternatives would increase from 0.22 to 0.63 USD/m^3. Similarly, the volumetric price in the UP tariff increases from 0.47 to 1.32 USD/m^3, which is higher than the estimated long-run marginal cost of water supply in Nairobi. This reflects the fact that NCWSC is assumed to have a constant, relatively high level of NRW throughout the simulation period and does not operate at 100% collection efficiency. At the status quo and intermediate levels of cost recovery, customers receive a rebate under the UP + R tariff. However, to reach full cost recovery, customers must be assessed a positive fixed charge. In the final year of the simulation, customers face a fixed charge of 17 USD/month.

As shown in Table 4, there is a similar pattern in the relative performance of the tariff alternatives as in the status quo and intermediate levels of cost recovery. The IBT and UP tariff alternatives perform similarly to one another, and the UP + R tariff outperforms the other tariff alternatives across each of the metrics of tariff performance considered.

Although the tariff alternatives exhibit similar relative performance as in the status quo and intermediate levels of cost recovery, the full cost recovery scenario highlights the implications of the utility moving toward financial self-sufficiency. At full cost recovery, the IBT and UP tariff alternatives result in a 20%–21% reduction in aggregate water use in year 5 of the simulation relative to the dynamic baseline. As in the status quo and intermediate cost recovery scenarios, the UP + R yields a 28% simulated reduction in water use compared to water use in the dynamic baseline in 5 year.

In the full cost recovery scenario, customers continue to receive subsidies throughout the first four years of the planning period as the utility increases prices annually to reach full cost recovery in the final year of the simulation. However, all of the tariff alternatives result in a 50% or larger reduction in the net present value of the subsidies delivered through the tariff over the simulation period. This decrease in the net present value of subsidies, and the price increases required to achieve full cost recovery, are accompanied by substantial reductions in customer welfare (Table 4) relative to the dynamic baseline across all tariff alternatives. However, as observed above, the UP and UP + R yield the smallest reductions in consumer welfare.

Despite the welfare losses customers experience as the utility moves along the path to full cost recovery, the transition to full cost recovery under all tariff alternatives yields considerable reductions in net losses. In particular, the IBT tariff alternatives yield 25%–27% reductions in net losses relative to the baseline tariff at the status quo level of cost recovery. The UP tariff performs slightly better, generating a 31% reduction in net losses. The UP + R tariff reduces net losses by nearly 50%.

5.4. Model Extensions

The main simulation results above reflect the assumption that customers respond to average, rather than marginal, prices. The results also reflect the assumption that the UP + R tariff alternative has a 100% surcharge for wastewater service, rather than the 75% applied in the other tariff alternatives. Supporting Information S3 presents the results of the simulations when the surcharge for wastewater service is assumed to be 100% for all tariff alternatives. Supporting Information S4 presents the results of the simulations when customers are assumed to respond to marginal prices.

6. Discussion and Conclusion

The simulations presented in this study provide several insights concerning the performance of alternative tariff structures in Nairobi and for the design and evaluation of water and sanitation tariffs in low- and middle-income countries more broadly. Overall, the simulations show that the IBT tariff alternatives considered perform similar to one another with respect to the six performance metrics considered. These results support the findings of Nauges and Whittington (2017), who examine the performance of nine IBTs relative to economic efficiency and subsidy incidence. These results suggest that policymakers and tariff consultants may be misdirecting their efforts by focusing too narrowly on determining the appropriate size of the lifeline block, the number of blocks in an IBT, and the relative prices between blocks.

Economists have long recommended the UP + R tariff to promote economic efficiency and achieve cost recovery (Boland & Whittington, 2000; Coase, 1946; Saunders et al., 1977). The simulations presented in this paper find that the UP + R tariff outperformed the IBT and UP tariff alternatives considered with respect to not only economic efficiency but also subsidy incidence, the welfare effects on customers, and water conservation at all levels of cost recovery. This finding holds regardless of whether customers respond to average or marginal price.

Water utility professionals and regulators do not place sufficient weight on economic efficiency when designing and approving water tariffs. The simulations presented in this study suggest that tariffs that promote economic efficiency perform very well in terms of other policy-relevant metrics used to assess tariff performance. With the increasing pressure of water scarcity and the need to allocate scarce public resources to promote economic development, the primary objective of utility professionals and regulators in the design of water tariffs should be economic efficiency.

Utilities may find the UP + R tariff administratively or politically difficult to implement. The simulations presented here suggest that a simple tariff with a uniform volumetric price (i.e., the UP tariff) performs equally well as, or better than, the IBT tariff alternatives considered across all of the performance metrics evaluated. While a UP tariff does not have the efficiency-promoting properties of a UP + R tariff, a UP tariff is easy for utilities to administer, easy for customers to understand, and sends a clearer signal to customers about the cost of delivering water and sanitation services than IBTs. The performance of the UP + R and UP tariff alternatives call into question the widespread use of IBTs in low- and middle-income countries and the perception among utility managers, regulators, and tariff consultants that IBTs represent best practice for pricing water and sanitation services in these contexts.

Utilities in low- and middle-income countries often implement tariffs that do not cover the cost of providing water and sanitation services. Figure 3 compares the average monthly revenue and cost in each year of the simulation for the baseline tariff to the UP tariff at three cost recovery levels. Conditions do not remain the same when utilities fail to improve cost recovery; subsidies delivered through the tariff rise over time as

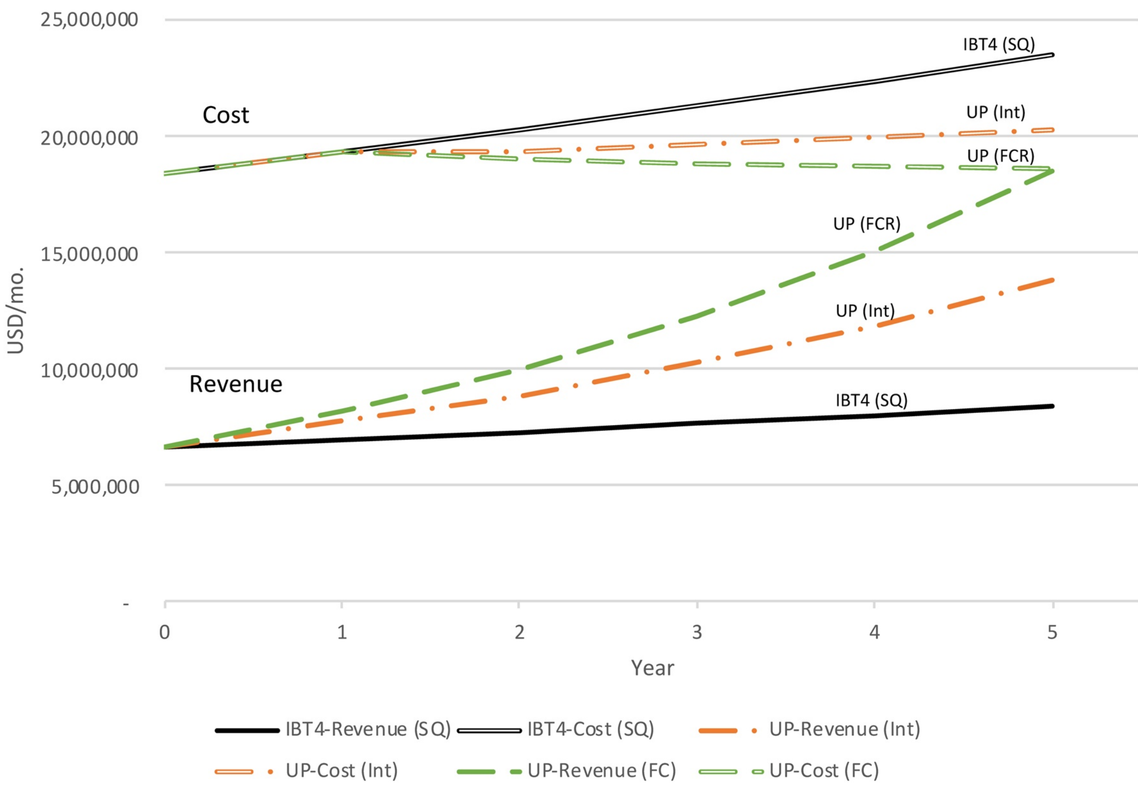

Figure 3. Annual average monthly revenue and cost under the baseline (IBT4) and uniform price (UP) tariff at status quo (SQ) cost recovery, intermediate (Int), and full cost recovery (FCR).

population grows, placing additional financial burdens on the utility or higher levels of government and may result in the utility deferring maintenance and running down its capital stock. Improving cost recovery can promote more efficient water use, improve the financial viability of utilities, and deliver net social benefits. While there are clear benefits associated with getting utilities on the path to full cost recovery, existing customers will experience welfare losses as prices rise from the low, subsidized levels they currently face. The path to full cost recovery will thus be politically difficult for many utilities. Utility managers and policymakers must therefore ensure that customers understand—and experience—the benefits of improved services that a financially sustainable utility can deliver.

While the simulations presented in this study have several implications for the pricing of water and sanitation services in low- and middle-income countries, some caveats warrant mention, as well as areas for future work. First, the simulations are dependent upon water use data from a particular location at a specific point in time. While conditions in Nairobi reflect those in many large, fast-growing cities in low- and middle-income countries, tariff design requires careful consideration of and attention to local conditions.

Second, these simulations used an illustrative set of tariffs to examine the relative performance of alternative tariff structures. Several factors are held constant across the tariff alternatives, including the magnitude of the meter rent, the price in the lifeline block for block tariffs, the sewerage surcharge, and pricing for kiosks and bulk customers. There is scope for additional work to examine how each of these factors affects tariff performance.

Third, the trade-off between the change in customer welfare and reduced subsidies associated with improved cost recovery is not a complete measure of the welfare effects associated with the tariff reform programs considered. The analysis does not include the scarcity value of water nor the economic distortion related to financing the subsidies delivered through the tariff. Thus, tariff reform programs that reduce water use and reduce subsidies are likely to have larger economic benefits than these simulations suggest.

Finally, when setting water and sanitation tariffs, policymakers will have to pay careful attention to the political economy of tariff reform, including local perceptions of fairness and equity, the capacity of utilities to implement complex tariffs, and the incentives that tariffs create for both utilities and customers. These simulations show that existing customers will bear the direct losses of the reform program in terms of increased water bills. However, customers will gain in terms of improved water and sanitation services and reduced taxes and inefficiencies elsewhere in the economy. Policymakers have yet to find a way to make this deal structure attractive to households in low- and middle-income countries. That is, the task before them.

Data Availability Statement

Nairobi City Water and Sewerage Company provided data to researchers under a cooperative Memorandum of Understanding. Because the billing data contain sensitive private information, the agreement states that researchers may not share the data set with anyone not party to the agreement. Nairobi City Water and Sewerage Company has a process by which researchers can seek access to data for research purposes.

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