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# Pipes, Taps and Vendors: An Integrated Water Management Approach

by

## GEORG MERAN, MARKUS SIEHLOW, and CHRISTIAN VON HIRSCHHAUSEN\*

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This paper applies a microeconomic-based stylized model to identify the optimal modal split of water supply infrastructure in regions of the Global South against the background of the Sustainable Development Goal (SDG) No. 6. We assume a linear city, with some plausible assumptions on income and willingness-to-pay, and then calculate the optimal tap density, leading in turn to an optimal modal split between piped and unconnected water consumption. From an economic perspective, not all water users need to be connected to a centralized, pipeline infrastructure, and the non-connected households should be served by non-mobile or mobile vendors. The analysis is firstly made for the case of totally inelastic demand functions for simplification reasons and afterwards the analysis becomes more complicated and realistic by addressing elastic demand functions which are based on a simplified version of the Stone-Geary utility function. In terms of policy implications, the paper suggests a role for decentral, offgrid solutions to generalized water supply, with a certain role for water vendors.

JEL: C31 (Multiple or Simultaneous Equation Models - Multiple Variables - Spatial Models); R12 (Size and Spatial Distributions of Regional Economic Activity); O17 (Formal and Informal Sectors - Shadow Economy); Q25 (Water)

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## 1 Introduction

In 2010, the human rights to water were established, which ensure the universal access to safe, clean and affordable drinking water (UN, 2010). Despite the progress that has been made on the Sustainable Development Goals in recent years, 785 million people remained without even basic drinking water services in 2017. Nearly half of these people live in Sub-Saharan Africa, while about one-fifth live in South Asia (UN, 2019). The Millenium Development Goals were followed by the Sustainable Development Goals (SDGs) which were adopted by the UN General Assembly on September 25th 2015 (UNDP, 2015). The target No. 6.1 of the SDGs postulates the "universal and equitable access to safe and affordable drinking water" for all humans by 2030 (UN, 2015). For reaching this universal and challenging goal, the informal economy may play an important role.

In squatter settlements, shanytowns, slums and many rural areas, the informal economy provides the poor, which are not served by the respective municipality, with an alternative for urban services, such as water, sanitation, transportation and trash-collection (Soto (1989); Whittington et al. (1991); Njiru (2004); Roy (2005); Opryszko et al. (2009); Ishaku et al. (2010); Olajuyigbe et al. (2012); Onyenechere et al. (2012); Ayalew et al. (2014); Fox (2014); Mehta et al. (2014); Wutich et al. (2016)). Therefore, the informal economy, e.g. informal water supply, bridges the gap between the sparse urban services delivered by municipalities and the real needs (Portes and Haller (2010); Wutich et al. (2016)).

Specifically, water vendors play an important role in the informal water supply, because they serve those people with water that are not connected to the public water supply. Zaroff and Okun (1984), Lovei and Whittington (1993), Snell and Mundial (1998), Njiru (2004), Kjellén and McGranahan (2006), Sansom and Bos (2008), Opryszko et al. (2009), Wutich et al. (2014) and Wutich et al. (2016) focus on the description of the various operation modes of water vendors from different perspectives. Water vendors usually deliver water to the home of the poor by using hand-carried donkey carts or trucks (mobile vendors) or they operate reselling stations from where consumers can collect the water (water kiosks).

Despite the essential importance of the informal water supply, there are also some disadvantages related with water vending compared to the public water supply. For instance, water from vending may be the reason for water-related diseases, because of the low quality of vended water compared to municipal water (Whittington et al. (1989); Zaroff and Okun (1984); Kjellén and McGranahan (2006); Olajuyigbe et al. (2012); Hutin et al. (2003)).<sup>1</sup> Furthermore, vended water is often more expensive than municipal water from the public water supply (Crane (1994); Snell and Mundial (1998); Collignon (1999); Kjellén (2000); Solo (2003); Kariuki and Schwartz (2005); Opryszko et al. (2009); Ishaku et al. (2010); Bayliss and Tukai (2011); Olajuyigbe

<sup>&</sup>lt;sup>1</sup>However, a few studies, such as Collignon and Vézina (2000) or Solo (1999), state that vended water is comparable or better than water from other local sources.

et al. (2012); Dauda et al. (2015); Rahaman and Ahmed (2016)).<sup>2</sup> According to Kjellén and McGranahan (2006), these high prices may result from the abuse of market power by the water vendors. However, other studies, like Whittington et al. (1991), Solo (1999), Collignon and Vézina (2000), Kariuki and Schwartz (2005) and Opryszko et al. (2009), justify a higher price level for vended water than for municipal water due to higher specific investment and operation costs. The investment, operation and unit costs for selected water vendors in selected regions are presented for instance by Lovei and Whittington (1993), Collignon and Vézina (2000), Al-Hamdi and Alaerts (2000), Kayaga and Franceys (2007) and Keener et al. (2009). Studies such as Al-Hamdi and Alaerts (2000) compare the unit costs of vended water with those of municipal water, which illustrates the cost advantage of the public water supply. Of course, the unit cost level depends not only on the technology used and the operation mode, but also on the amount of supply. Nauges and Van den Berg (2008) analyze the size of economies of scale and scope for the public water supply in selected regions. Beside the accounting costs, there are opportunity costs, which result from, for instance, hauling activities. Whittington et al. (1990) estimate such hauling costs for various scenarios.

This paper contributes to the discussion by identifying the main drivers of what we call the "optimal modal split" between water supply through larger networks, and the self-provisioning of water through vendors or – most often for poverty reasons – an undersupply of clean water after all. The general opinion is that connected water supply should be the ultimate objective of a developed system, whereas there may be good economic reasons to rely on a certain degree of unconnected water supply for spatially scattered users, in particular the sub-urban poor. Therefore, similar to argumentation put forward by McGranahan et al. (2006), Chaudhury (2013) as well as Wutich et al. (2016), water vending is a necessary path to achieve the ambitious political goals formulated by the human rights for water and the SDG No. 6.

The paper applies a microeconomic-based stylized model to derive the potential impact of external and internal factors, such as cost structures, on the development of the system. We assume a linear city, with some plausible assumptions on income and willingness-to-pay, and then calculate the optimal tap density, leading in turn to an optimal modal split between piped and unconnected water consumption.

The paper is structured in the following way: The next section sets the scene, by discussing the main levers of water supply in a developing context, and by deriving a model setting that represents a broad range of water supply issues identified by the literature. Section 3 then provides the basic model of the "linear city" of water supply, and the main assumptions on costs, willingness-to-pay, and other variables. In section 3.2 we present the derivation of the optimal modal split, by maximizing the social benefit of connected and unconnected water supply. Therefore, the service parameters such as the connected households, the distance between the taps, and the action of the vendors are calculated. We also discuss potential deviations from this

 $<sup>^{2}</sup>$ According to Wutich et al. (2016), the costs for vended water range from 4 to 30 times the cost of municipal water.

optimum, when taking into account "non-economic" aspects such as the human right to water. Whereas in Section 3 we assume inelastic demand, we introduce elastic demand in Section 4, based on a simplified version of a Stone-Geary utility function. In Section 5, we perform some numerical analysis based on plausible assumptions. This analysis also identifies key parameters that determine the tap density. Section 6 concludes and derives some policy implications.

## 2 Institutional and Technical Setting

In addition to the municipal water supply, water vendors play an important role in the water supply system especially for those households which are not connected to the municipal water supply. In this section, we set the scene for the analysis of water supply by discussing the basic elements of a model of optimal modal split between centralized, municipal, grid-based supply by a water utility, the supply by mobile water vendors and the self-provisioning, e.g. through boreholes or water kiosks (see Figure (2.1)). Assume a water utility in some urban center in an emerging or developing country, which provides municipal water to its fairly wealthy constituency in the core of the city (left hand side). This water utility can operate as a non-profit, welfare-oriented actor pursuing goals of integrated water resource management (IWRM), or it can be considered as a profit-maximizing agent. Different forms of organization are possible for the municipal water supply. It can be structured by different organizational models with respect to ownership (private, community-based, etc.) and financing (Kariuki and Schwartz, 2005). Depending on the goal of the municipal water supplier, the utility will strive to provide access to the periurban region as long as it serves its goals.<sup>3</sup>

Located at the right side of the figure, residual households which are not connected to the municipal water supply grid have two options: Either to supply themselves with water from wells, boreholes, surface water bodies etc. where access is free, or to purchase water from water vendors. In areas with inadequate sanitation, this may run the risk of diseases from unpure water. However, if water from the freely accessible boreholes, wells, and surface water bodies is clean and safe, self-supply can be seen as an adequate option.

With respect to vendors, it is possible to distinct between the non-mobile and mobile vendors (Kariuki and Schwartz, 2005). The non-mobile vendors can be publicowned standpipes or taps, privately-owned water kiosks or households with an access to the public water supply which resell the municipal water to the consumers with no access to public water supply (informal standpipe). Mobile vendors procure water at a connected tap, and transport it to more remote areas, most often by handor motorcycle-drawn carts, tankers etc. These water vendors can be modeled in

<sup>&</sup>lt;sup>3</sup>If the municipal water supplier is welfare-oriented, the utility will provide access to the periurban region as long as it makes sense from a social welfare perspective. However if the municipal supplier is profit-oriented, it will provide access in the periurban region as long as it can increase its profits.

different ways: they may be in competition with each other, thus providing water at incremental costs, or they are cartelized or monopolistic; in that case, they may exploit the consumers' willingness-to-pay, and perhaps exclude some people from satisfying their basic water needs.<sup>4</sup>



Figure 2.1: Decentralized water sector in urban and peri-urban areas

## 3 The Model

Our model is based on an analytical framework often found in spatial economics, i.e. the linear city. This approach dates back to the work by Hotelling (1929) who dealt with spatial competition. It has been been further developed by Salop (1979) who analyzed incomplete competition in the space with the help of a circular city. Meanwhile it is an integral part of industrial economics, see e.g. Tirole (1988) as well as Fujita et al. (1999).

It is assumed that all water customers are arranged along a line, the linear city (see Figure Figure (2.1)). The customer density is constant along the line (identical distribution). All customers demand just one unit of water, say 1  $m^3$  per month. The willingness to pay V(s) = a - bs is decreasing everywhere along the linear city from left to right, i.e. from the urban to the peri-urban areas: The urban population (left side) is relatively rich, followed by the middle class and finally the poor, which settle on the right side. This spatial model structure is useful to combine economic and spatial analysis, and to determine the geography of water supply. Figure (3.1) shows the spatial structure, i.e. the structure of the various modes of water supply,

<sup>&</sup>lt;sup>4</sup>The issue of market structure and price formation is dealt with in a companion paper.

which is what we call the modal split. In this respect we follow a discrete choice approach as applied by Whittington et al. (1990) where only the household decision for the supply mode is modeled. The price elasticity of demand function of water is not taken into account until Section 4.





The water utility is located to the left.<sup>5</sup> It conveys water to the connected households up to  $\hat{s}$ . As mentioned above, we assume that household's income decreases from left to right, only high and middle income households are connected to a water pipe. The poor are located on the right side of the figure. Between  $\hat{s}$  and  $\tilde{s}$  the water supply is based on accessible taps and the service of water vendors. Both, customers in the vicinity of the taps and water vendors can receive water from the water kiosks placed in this interval. In the immediate vicinity of the kiosk, the household members fetch their own water (interval  $\hat{s}$  and  $\hat{s}$ ). If they live further away, they are supplied by vendors (interval  $\hat{s}$  and  $\tilde{s}$ ). Subsequently, we will derive the exact length of the unconnected water supply, i.e. we will derive where the segments for water collecting by customers and the segments of water supply by vendors are located. The stretch between  $\tilde{s}$  and  $\bar{s}$  represents the very outskirt of the linear city that may not be supplied at all. In this segment we have a supply situation that contradicts the UN directives and we have to ask ourselves how to close this gap.

The simple model does not include other sources, e.g. water wells, boreholes or the collection of surface water. Also, we do not consider illegal tapping. However, despite the simplicity we can derive some insightful results. Let us proceed by defining the costs of the various actors of the linear city.

<sup>&</sup>lt;sup>5</sup>The model of the linear city can be extended arbitrarily. The waterworks can also be located in the centre of the city with a right and left water pipe. Star-shaped distribution branches can also be arranged in all directions.

#### 3.1 Cost structures

Roughly, the water utility has two cost components. The water supply costs depend on the total amount of water provided and the capacity of the transportation and distribution system. From empirical studies we know that the cost structure of water utilities varies considerably, as indicated by different estimated measures of density, scale and scope economies <sup>6</sup>. We assume that the water utility displays (weak) diseconomies of scale. Increasing the volume of water produced, the number of connections to be served, and the network length by a factor  $\lambda > 1$  leads to an increase in costs greater than  $\lambda$ . This can be attributed to the assumption that further down along the city's geographical line the expansion of household connection gets more expensive due to deficiencies of the complementary infrastructure of city areas where people with lower income live (streets, house foundations, etc.).

Hence, total costs of total water supply and household connections are specified as

$$C_{WU} = m\tilde{s} + k\hat{s} + \frac{\kappa}{2}\hat{s}^2 \tag{3.1}$$

where  $m\tilde{s}$  are the costs of water treatment. The parameters k and  $\kappa$  determine the costs of household connections along the city line displaying increasing incremental costs. These costs include the costs of the water mains and the branch line connections. Note that the sole dependence of the cost function on the area served, i.e. the stretch s, is the result of the assumption that all customers along the line consume the same amount of water, say, 1  $m^3$ . Collecting water is rather cumbersome. Often it is the women who bring water with the help of canisters. The costs relate not only to the purchase price, but also to the lost time<sup>7</sup>, which is missing for other productive activities. These opportunity costs have to be taken into account in the supply cost function.

Figure (3.2) shows the cost structure of the line segment between  $\hat{s}$  and  $\tilde{s}$ . In this area, customers collect water from kiosks or are supplied by vendors. Take, for example, the location of tap 2. A customer<sup>8</sup> located at point A' incurs costs A to collect 1  $m^3$  of water from tap 2. Mathematically, these costs are

$$D = \delta_2 + \delta_1 s$$
, where  $s = A'$  (3.2)

 $\delta_2$  are the time costs of filling water into a canister of a capacity of, say, 1  $m^3$ . These costs do not depend on the distance between the tap and the household.  $\delta_1$  are monetarized time costs to haul  $1m^3$ , say, s = 100 meters. If the household is located at A' hauling costs are  $\delta_1 A'$ . Hence, total collecting costs of all customers in the vicinity of taps up to A' are:

$$D_F = \delta_2 \int_0^{A'} ds + \delta_1 \int_0^{A'} s ds = \delta_2 A' + \frac{\delta_1}{2} (A')^2$$
(3.3)

<sup>&</sup>lt;sup>6</sup>See Nauges and Van den Berg (2008).

<sup>&</sup>lt;sup>7</sup>For estimations see Whittington et al. (1990).

<sup>&</sup>lt;sup>8</sup>In Figure (3.2) we assume without loss of generality that  $\delta_2 = 0$ 



Figure 3.2: Tap density

Customers at point B' incur collecting  $costs^9$  of  $B = \delta B'$ . Furthermore, customers at B' are indifferent whether to collect water from tap 2 or tap 3 provided the water prices charged at tap 2 and tap 3 are equal. Thus, point B is the gravitational threshold which divides the catchment areas of tap 2 and tap 3 if only water collecting is possible. However, in our model customers can choose between water collecting and water provision by vendors and the task remains to find the optimal split between both modes. Optimality refers to a supply structure that minimizes the costs. To do so, we have to derive the cost structure of vendors. Thereby, we have to distinguish between a supply structure with many vendors and few large ones (or one large one). We begin with the case of many small vendors.

Vendors' costs are twofold:<sup>10</sup> There is the time loss that occurs when filling cans at the kiosk. The same applies to the selling costs, which come from the lost time of selling the water to customers, i.e. decanting water into the jerrycans of customers. If we weight this amount of time with the income per hours attainable in other occupations (opportunity costs) we can derive the first cost component  $c_2$ . This component contains both cantation and decantation. We can also include capacity costs of the small cart the vendor is pulling. Therefore, we assume  $c_2 > \delta_2$ . In addition to these opportunity costs, vendors also face hauling costs. These hauling costs are lower per  $1m^3$  than hauling costs of collectors, because vendors use a technology which allows a faster distribution. Hence, hauling costs of vendors are less per  $m^3$ , i.e.  $c_1 < \delta_1$ .

<sup>&</sup>lt;sup>9</sup>We have dropped the subscript, i.e.  $\delta = \delta_2$ 

 $<sup>^{10}\</sup>mathrm{We}$  follow the analysis of Lovei and Whittington (1993) to develop the cost function of small vendors.

Total supply costs of a vendor supplying a customer at A' with 1  $m^3$  are then

$$c_2 + c_1 A' \tag{3.4}$$

with  $\delta_1 > c_1$  and  $c_2 > \delta_2$ . Both marginal cost functions intersect at  $\dot{s}$  implying that customers to the right of  $\dot{s}$  incur less costs if served by a vendor instead of collecting the water from the tap. Total costs to supply all customers from  $\dot{s}$  to B' are

$$C_V = c_1 \int_{\dot{s}}^{B'} s ds + c_2 \int_{\dot{s}}^{B'} ds = \frac{c_1}{2} \left[ (B')^2 - (\dot{s})^2 \right] + c_2 (B' - \dot{s})$$
(3.5)

If customers are supplied by one large vendor the cost structure is different due to economies of scale. Large vendors operate with big trailers pulled by , e.g., donkeys or with trucks. Due to the high capacity they do not have to return to the tap to refill. Hence the costs structure is linear:

$$C_V^s = c_1^s \int_{\dot{s}}^{B'} ds + c_2^s \int_{\dot{s}}^{B'} ds = c_1^s (B' - \dot{s}) + c_2^s (B' - \dot{s})$$
(3.6)

where  $c_2^s > c_2$  are filling and capacity costs per  $1m^3$  and  $c_1^s < c_1$  are hauling costs per  $1m^3$ . In the following we only consider the case of many vendors. All our results also apply to the case of few or one large supplier.

After all cost functions of the various supply modes have been defined and specified, the optimal supply structure of the water supply can be derived.

#### 3.2 The Optimal Modal Split

The optimal modal split can be derived with the help of a top-down integrated water resource management (IWRM) approach. How far should the pipe-born water supply be extended, how many customers should ideally fetch water from the tap and what distance should water vendors cover? Finally, how many kiosks should optimally be installed along the line of the linear city?

Dividing this task into two steps, we begin with determining the optimal number of kiosks in a given uni-dimensional area T (see again Figure (3.2)) where customers are evenly distributed. To the left of the interval there are other customers that are connected to the water distribution system and beyond the right border there are either customers not integrated in water supply system or the border represents the city boundary. Since taps can be accessed from two sides it is optimal not to position the kiosks at the borders, but rather inwards. It remains to determine the optimal number of kiosks, the optimal distance and the areas in which the vendors operate. This task can be accomplished by solving the following minimization program:

$$\min_{\dot{s},\bar{s},n} \left[ n \left\{ 2 \left[ \frac{\delta}{2} \dot{s}^2 + \frac{c_1}{2} \left[ \left( \frac{\bar{s}}{2} \right)^2 - \dot{s}^2 \right] + c_2 \left( \left( \frac{\bar{s}}{2} \right) - \dot{s} \right) \right] \right\} + rn\bar{s} + \rho n \right]$$
(3.7)  
s.t.  
 $n\bar{s} = T$   
 $\dot{s} \le (\bar{s}/2)$ 

where n is the number of taps and  $\bar{s}$  is the distance between two taps.  $\dot{s}$  indicates the width of the collecting segment and  $2(\bar{s} - \dot{s})$  is the area vendors supply. rdenotes the utilities water distribution costs per  $m^3$  delivered<sup>11</sup> and  $\rho$  are the set-up and maintenance costs per kiosks which are independent of the amount of water supplied. From the Kuhn-Tucker-conditions we can derive the optimal collecting range and the optimal vendor service area, the optimal distance between two taps and the optimal number of taps<sup>12</sup>.

$$\dot{s} = \frac{c_2}{\delta - c_1} \qquad \frac{\bar{s}}{2} = \sqrt{\frac{1}{c_1}(\rho - c_2 \dot{s})} = \sqrt{\frac{\rho(\delta - c_1) - c_2^2}{(\delta - c_1)c_1}}$$
(3.8)

The optimal collecting range can be explained with the help of Figure (3.2). The collecting costs for customers in the stretch  $[0, \dot{s}]$  are lower than the costs of being supplied by vendors. This turns around at  $\dot{s}$  where vending costs are lower than water fetching costs. The optimal distance between two taps depends positively on the set-up costs  $\rho$  and negatively on  $\delta$ , the slope of marginal collecting costs. The more expensive collecting is the higher the density of taps and vice versa<sup>13</sup>.

Having optimized the structure of the tap density and vending areas we are now able to derive the cost function of this mixed supply line with respect to its length. Inserting the optimal values of  $\dot{s}$  and  $\bar{s}$  into Equation (3.7) yields<sup>14</sup>

$$C_{tv} = \left[c_1 \frac{\bar{s}}{2} + c_2 + r\right] T = c_{tv} T \qquad (3.9)$$

where T indicates the length of that line.

It remains to determine the optimal modal split between the range of the area of connected households and the area of customers supplied by the mixed structure of taps and vendors. This can be achieved by the following program:

$$\max_{\{\tilde{s},\hat{s}\}} \left[ \int_0^{\tilde{s}} V(s) ds - m\tilde{s} + k\hat{s} + \frac{\kappa}{2}\hat{s}^2 - \left[ c_1 \frac{\bar{s}}{2} + c_2 + r \right] (\tilde{s} - \hat{s}) \right]$$
(3.10)

The optimality conditions are

$$V(\tilde{s}) - \left[c_1 \frac{\bar{s}}{2} + c_2 + r\right] - m = 0$$
(3.11)

$$-k - \kappa \hat{s} + \left[c_1 \frac{\bar{s}}{2} + c_2 + r\right] = 0$$
(3.12)

 $^{14}\mathrm{See}$  Appendix 1.

<sup>&</sup>lt;sup>11</sup>The term  $rn\bar{s}$  is an abbreviation for  $rn\bar{s}\bar{w}$ , where  $\bar{w} = 1m^3$  and  $\bar{s}\bar{w}$  is total water supplied at each kiosk. With this specification we ignore a slight asymmetry that occurs at the last tap to the far right. There is no need for a pipe between the tap and  $\tilde{s}$ . We still include this branch to keep the model symmetric and, hence, simple. The asymmetry would disapear in a model that is based on a circular city.

<sup>&</sup>lt;sup>12</sup>The derivation presupposes that the relevant parameters are such that an inner solution exists, i.e.  $n > 0, 0 < \dot{s} < \bar{s}$ . See Appendix 1.

<sup>&</sup>lt;sup>13</sup>Recall that  $n = T/\bar{s}$ .

Figure (3.3) depicts the optimality conditions<sup>15</sup>.



Figure 3.3: Optimal modal split

From left to  $\hat{s}$  households are connected to the water utility. At this point marginal costs of water supplied in households are equal to water supply without household connections. To the right of this point the area of water supply by taps and vendors begins. This area ends where total marginal costs  $c_{tv} + m$  equals the marginal willingness to pay. This is the optimal modal split of water supply.

The IWRM approach usually applies a planning approach where economic rents are maximized while taking into account technical constraints, e.g. hydrological laws. However, one must be careful when implementing this concept in practice. Two points are of particular importance:

• The pure maximization of the economic rent does not take into account the indispensable human right to water access. The result of Equation (3.10) may lead to  $\tilde{s} < \bar{s}$ . If customers are excluded from the water supply system, we have to correct the optimization procedure by including the constraint  $\tilde{s} \geq \bar{s}$ . Then we end up with a slightly different optimal modal split that covers all customers in the linear city. A brief inspection of Equation (3.12) shows that  $\hat{s}$  does not change. Instead, by Equation (3.11), the stretch of the tap-vendor area increases such that at  $\bar{s}$  the marginal willingness to pay is less than marginal costs.

<sup>&</sup>lt;sup>15</sup>Notice once more, that we have simplified the model in that the number of taps are treated as real number, not as integer. Thus, the model is an approximation of an operation research approach that would apply integer programming methods.

• The planning approach sets water quantities and the line length of the various service modes in the linear city. In reality, however, consumers and also vendors are not quantity regulated. The regulatory problem is therefore to induce the optimal split by means of appropriate distance-related price regulation. The price determination in turn depends on whether the vendors are employees of the regulated water company or whether they operate independently in a free market. In a further paper we address these issues and also take a competition policy approach. Open competitive water markets result in distance-related water prices that induce the optimal split.

### 4 Extension: Elastic water demand

#### 4.1 Stone-Geary utility function

So far we have assumed that the water demand is completely inelastic. In this section we allow for elastic demand by introducing a utility based approach. Assume that the demand function of households in the linear city can be derived from a quasilinear utility function. All households are identical with respect to preferences. Furthermore, we take into account an existential minimum of water consumption, so that the right to access to water is incorporated into the model. For that we introduce a simplified version of the Stone-Geary-utility function<sup>16</sup>.

$$B(w - w_s) = A(w - w_s)^{\alpha} \quad \alpha < 1 \tag{4.1}$$

 $w_s$  constitutes the subsistence level of water needed (life line) and w is the water consumption of consumers. Total utility of consumers fetching water by themselves in the interval  $[0, \dot{s}]$  is

$$B(w_1 - w_s) + y - \delta s w_1 - T_1, \quad \alpha < 1$$
(4.2)

Income of households is y and  $T_1$  is the charge for water consumption.

Similarly, total utility of customers served by vendors and located in the interval  $(\dot{s}, \bar{s}/2)$  is

$$B(w_2 - w_s) + y - (c_2 + c_1 s)w_2 - T_2, \quad \alpha < 1$$
(4.3)

Notice that we follow a normative approach<sup>17</sup>. This implies, that the allocation of water  $w_i$  and the charge  $T_i$  is assumed to be fixed by a regulatory authority. Thereby, we follow two extreme normative lines. First, we apply the prevalent welfaristic approach and maximize total utility subject to various constraints. Subsequently, we turn to a strictly egalitarian approach and construct a water allocation system that guarantees strict equality of utility among all customers regardless of their location

 $<sup>^{16}</sup>$ The use of a Stone-Geary utility function assures that the price elasticity of water is less that 1, see Olmstead et al. (2007)

 $<sup>^{17}\</sup>mathrm{A}$  companion paper will deal with pricing issues in unconnected water markets under various forms of competition.

along the line of the linear city. This is the Rawlsian approach. In the following we restrict our analysis to the mixed area, thus excluding the determination of the geographical stretch of connected households<sup>18</sup>.

The maximization program for the utilitarian approach is:

$$\max_{q} 2n \left\{ \int_{0}^{s} [B(w_{1} - w_{s}) + y - \delta s w_{1} - T_{1}] ds + \int_{s}^{\bar{s}/2} [B(w_{2} - w_{s}) + y - (c_{2} + c_{1}s)w_{2} - T_{2}] ds \right\}$$

$$(4.4)$$

where  $q = \{w_1(s), w_2(s), T_1(s), T_2(s), \dot{s}, \bar{s}, n\}$ . The constraints are:

$$2n\left\{\int_{0}^{\dot{s}} [T_{1} - (m+r)w_{1}(s)]ds + \int_{\dot{s}}^{\bar{s}/2} [T_{2} - (m+r)w_{2}(s)]ds\right\} - \rho n \ge 0 \qquad (4.5)$$

- $\dot{s} \le \bar{s}/2 \tag{4.6}$
- $n\bar{s} = \bar{\bar{s}} \tag{4.7}$

From the optimality conditions<sup>19</sup> we can derive the following optimality conditions with respect to  $w_i(s), i = \{1, 2\}$ :

$$B'(w_1 - w_s) - (m+r) - \delta s = 0 \tag{4.8}$$

$$B'(w_2 - w_s) - (m+r) - (c_2 + c_1 s) = 0$$
(4.9)

With respect to  $\dot{s}$  and  $\bar{s}$  we obtain:

$$\dot{s} = \frac{c_2}{\delta - c_1} \qquad (4.10)$$

$$2\left\{\int_{0}^{\dot{s}} [B(w_{1}(s) - w_{s}) + y - ((m+r) + \delta s)w_{1}(s) + y]ds + (4.11)\right\}$$

$$\int_{\dot{s}}^{\bar{s}/2} [B(w_{2}(s) - w_{s}) + y - ((m+r) + (c_{2} + c_{1}s))w_{2}(s) + y]ds = [B(w_{2}(\bar{s}/2) - w_{s}) + y - ((m+r) + (c_{2} + c_{1}(\bar{s}/2)))w_{2}(\bar{s}/2) + y]\bar{s} + \rho$$

The interpretation of 4.8 and 4.9 is straight forward. They simply require that the water consumption should be set such that the marginal benefit is equal to its marginal costs that depend on the location of the customers. It is obvious that consumption decreases the further away the consumer is from the kiosk<sup>20</sup>.

 $<sup>^{18}\</sup>mathrm{It}$  is straightforward to include these households into the analysis.

 $<sup>^{19}\</sup>mathrm{See}$  Appendix 2.

<sup>&</sup>lt;sup>20</sup>Utilizing the Stone-Geary specification we get  $w_1(s) = w_s + (A\alpha/((m+r) + \delta s))^{(1/(1-\alpha))}$  and  $w_2(s) = w_s + (A\alpha/((m+r) + c_2 + c_1 s))^{(1/(1-\alpha))}$  which shows that consumption decreases with respect to the distance from the kiosk.

#### 4.2 Optimal tap structure

4.10 determines the optimal length of the collecting area  $\dot{s}$ . Of course, the length of intervals should be chosen such that the geographical costs are minimized. This is the case where marginal costs of self-collection are equal to the marginal delivery costs of vendors. We have obtained the same result for the simple case of inelastic demand (see 3.8). 4.11 determines the optimal number of taps. The right hand side shows the marginal costs of adding an additional tap<sup>21</sup>. These costs consist of the standup costs  $\rho$  and the opportunity costs of decreasing the length of the service line  $\bar{s}$ , i.e. the distance between two taps. If we increase n the length has to be decreased<sup>22</sup>. Increasing n requires to shorten  $\bar{s}$  such that an additional area of length  $\bar{s}$  fits into the space of length  $\bar{s}$ . Hence, the opportunity costs consist of lost net utility of the customers at the very end of the serving area multiplied by  $\bar{s}$ . In the following figure 4.1 is depicted.



Figure 4.1: The optimal length between two taps

The green rectangle corresponds to the opportunity costs. This rectangle plus the set-up costs of a kiosk  $\rho$  must be equal to the aggregated net consumer surplus of an additional kiosk which is the area under the four marginal consumer surplus functions.

 $<sup>^{21}\</sup>mathrm{Recall}$  that we treat the tap number as a real number. Therefore, we can conduct a marginal analysis.

<sup>&</sup>lt;sup>22</sup>Notice, that the total length of the stretch to be supplied by water is  $\overline{\overline{s}} = n\overline{s}$ .

#### 4.3 Water charges

It remains to specify the water charges  $T_i$ . Since we have assumed a quasi-linear utility function, the marginal utility of income is constant. Hence, with respect to the charges, the maximization program yields no unique solution. However, we can find a tariff function that satisfies the optimality conditions<sup>23</sup>. This is, for example, the case for the well known two-part tariff proposed by Coase (1946). One simply has to set

$$T_1(s) = (m+r)w_1(s) + \rho/\bar{s}$$
(4.12)

$$T_2(s) = (m+r)w_2(s) + \rho/\bar{s}$$
(4.13)

This tariff system satisfies the budget constraint from Equation (4.5). The volumetric parts of both tariffs are total marginal costs and the fixed part  $\rho/\bar{s}$  covers the set-up costs of kiosks. Of course, this tariff system leads to an unequal distribution of consumers' utility. Those in the vicinity of a tap are better off than those in far distance of a kiosk (see Figure (4.1)).

If this distribution is considered unfair, the tariff system must be altered. In the following we assume that complete equality should be reached. This can be achieved with the help of the Rawlsian Maxmin approach implying that all customers along the linear city should achieve the same utility level. This is an extreme provision which only serves as a counterpoint to the utilitarian approach of equation (4.4). In reality, the water supply and water tariff system cannot solely serve as a fully fledged distribution instrument. Since the model is designed for a continuum of customers<sup>24</sup>, we apply the maximization program as follows.

All customers should receive the same level of utility regardless of the geographical position. This implies for customers in the interval  $[0, \dot{s}]$  and  $[\dot{s}, \bar{s}]$ , respectively:

$$B(w_1 - w_s) + y - \delta s w_1 - T_1 = k \tag{4.14}$$

$$B(w_2 - w_s) + y - (c_2 + c_1 s)w_2 - T_2 = k$$
(4.15)

Rearranging yields the water charges  $T_i$ 

$$T_1 = B(w_1 - w_s) + y - \delta s w_1 - k \tag{4.16}$$

$$T_2 = B(w_2 - w_s) + y - (c_2 + c_1 s)w_2 - k$$
(4.17)

The maximization program for the Rawlsian case is:

$$\max_{q} \quad 2n\left\{\int_{0}^{\dot{s}}kds + \int_{\dot{s}}^{\bar{s}/2}kds\right\}$$
(4.18)

 $<sup>^{23}</sup>$ See Appendix 2.

<sup>&</sup>lt;sup>24</sup>The usual Rawlsian social welfare function is defined as  $\sum Min[B_1, B_2, \dots, B_n]$ .

subject to the budget constraint

$$2n\left\{\int_{0}^{s} [B(w_{1} - w_{s}) + y - \delta sw_{1} - (m + r)w_{1}(s) + y - k]ds + \int_{\dot{s}}^{\bar{s}/2} [B(w_{2} - w_{s}) + y - (m + r)w_{2}(s) - k]ds\right\} - \rho n \ge 0$$

$$(4.19)$$

and

$$\dot{s} \le \bar{s}/2 \tag{4.20}$$

$$n\bar{s} = \bar{\bar{s}} \tag{4.21}$$

where  $q = \{w_1(s), w_2(s), k, \dot{s}, \bar{s}, n\}$ . Notice that the budget constraint is derived by inserting Equation (4.16) and Equation (4.17) into Equation (4.5). In Section (7.3) we show that the optimality conditions with respect to  $q = \{w_1(s), w_2(s), \dot{s}, \bar{s}, n\}$ are the same as for the utilitarian program, i.e. Equation (4.8) - Equation (4.11). This is due to the separability of the utility function. Since water demand has no income effects, the distribution task can be carried out by the tariff functions. In contrast to the utilitarian approach, the water charge functions must be precisely determined so that the benefit levels are the same for all water customers. The tariff system must take the costs of water collection into account. This can be inferred from Equation (4.16) and Equation (4.17). Differentiating with respect to s yields

$$T'_{1} = (B'(w_{1} - w_{s}) - (m + r) - \delta s)w'_{1} - \delta w_{1}(s)0 = -\delta w_{1}(s) < 0$$

$$(4.22)$$

$$T'_{2}(s) = (B'(w_{2} - w_{s}) - (m + r) - (c_{2} + c_{1}s))w'_{2}(s) - c'_{1}w_{2}(s) = -c'_{1}w_{2}(s) < 0$$

$$(4.23)$$

Water expenses decrease with respect to the distance between kiosks. On the other hand, water consumption also falls in line with s. From Equation (4.8) and Equation (4.9) we have

$$w_1'(s) = \delta/B_1'' < 0 \quad \text{and} \quad w_2' = c_1/B_2'' < 0$$
 (4.24)

In the following section we will analyze the relation between water consumption and water expenses with the help of a numerical example. However, it should be made clear that the exact shape of the tariff function T(w) cannot be used to draw any conclusions about the distributional effect. Whether we receive a progressive or digressive function is actually irrelevant, because  $T_i$  is designed in such a way that all customers achieve the same degree of benefit. One should also keep in mind, that the derivation is a first best exercise under full information and no transaction costs. The tariff system and the optimal water distribution infrastructure are determined by a hypothetical institution that adheres to the principles of integrated water resource management.

## 5 Numerical Example

#### 5.1 Parameter estimates

In this section we apply the model with elastic demand for a fictive linear city, based on cost rates and information in the scientific literature.

Cook et al. (2016) state an average velocity of a water fetcher of 2.75 kilometers per hour to transport a 20L container. By combining this information with time costs of 0.6 USD per hour (Whittington et al. (1990)), we set the cost rate  $\delta$  for a person who fetches the water from a kiosk to the value<sup>25</sup>  $\delta = 21.6$ .

For the water vendor a velocity of 500 meters per hour for transferring 1 cubic meter of water can be assumed, based on Lovei and Whittington (1993). For the water fetcher we assume time costs of 0.6 USD per hour (Whittington et al. (1990)). Based on these values<sup>26</sup> we assume  $c_1 = 2.4$  for the water vendor parameter.

The mobile water vendors also have costs such as decanting costs and rental costs which are independent of the water transfer distance. These costs are addressed by the cost rate  $c_2$  in the model. Based on Whittington et al. (1989), the rental of equipment for transferring 600 Liters a day costs about 10 Ks a week, which is equivalent to 0.6 USD. Therefore<sup>27</sup>, it is possible to put the rental costs to 0.14286 which is one element of the cost rate  $c_2$ . Furthermore, the decanting of 1 cubic meter of water needs about 2 hours (Whittington et al. (1989)). If the time costs are 0.6 USD per hour (Whittington et al. (1990)), the decanting costs can be assumed with the value of 1.2, which is the second element of the cost rate  $c_2$ . Adding both components, we obtain the value  $c_2 = 1.34$ .

The cost rate  $\rho$  for the water kiosk can be assumed  $\rho = 2$ , because of monthly cost of 60 USD for rental equipment and other regular expenses (Whittington et al. (1989)).

Based on OECD (2005) the total cost for the municipal water supply can be assumed with 0.85 USD per cubic meter, which incorporates the cost for water treatment of about 0.34 USD per cubic meter. Hence, the parameter m which represents the cost rate for treating the water is set to m = 0.34, while the parameter r which represents a transfer cost rate can be assumed with the value r = 0.51.

Finally, the value of the utility function parameter  $\alpha$  is set to 0.3 (Dalhuisen et al. (2003)). Table 5.1 illustrates the assumptions of the exogenous parameters for the numerical application of the presented model.

<sup>&</sup>lt;sup>25</sup>Total time to haul 20 litres for one km is 1/2.75=0.36 hours. To haul one  $m^3 = 1000$  litres 18 hours are required. One hour costs 0.6 US-\$. Since the distance has to be taken twice we have  $2 \cdot 0.36 \cdot 18 = 20.6$ . Notice, that we have not taken into account that hauling the empty canister from home to the kiosk requires less time.

 $<sup>^{26}</sup>$ Given the velocity of 500 meters per hour the vendor needs 2 hours to serve a distance of 1000 meters to the tap (round trip).

 $<sup>^{27} \</sup>rm Linear$  expansion implies that the costs of a capacity of 1  $m^3$  are 1 US-\$ per week which is 1/7 US-\$ per day.

Table 5.1: $A$	Assumed	parameter	values	for	the	numerical	example
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δ	$c_1$	$c_2$	$\rho$	m	r	$\alpha$
21.6	2.4	1.34	2	0.34	0.51	0.3

#### 5.2 Some stylized results

For the given scenario, the optimal distance between the taps is about 6 kilometers. The fetching zone stretches over 1.2 km, which means that consumers who live not more than 1.2 km far away from the next tap should collect the water from the water kiosk, while consumers who are further than 1.2 km from the next tap will be served by the mobile water vendors.

We can also perform some sensitivity analyses on the estimated parameters, such as the optimal tap density or the fetching zone. Figure 5.1 shows the impact of the level of the cost rate for operating the water kiosk  $\rho$  on the tap density. It becomes obvious that the lower the cost rate the more kiosks can be operated efficiently, and hence the tap density would decrease; the effect seems to be quite strong.



Figure 5.1: Tap density and kiosk operating costs  $\rho$ 

Figure 5.2 shows the impact of water demand characteristics on the optimal tap density. The parameter  $\alpha$  in the Stone Geary utility function represents the strength of water availability for poor individuals on utility.

With increasing  $\alpha$  the utility of water rises and therefore demand increases. Aggregated net consumer surplus rises for a given tap distance quicker than its opportunity costs which consists of the net benefit of the customer furthest away from a tap (see Figure (4.1)). Thus, the optimal distance decreases with  $\alpha$ .



Figure 5.2: Tap density and  $\alpha$ 

## 6 Conclusion

This paper provides support to the idea that offgrid water vendors have an important role to play in the delivery of poor households, and, thus, in the fulfilment of ambitious political goals such as the human right to water and the Sustainable Development Goal No. 6. To analyze the question we have established a spatial economic model of water provision in periurban areas: A water utility located in the (wealthy) city center develops a water supply network, but for economic reasons this network can not cover the peri-urban and the rural area. From an economic perspective, water vendors thus have a central role.

Our model looks for the "optimal" modal split between infrastructure-based water supply by a public utility, and the decentralized, off-grid water vendors. This optimal modal split can be found with the help of a micro-economic model. We assume a linear city and develop a stylized cost structure for the public utility, the vendors and the water consumers. The analysis was carried out for a totally inelastic demand function in section 3.2 and for an elastic water demand in section 4 based on a simplified form of the Stone-Geary utility function. In the development context of our paper, elastic demand is certainly a plausible assumtion, and the Stone-Geary utility function allows to take this into account.

Even though the model is relatively simple, it provides interesting results. We obtain terms for the "optimal" modal split, situated between the dense city center and the periurban area. The model also allows us to identify the optimal length between taps, the tap density, and the corresponding water charges. In our economic approach, we have to take into account the opportunity costs for transporting water supply.

With a grain of salt, the model also allows some numerical applications to establish the links between supply (mainly cost functions) and demand characteristics. Therefore, a numerical application of the model with elastic demand is presented for a fictive linear city with model parameter assumptions based on the empirical literature. We found an optimal distance between the tap of about 6 kilometers and a fetching zone of about 1.2 kilometers. The numerical exercise also allows some sensitivity analysis on key parameters. Thus, increasing the operatoin costs for water kiosks raises the optimal distance between these kiosks significantly. On the contrary, even a strong, utility-driven relative increase in water demand does not seem to affect the tap density significantly.

We also need to be aware of the limitations of the model. Thus, the linear city is a simplification, compared to real, existing cities due to the assumed homogenous spatial structure of costs and demand. A multitude of forms of the water vendors market structure is conceivable. Opportunistic behavior (e.g. water-theft due to hidden information) as well as different forms of cooperation and collusion between the actors in the informal water market, which occur quite often in reality, are not implemented and analyzed in this framework. Hence, further research is needed to extend the model and include additional features.

In terms of policy implications, the paper suggests a role for decentral, offgrid solutions to generalized water supply, with a likewise strong role for water vendors. This is a controversial topic, as the considertation of economic factors in critical water supply issues is subject to different, often contradictory value judgements. We consider the introduction of explicit cost and demand parameters a useful extension of the ongoing debate. Of course, the translation of the model findings to concrete challenges on-site requires to take into account the local contexts, for which this paper provides theoretical foundations.

## 7 Appendix

#### 7.1 Appendix 1

The Karush-Kuhn-Tucker conditions to the minimization program of equation (3.7) are:

$$2n\delta \dot{s} - 2nc_1 \dot{s} - 2nc_2 - \mu \ge 0 \tag{7.1}$$

$$n(c_1/2)\bar{s} + nc_2 + rn - \lambda n + (\mu/2) = 0$$
(7.2)

$$2\left[\frac{\delta}{2}\dot{s}^{2} + \frac{c_{1}}{2}\left[\left(\frac{\bar{s}}{2}\right)^{2} - \dot{s}^{2}\right] + c_{2}\left[\left(\frac{\bar{s}}{s}\right) - \dot{s}\right]\right] + r\bar{s} + \rho - \lambda\bar{s} = 0$$
(7.3)

where the Lagrangean  $\lambda$  ( $\mu \leq 0$ ) refers to the first (second) constraint.

Two cases can be distinguished: either it is not optimal to have vendors at all or there exists an optimal mix of collecting and vending. The occurrence of the two cases depends on certain parameter constellations. Let us begin by assuming that  $\dot{s} < (\bar{s})/2$ , i.e. a mixed supply area is optimal. We know from the KKT-conditions that in this case  $\mu = 0$ . The optimal collecting area  $\dot{s}$  follows from Equation (7.1) immediately. To derive the optimal distance between two taps  $\bar{s}$ , solve Equation (7.2) for  $\lambda$ , multiply it by  $\bar{s}$  and insert it for  $\bar{s}\lambda$  in Equation (7.3). The equation reduces  $\operatorname{to}$ 

$$-c_2\dot{s} - \frac{c_1}{4}\bar{s}^2 + \rho = 0 \tag{7.4}$$

which can be solved for  $\bar{s}$  yielding Equation (3.8).

We have assumed that  $\dot{s} < (\bar{s})/2$ . Inserting the solutions from Equation (3.8) leads to

$$\frac{c_2}{\delta - c_1} = \sqrt{\frac{\rho(\delta - c_1) - c_2^2}{(\delta - c_1)c_1}}$$
(7.5)

Rearranging and reducing yields the parameter constellation

$$c_2 < \sqrt{(\rho/\delta)}(\delta - c_1) \tag{7.6}$$

as a necessary and sufficient condition for  $\dot{s} < (\bar{s})/2$ .

#### 7.2 Appendix 2

Program Equation (4.4) can be solved in a two step procedure. First, we derive the optimal functions  $\{w_1(s), w_2(s)\}$  for given  $\{\dot{s}, \bar{s}, n\}$  with the help of the Euler equations. This is straightforward and leads to Equation (4.8) and Equation (4.9). For  $T_i$  we get

$$\lambda = 1 \tag{7.7}$$

where  $\lambda$  is the Lagrangean with respect to the budget constraint.

Reinserting the optimal consumption functions  $w_i$  into the welfare function and deriving the program with respect to  $\dot{s}$  yields:

$$2n \Big[ ((B(w_1(\dot{s}) - w_s) + y - ((m+r) + \delta \dot{s})w_1(\dot{s}) + y) - (7.8) \\ (B(w_2(\dot{s}) - w_s) + y - ((m+r) + (c_2 + c_1 \dot{s}))w_2(\dot{s}) + y)) \Big] - 2n \Big[ (T_1(\dot{s}) - ((m+r) + \delta \dot{s})w_1(\dot{s})) - (T_2(\dot{s}) - ((m+r) + (c_2 + c_1 \dot{s}))w_2(\dot{s})) \Big] = 0$$

This equation is satisfied if  $\dot{s} = c_2/(\delta - c_1)$ . Utilizing  $\lambda = 1$  and deriving Equation (4.4) s. t. to Equation (4.5) with respect to  $\bar{s}$  yields

$$(B(w_2(\bar{s}) - w_s) + y - ((m+r) + (c_2 + c_1\bar{s}))w_2(\bar{s}) - \mu + \sigma/2 = 0$$
(7.9)

where  $\mu$  ( $\sigma$ ) is the Lagrangean for Equation (4.6) and Equation (4.7), respectively.

In the following, we assume that  $\dot{s} < \bar{s}/2$ , i.e. there exists a vending area. Thus,  $\mu = 0$ .

#### 7.3 Appendix 3

Similar to the welfare maximization program Equation (4.18) can be solved in a two step procedure. First, we derive the optimal functions  $\{w_1(s), w_2(s)\}$  for given  $\{k, \dot{s}, \bar{s}, n\}$  with the help of the Euler equations. This is straightforward and leads to the optimality conditions Equation (4.8) and Equation (4.9).

In the following we assume that Equation (4.20) is not binding, i.e. there is a stretch where vendors sell water. The first order conditions with respect to  $\{k, \dot{s}, \bar{s}, n\}$  are where  $\lambda$  ( $\mu$ ) is the Lagrangean attached to the constraint Equation (4.19) and Equation (4.21), respectively:

$$k: \quad 2n[\bar{s}/2 - \lambda \bar{s}/2] = 0 \tag{7.10}$$

$$\dot{s}: \quad \lambda \left\{ \left[ B(w_1(\dot{s}) - w_s) + y - \delta \dot{s} w_1(\dot{s}) - (m+r) w_1(\dot{s}) - k \right] - \left[ B(w_2(\dot{s}) - w_s) + y - (m+r) w_2(\dot{s}) - k \right] ds \right\} = 0$$
(7.11)

$$\bar{s}: \quad k + \lambda [B(w_2(\bar{s}/2) - w_s) + y - k - (m+r)w_2(\bar{s}/2)] - \mu = 0$$
(7.12)

$$n: \quad k\bar{s} - \rho - \mu\bar{s} = 0 \tag{7.13}$$

From Equation (7.10) it follows that  $\lambda = 1$ . Equation (7.11) is satisfied for  $\delta \dot{s} = (c_2 + c_1 \dot{s})$ . Inserting Equation (7.13) into Equation (7.12) and taking Equation (4.14) and Equation (4.15) into account yields Equation (4.11).

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