

Research Paper

An assessment of penetration for pay-to-fetch water kiosks in rural Ghana using the Huff gravity model

Philip T. Deal and David A. Sabatini

ABSTRACT

Safe water enterprises across the developing world are attempting to meet demand for higher levels of water service. Existing, often free, water sources can make it difficult for these businesses to convince consumers to use a better-quality source or capture sufficient revenue for cost recovery. For this reason, it is imperative to develop a realistic understanding of penetration for small-scale water utilities. A cross-sectional assessment of 60 rural communities was used to evaluate the market share of a private service provider in Ghana. Household survey responses were used to identify the most attractive qualities of available water sources. Distance, taste, appearance, and affordability were found to be the most common motivational drivers. Using this information, a Huff gravity model was developed to assess the actual and potential market penetration and market share for the company in each community. The model and actual results agreed that about 38% of respondents would be regular customers at the given price. Even if water were free, the model predicted that the attractiveness of other sources would make it difficult to capture more than 58% of the sampled households. This illustrates the complexity of the water service ecosystem in a developing, rural context.

Key words | Huff gravity model, rural water supply, safe water enterprise, sub-Saharan Africa, willingness-to-pay

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HIGHLIGHTS

- Novel application of the Huff gravity model on communal water sources to predict market penetration and market share of safe water enterprises.
- Unique dataset of household responses on top motivations for water source use.
- Penetration methodology verified by survey results, willingness-to-pay assessment, and market share evaluation.

INTRODUCTION

Safe water enterprises (SWEs) have become increasingly pervasive in water service provision across the world. SWEs are described as market-based approaches that deliver high-quality drinking water through decentralized solutions (Bhatnagar *et al.* 2017). Businesses vary in their

treatment, transportation, delivery, and payment methods. Examples include home delivery of chlorinated water in India, ultrafiltration kiosks in Kenya, and private storefronts using reverse osmosis in Indonesia and Haiti (Cherunya *et al.* 2015; Patrick *et al.* 2017). These companies are

making efforts to increase levels of professionalism, institutional formality, and physical access to treated water in rural contexts (RWSN 2019).

However, the availability of treated water does not equate to usage. Market penetration rates historically range between 10 and 60% (Opryszko *et al.* 2013; Bhatnagar *et al.* 2017; Deal & Sabatini 2020). Previous studies have cited examples such as proximity, rainfall, or price as potential reasons for choosing between sources (Martínez-Santos 2017; Foster & Willetts 2018). This can lead to seasonal shifts in priority, periodic use of unimproved sources, or households choosing multiple sources for different domestic needs. Thus, it is imperative that market penetration be accurate in order to justify population coverage statistics and economic viability of SWEs. Due to pre-existing alternatives, it may be incorrect to assume that an SWE can achieve complete market saturation. More specifically, it can be hypothesized that an SWE, acting as a communal water provider, will be unable to reach a penetration rate approaching 100% as long as existing competition is readily available.

In this study, an assessment of rural households in Ghana investigated how motivational drivers relate to the uptake of SWE services. This article will first describe the study area and methodology of the research. Then, penetration rates at the district and community levels will be analyzed in relation to key respondent motivators. These results will culminate in a geospatial analysis of market demand using the Huff gravity model (Huff 1966), which estimates the probability that a given household will select each water source within their community. Finally, the effects of competition and water source attractiveness on rural water supply will be discussed.

STUDY AREA AND METHODS

Description of study area

The study occurred within in the Wassa East District of Ghana. In 2016, a baseline assessment estimated that the district had a population of around 90,000 people in 137 communities (Wassa East District Assembly 2016). The district is predominantly rural, with only three densely populated areas. It is within a tropical climate zone, with

a mean annual rainfall of 1,500 mm. The total land area is about 1,652 km², but almost 600 km² is considered a forest reserve (GSS 2014). The district capital, Daboase, is about 38 km from Takoradi, the capital of the Western Region. About 69% of people claim commercial or subsistence farming as their primary employment, and nearly 80% of people do not have an education beyond Junior High School (Deal & Sabatini 2020). A map of the district, along with sampled communities, is shown in Supplementary Appendix A.

Access Development is a private, safe water enterprise in the district. The company extracts groundwater using solar-powered kiosks, which use microfiltration, UV disinfection, and chlorination for treatment. The company maintains their systems using circuit rider methods of operation. Area mechanics are stationed at various geographic locations across the district. They regularly visit each managed water source to provide maintenance and ensure continual water supply. Vendor communication and remote sensing assist in rapid response times.

The SWE is under a non-exclusive contract with the local government to work within the entire district, allowing for economies of scale. Customers collect water at the kiosk using the pay-to-fetch model. The price of water is set based on local market trends and efforts to cover operational costs and asset renewal. This is formally recorded in a signed agreement between the local government, each individual community, and the SWE. Other service providers in the area are predominantly community-based managers or religious institutions, but mining companies and public utilities exist in a few medium-sized towns as well. Deal & Sabatini (2020) provide further details on the institutional context and stakeholder exchanges.

Data collection and survey techniques

A cross-sectional study design (Jacobsen 2011) was utilized to collect quantitative data from households within the district. Two-stage cluster sampling was used to randomly select households from 30 intervention and thirty control communities. The data were used to determine the overall *market penetration rate*, which represents the proportion of households in intervention communities that choose to use SWE water at least weekly (Farris *et al.* 2010). Data collection was completed in 2019, after intervention communities had

been under contract with AD for 6 months to 2 years. Water sources within each community were evaluated for reliability and quality. Testing included fecal coliforms, turbidity, conductivity, chlorine, and iron (Deal & Sabatini 2020).

Systematic random sampling of households occurred within each community. Enumerators received satellite maps, GPS coordinates, and sampling intervals to identify sampled households. Data were collected using the mWater platform. Unique mWater IDs were used to match household responses to previously identified water source characteristics and locations. Household heads or their spouse were given priority, though other adults were surveyed if necessary. GPS tracking allowed for the verification of survey completion. About 1,152 households were evaluated in total, and about 57% of respondents were female. Twenty-four households were removed through quality control checks of duplication, age, inconsistency, improper mental states, or poor accuracy ratings (Deal & Sabatini 2020).

Informed consent was required prior to participating in the study. Identifying information was removed for the subjects' protection. The research protocol was cleared by the University of Oklahoma IRB. Data collection was carried out by local enumerators after completing training for ethical, in-person interviews. During preliminary survey testing, questions were asked in English, Fante, and Ewe after translation into local dialects.

Motivational options were presented from a pre-determined list derived from historical sources (Cherunya *et al.* 2015; Martínez-Santos 2017; Foster & Willetts 2018), both from positive and negative perspectives (Supplementary Appendix B). When open-ended responses occurred, they were reallocated to their respective categories. The statistical analysis of respondent data was completed using IBM SPSS Statistics 26.

Data analysis

Actual penetration results were compared with the market demand produced by the Huff gravity model (Huff 1966). This competitive location model combines the variables of distance, facility attractiveness, and demand to predict the market share that a given store location can capture. It has historically been used to identify optimal locations for grocery stores, gas stations, shopping centers, or other retail outlets. While any environment with an extensive

pipled water system might not find this tool appropriate, many rural and peri-urban areas still use communal water sources where these predictions could be valuable.

In this study, Equation (1) defines the market penetration, or the probability (P_{ij}) that a given household located at given location, i , would choose to collect water from source, j . This assumes that A_j is a measure of the attractiveness of each water source, and D_{ij} is the distance between the household and the water source. Euclidean distance was calculated using Equation (2), which is based on the radius of the earth, r , the latitude, ϕ , and the longitude, λ . The Multiplicative Competitive Interaction (MCI) model for attractiveness was used to test multiple factors, as shown in Equation (3) (Cooper & Nakanishi 1988). The MCI model is an econometric model for analyzing market shares. The variables, α and β , act as empirical model parameters, where the default α value is assumed to be 1, and β falls between -1 and -2 (Dolega *et al.* 2016). Then, the model (Equation (1)) was transformed into a linear form using Equation (4). This allowed for linear regression analysis and optimization of the model. The variables, Π_i , Λ_j , and Δ_i , are the geometric means of P_{ij} , A_{jh} , and D_{ij} , respectively.

After the market penetration of SWE water (P_{SWE}) is estimated, the theoretical results can be compared with the market share (M_s) derived from respondent data. Market share, shown in Equation (5), represents the percentage of an industry's total sales that is earned by a particular company over a specified time period (Farris *et al.* 2010). Actual results are derived using consumer data for the mean spending on SWE water (\bar{S}_{SWE}) and total water (\bar{S}_T), which also represents potential buying power.

$$P_{ij} = \frac{A_j^\alpha D_{ij}^{-\beta}}{\sum_{j=1}^n A_j^\alpha D_{ij}^{-\beta}} \quad (1)$$

$$D_{ij} = 2r * \arcsin \left(\sqrt{\sin^2 \frac{\phi_i - \phi_j}{2} + \cos \phi_j \cos \phi_i \sin^2 \frac{\lambda_i - \lambda_j}{2}} \right) \quad (2)$$

$$A_j^\alpha = A_{j1}^{\alpha_1} * A_{j2}^{\alpha_2} * \dots * A_{jh}^{\alpha_h} \quad (3)$$

$$\log \left(\frac{P_{ij}}{\Pi_i} \right) = \sum_{h=1}^H \alpha_h \log \left(\frac{A_{hj}}{\Lambda_j} \right) - \beta \log \left(\frac{D_{ij}}{\Delta_i} \right) \quad (4)$$

$$M_s = \frac{\bar{S}_{SWE}}{\bar{S}_T} = \frac{P_{SWE} \bar{S}_T}{\bar{S}_T} = P_{SWE} \quad (5)$$

RESULTS AND DISCUSSION

Descriptive analysis

Intervention communities had, on average, a choice of about 6 communal water sources, with a range from 2 to 14 options. Each community had a relatively new (6 months to 2 years) SWE water source available and functional, specifically 52 of the 177 identified sources. The SWE sources included 48 kiosks with vendors selling water using pay-to-fetch and four boreholes under a monthly tariff scheme. Community penetration rates for SWE sources tended to increase as available alternatives decreased, emphasizing the importance of local options (see Supplementary Appendix C). The control communities had a total of 145 water sources with a statistically similar distribution of surface, groundwater, and piped sources. When surveyed, households were asked what motivated them to choose or *not* choose a given primary source, with results summarized in Figure 1.

From the positive perspective (Figure 1(a)), top motivations included close proximity (distance), appearance, and taste. Intervention households saw increased proportions of good quality and affordability determinants. When households were asked what motivated them *not* to choose an alternative drinking water source (Figure 1(b)), distance and taste were still relevant. However, never being able to afford or only sometimes being able to afford

had noticeable spikes in intervention households. This information provides evidence for a sub-section of the population that feels they cannot afford to regularly pay for water, thus limiting the market in a rural context. Further delineations between specific customer classifications are illustrated in Supplementary Appendix D.

It is also important to note that the community penetration rate of SWE water was statistically correlated with negative motivations of poor taste ($p = 0.042$) and, separately, not having the ability to pay ($p = 0.049$). Essentially, an individual community cluster may have a spike of complaints for either factor, which suggests an underlying cause for the lower local uptake observed. Upon further investigation, four communities with greater affordability complaints were observed to resist patronage of kiosks in an effort to lower pay-to-fetch costs. As another example, when isolating communities with elevated chemicals related to poor taste ($n = 14/30$), a significantly lower mean penetration rate was observed (30.4 versus 57.0%; $p = 0.013$). Tested chemicals included chlorine, conductivity, and iron (WHO 2017; Deal & Sabatini 2020). Quality (*E. coli*) and appearance (turbidity) indicators were also examined, but no significant trends with penetration were observed.

Finally, Figure 2 summarizes the consumer data in the dry season for spending on total water, sachet water, and SWE water per week according to each customer class (see Supplementary Appendix D). Also, collected volumes from a household's primary source are compared with the

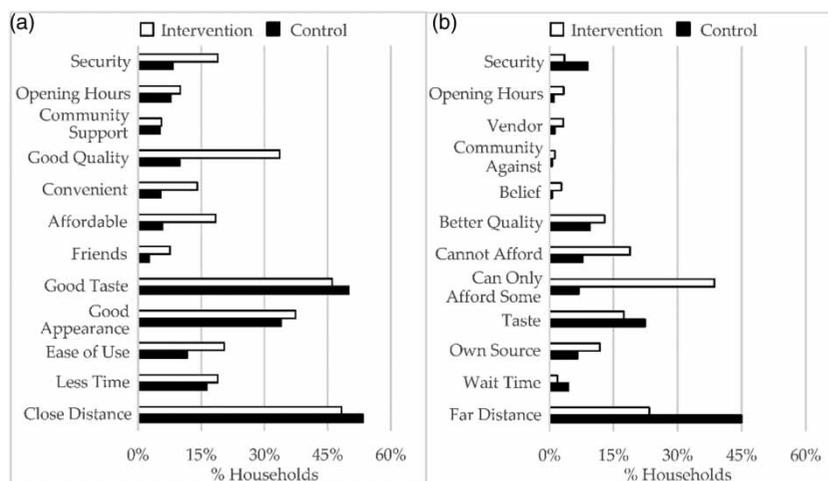


Figure 1 | Motivations to (a) choose or (b) NOT choose a given primary source.

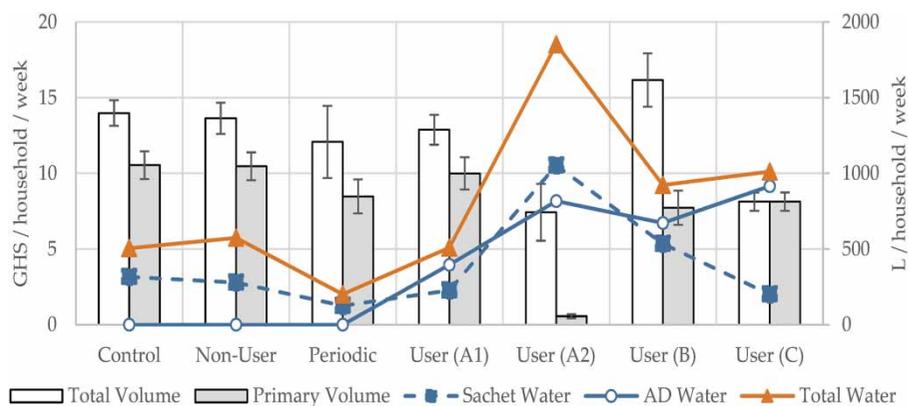


Figure 2 | Household water volume collected and water spending per week by customer classification.

total volume collected each week. The differences observed represent a portion of the sample population that uses multiple sources to meet their domestic needs (Deal & Sabatini 2020). In the intervention group, mean total spending on water was 7.07 GHS per household per week and mean total volume collected was 1,345 L per household per week.

Huff gravity model

The descriptive data analysis provided the necessary information to develop a Huff gravity model for each community in the district. The key assumption of this model is that each consumer is influenced by their distance from a given retail location and the attractiveness of the source. Table 1 summarizes the variables used within the

model, and Figure 3 shows the progression of model development for an example community.

In Figure 3(a), it can be observed that there are five water sources within the community, each functional at the time of the survey. For reference, WP1 and WP3 are unprotected hand dug wells, WP2 is a protected hand dug well, WP4 is an SWE kiosk, and WP5 is a collection point along a stream. Randomly selected household sample locations are also noted. Figure 3(b) represents the highest probability value predicted by the model for all water sources, and a push-pull effect can be observed. This is the product of the attractiveness and distance for each water point in Equation (1). While attractiveness is static according to the model variables chosen, distance inversely reduces attraction.

Table 1 | Motivational variables associated with penetration and their Huff model scoring limits

Motivation	Variable	Type	Scoring limits	
			Low	High
Availability	Functionality	Binary	Not functional	Functional
	Annual reliability	Ordinal	<6 months	12 months
Taste (Chem.)	Chlorine	Binary	>0.3 mg/L	<0.3 mg/L
	Conductivity	Binary	>300 μ S/cm	<300 μ S/cm
	Iron	Binary	>0.3 mg/L	<0.3 mg/L
Appearance (Chem.)	Turbidity	Binary	>5 NTU	<5 NTU
Quality (Bio.)	Free coliforms	Ordinal	>100 MPN/100 mL	0 MPN/100 mL
Organoleptic rank	Taste, odor, appearance, lather	Ordinal	Lowest rated choice	Highest rated choice
Affordability	Price	Ordinal	0.30 GHS/18 L	Free
Social pressure	Community resistance	Binary	Observed	Not observed

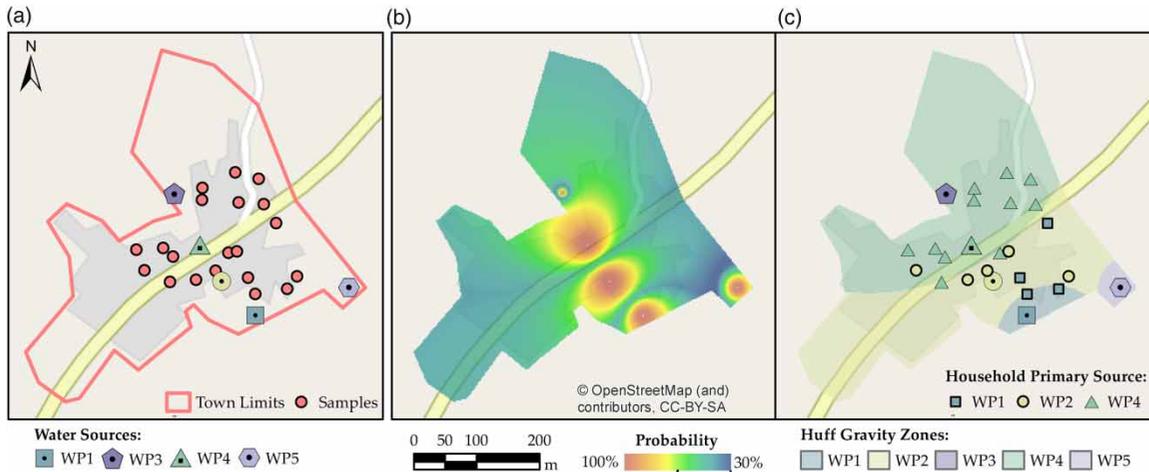


Figure 3 | Huff model analysis: (a) sample distribution for an example community, (b) max probability distribution for all sources (gravity map), and (c) highest probable water source versus respondent's primary source.

Figure 3(c) maps out each source's radius of influence, as well as the actual primary drinking water source for each household. The spatial influence is clearly evident, supporting the motivation of close proximity for many households. While a few households appear to be incorrectly assigned to a particular source, it is important to use both Figure 3(b) and 3(c). Some sources far away only have around a 30% chance of using the predicted source, meaning that the others are offering considerable competition.

Attractiveness was calculated by incrementally adding the variables identified in Table 2. These variables were determined from the descriptive analysis and historical determinants (Martínez-Santos 2017). They were restricted to traits of the water source independent of household traits, such as socioeconomic status or size, in order to simulate a new installation decision for a safe water enterprise. Some determinants, such as reliability, quality, and taste rank, were considered ordinal, while other determinants were considered binary, such as functionality and social pressure. While ordinal variables offered incremental improvements to attraction, binary variables could attribute a harsh penalty if a condition was violated (see Table 1). Each was optimized based on the best performance of the model using multinomial linear regression in the log-normal form of the probability function (Equation (4)). Table 2 shows the details of the model progression.

From Table 2, gradual improvements are observed from Model I to VII with respect to the regression fit. Distance was consistently a significant determinant. However, reliability and functionality seemed to have some redundancy due to their dependent nature. The penalty for non-functionality ($A_j = 0.01$) serves the important role of ruling out unavailable water sources, but must be non-zero due to the log transformation. The chemical taste determinant, which applied a penalty to sources with high conductivity or iron, was found to be more significant as other factors were applied. For this reason, it was kept instead of the taste rank factor. The opposite decision was used for appearance, where turbidity was generally found to be counterproductive and appearance rank performed better. The effect of the rank variables, as shown in model IV, was similar for all organoleptic properties, as they seemed to highlight the favored water sources in a given community. Quality was also found to be counterproductive, suggesting that the majority of households do not strongly consider it. This is not surprising, given that public water quality testing in the district is rather limited. Social pressure and price proved to be rather important, but for different reasons. When a penalty was applied to sources that were observed to have negative social pressures, such as a borehole with evidence of worms or attempts to reduce kiosk prices, a significant jump in correlation occurred for model VI. While a price factor did not have a significant effect on the linear regression

Table 2 | Results of multiple-regression analysis for different models of probability, modeled determinants of water source usage are shown, and the subsequent penetration rates for SWE water sources are included

Model predictions		Variable p-values ^c															
Models	Penetration (%) ^a	Adj. R ²	Ln (Adj. R ²)	F-value	F-sig. ^b	Dist.	Func.	Reliability	Taste (Chem.)	Turbidity	Quality	Taste rank	Odor rank	Appear. rank	Lather rank	Social	Price
I	45.7	0.279	0.018	123.9	<0.001	0.009											
II	53.3	0.526	0.325	354.2	<0.001	0.001	0.140	0.001	0.260								
III	68.6	0.468	0.343	280.8	<0.001	0.009	0.268	0.003	0.246	0.469	0.001						
IV	57.0	0.600	0.738	478.0	<0.001	<0.001	<0.001	<0.001				<0.001					
V	58.3	0.640	0.769	566.4	<0.001	<0.001	0.023	0.396	0.008				<0.001	<0.001	0.010		
VI	45.3	0.740	0.776	906.7	<0.001	<0.001	0.017	0.356	0.020				<0.001	0.001	0.008	0.001	
VII	38.8	0.725	0.775	839.3	<0.001	<0.001	0.017	0.363	0.021				<0.001	0.001	0.008	0.001	0.951

^aModel prediction of % households using SWE water services.

^bConfidence level 95%; F-sig = 0.05.

^cConfidence level 95%; p = 0.05.

($p = 0.951$), it dropped the penetration rate into the appropriate range. Given its good correlation with actual results, model VII was selected as the optimal choice. The comparison between actual and predicted probability values is shown in Figure 4.

With the market penetration rate of 38.8% derived from model VII, the theoretical and self-reported market values could be compared. The actual market share was 35.2%, which was based on the respondent mean spending on SWE water of 2.49 GHS per household per week. Assuming the mean spending on total water was 7.07 GHS, the model predicts the average household would spend 2.74 GHS each week on SWE water (Equation (5)), which was statistically similar to the actual results ($p = 0.454$).

While providing useful insights, each model has the following limitations. Tested determinants are not exhaustive, with factors such as age or flow rate potentially increasing accuracy. As most communities were rural in this study, network analysis was deemed unnecessary. This accounts for increased distance due to movement along street grids, but only a few peri-urban environments could have seen some benefits. Also, a few instances of error were observed where water sources were near schools or markets, and it is assumed respondents living far away may collect on the

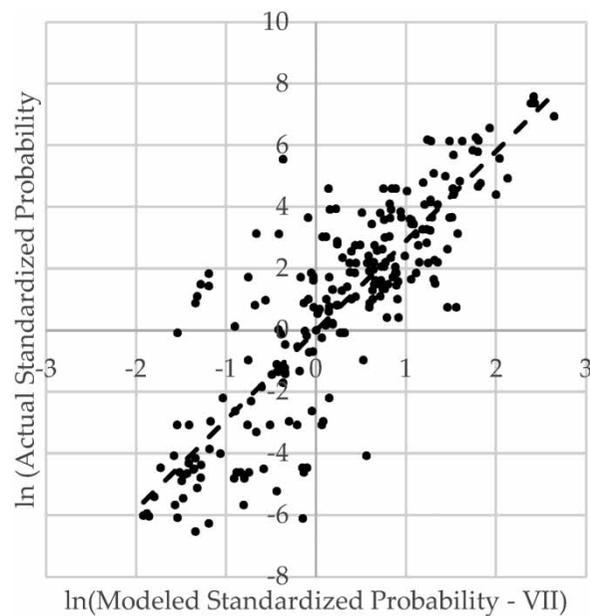


Figure 4 | Predicted versus actual probabilities for using a given water source using the log-normal standardized probability.

way home from work or school. Treating streams and other surface sources as lines or polygons rather than collection points could also impact model results. Due to the cluster sampling methodology, the assumption was made that mean water spending was representative of buying power for the district, but it should ideally be community specific (Drezner & Drezner 2004). Finally, this model will change with present day market structure and trends, such as new laws or companies. The temporal study conducted by Opryszko *et al.* (2013) showed that penetration can change over time, emphasizing the importance of recently collected data in future iterations.

Two additional limitations should be pursued in future research. First, considering fluctuations in facility attractiveness due to rainfall patterns would better represent seasonal priorities (Hope *et al.* 2020). In this region of Ghana, many households would set out large barrels to collect rain, essentially creating an onsite source of water based on rainfall patterns. Second, the use of multiple sources impacts purchase volumes and should be incorporated. In this study, only 20.1% of total water collected is from an SWE source, despite capturing 35.2% of the market share of revenue.

Discussion

The results presented in this study provide evidence to support the hypothesis that market saturation, or approaching 100% penetration, is unrealistic for a safe water enterprise using communal water sources. The Huff gravity model illustrates how existing alternatives still have attractiveness, either by being closer to the home, a cheaper price, or better tasting. These effects will most likely decrease as household piped connections become more prevalent, but are very applicable when central collection points exist.

For the Wassa East district, the actual SWE penetration rate within the intervention group was determined to be 37.8, 95% CI [31.4, 44.7], in a companion study (Deal & Sabatini 2020). The maximum penetration predicted in the various Huff models was 68.6%, which assumed that distance, reliability, and quality were the most valued traits of a water source. Understanding that taste and appearance are more valuable to the average household, it is more reasonable to assume that the

maximum penetration attainable *with existing competition* is roughly 58% (model V), without considering affordability. With all factors considered while holding the market rules constant, the Huff model predicted that penetration would reduce to 38.8% (model VII). This falls within the confidence interval of the household survey results and is corroborated by a concurrent willingness-to-pay assessment summarized in Supplementary Appendix E. The market share of available revenue (35.2%) also reflected the market penetration rate.

Affordability was a critical motivator for certain households within the intervention population. While this did not play a significant role in the control group (6–8%), 18.9% of intervention households claimed they could never afford SWE water regularly. Further, if mean spending on total water for the district is 7.07 GHS per week, a household can afford about 636 L from the SWE at its current price. This was sufficient for drinking, cooking, and some hygiene needs, but insufficient for bathing and cleaning volumes reported by the control group. This suggests an absolute limit for market penetration at the current price and emphasizes the importance of maintaining cheaper, but safe, alternatives in this context. Other improved sources likely allow for the use of multiple sources and take away from the financial sustainability of the SWE, and vice versa. However, their availability also provides leverage to keep the private company accountable in both price and performance of the service.

It was interesting to observe the market attempt to influence the price of water, which was captured by the ‘social pressure’ factor in the Huff model. For communities that wanted a price drop from 0.20 to 0.10 GHS/18 L, a ‘boycott’ occurred. The higher price, which is common for standpipes in a few of the medium-sized towns, was agreed upon in a signed agreement prior to construction. However, the community applied pressure to renegotiate to common handpump prices (0.10 GHS/18 L) after the capital investment had already occurred. In this circumstance, pressure was possible because of the existing alternatives available and because the local government had allowed their continued use. A change in regulation or contract terms, such as exclusivity rights, delegated management areas, or pro-poor legislation, could theoretically change these conditions.

However, the motivations behind the Huff model suggest that competition will continue to be a factor, regardless of formality, and should not be dismissed.

CONCLUSIONS

Overall, the Huff gravity model (model VII) and the household survey both agreed that the actual penetration in the Wassa East District should fall between 35 and 40% at the time of the study. This accounted for the attractiveness of individual water sources, the distance from each household, and the differing prices. For similar SWEs, this predictive model can be used to estimate market share based on company decisions on location and price. With only a water point inventory of a given area, it can help to determine the proportion of the population actually served, rather than assuming an entire community is benefiting. With the addition of consumer data, these results can be used as part of a financial projection tool to predict cost recovery for the targeted district. Practically, Access Development has applied this modeling technique in this capacity.

Formal SWEs are looking to fill gaps in water service provision in urban and rural communities across the globe. Many examples offer treated, improved water and reliable service to their customers in an effort to provide continuous supply and protective health benefits. Their goal is to offer a better product in scenarios where existing piped, communal, and unsafe water alternatives are already providing for the population. This study has shown that an SWE will inherently face reduced penetration due to competition and differing motivations of its customer base. It is critical that implementers, funders, and policy-makers understand these implications, allowing for effective institutional arrangements and a realistic perspective of the role that these businesses can fill in the water provision ecosystem.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. Visit: <http://dx.doi.org/10.17632/b6gs9fd33z.2>.

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