Article

Geographic Distribution of Registered Packaged Water Production in Ghana: Implications for Groundwater Management and Environmental Impacts

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Abstract: Packaged water consumption has grown rapidly in urban areas of many low and middle income countries, but particularly in Ghana. However, the sources of water used by this growing packaged water industry and its implications for water resource management and transport-related environmental impacts have not been described. This study aimed to assess the spatial distribution of regulated packaged water production in Ghana, both in relation to demand and for natural mineral water, to hydrogeological characteristics. 764 addresses for premises licenced to produce packaged water from 2009-2015 were mapped and compared to regional sachet water consumption and beverage import/export data examined. We find evidence to suggest packaged water is transported shorter distances in Ghana than in developed countries. For natural mineral waters, producers should be able to address the most widespread water quality hazards (including high salinity, iron and nitrates) in aquifers used for production through reverse osmosis treatment. The study suggests there is scope to integrate beverage product and groundwater regulatory databases to support groundwater management.

Keywords: water footprint; bottled water; groundwater; Africa; water resource management; urban

1. Introduction

With a projected increase in the urban African population of over 300 million between 2010 and 2030 [1], supplying water services to the region's growing cities remains a priority. Although the proportion of urban population using improved water sources rose from 83% to 87% between 1990 and 2015 in urban sub-Saharan Africa [2], many African cities became reliant on increasingly distant rivers and groundwater bodies to meet demand for piped water during the 1990s [3]. More generally, the water demands of megacities can extend far into surrounding agricultural areas [4]. Alongside the piped water demand from urban populations being met from more distant sources, consumption of packaged water (i.e. water sold in bottles or plastic bags) has also grown in low and middle countries [5], particularly in urban areas [6]. However, given that most studies of packaged drinking-water in low and middle income countries have focussed on its quality and consumption (e.g. [7,8]) and far fewer on its production [9,10], the implications of this emerging urban packaged water demand for water resource management in cities' hinterlands remains unclear.

There is similarly little evidence on the environmental impact of the packaged water industry in low and middle income countries. In the USA, however, environmental impact studies suggest whilst bottled tap water may be produced close to urban centres, natural mineral water products marketed as 'spring water' may be transported much longer distances from pristine environments, increasing

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the energy required to meet demand [11]. Under the Millennium Development Goals [12], depending on specific circumstances affecting individual countries, packaged water was sometimes considered unsustainable and therefore an 'unimproved' water source in monitoring safe water access. Quantification of the spatial distribution of packaged water production could thus help inform policy surrounding this growing industry through better understanding of its environmental impacts. It could also provide insights into the water-related challenges faced by an industry that consumers increasingly depend on.

Given this context, this study aims firstly to identify the spatial distribution of packaged water production licences issued by regulatory bodies in Ghana and secondly to compare the geography of regulated production with that of consumption, so as to better understand the energy implications of packaged water transportation. Finally, we aim to assess this pattern of natural mineral water production in relation to hydrogeological productivity, borehole drilling success rates, and vulnerability to contamination. In doing so, we seek to understand the water resource management implications of growing urban demand for packaged water in Ghana.

2. Materials and Methods

2.1. Packaged water production and hydrogeology in Ghana:

In Ghana, packaged water in the form of 500ml filled bags or 'sachets' is now widely consumed, with 43.1% of urban households reporting it as their main drinking-water source in 2014 [13], up from 15.2% in 2008 [14] and 3.0% in 2003. Despite Ghana's packaged water industry now being the main drinking-water supply for almost half of urban consumers, the origins of the water supplied remain unclear. The industry is regulated by the Ghana Standards Authority (GSA) and Food and Drugs Authority (FDA) [9]. The GSA are responsible for two standards, with a more stringent standard covering production of natural mineral water 'obtained directly from natural or drilled sources from underground water-bearing strata' [15]. Such waters should be collected under conditions that guarantee their purity and a prescribed chemical composition. A second standard covers other forms of packaged water, notably packaged tapwater but also groundwaters that may not meet mineral water requirements [16]. The FDA are responsible for product registration to these standards, which has been mandatory since 2012. However, an unknown proportion of small-scale producers, known as '*abalowe*', remain unregistered. Regulation of groundwater abstraction is the responsibility of the Water Resources Commission (WRC) [17], whilst tariffs for commercial users of piped water are set by the Public Utilities Regulatory Commission.

The extent of groundwater use for sachet water in Ghana is currently unknown, however there is evidence to show that groundwater is used for both regulated (under [15]) and unregulated sachet water supply in Ghana [18]. More recently, there is evidence that Ghanaian sachet producers have switched from packaging tap water to groundwater abstraction in the face of piped water supply interruptions and higher tariffs from the national piped water utility, Ghana Water Company Ltd [19].

Ghana can be divided into two main and two minor hydrogeological units. The major units include the basement complex which covers 54% of the country and dominates western Ghana and comprises i) Lower Proterozoic volcanics and metasediments of the Birimian system and Middle Proterozoic sediments of the Tarkwaian system and ii) the Mobile Belt of the Dahomeyan system (gneiss), Togo series (quartzite, schist and silicified limestone) and Buem formation (argillaceous and volcanic sediments) [20]. The second major unit is the Voltaian system which covers 45% of the country in central and eastern Ghana. This comprises Proterozoic-Palaeozoic sedimentary formations including sandstones, shales, mudstones and conglomerates. The first minor unit comprises three coastal aquifers of Cenozoic and Mesozoic sediments: i) recent sand deposits with thin freshwater lenses, ii) sandy clay Red Continental deposits which usually contain saline water and iii) Cretaceous

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limestone at a depth of 100 m usually containing freshwater [21]. The second minor unit includes recent alluvial sand and gravel deposits, which are locally important [22]. Average borehole yields are highest for the Birimian units of the basement complex and the coastal and alluvial units (3.3-4.3 L/s) [23] and lowest for the Dahomeyan units of the basement complex (typically <1 L/s). Borehole success rates follow similar patterns and both borehole success rates and yields vary considerably within and between hydrogeological units and sub-units [22].

Although groundwater is considered to be of generally good quality in Ghana [22], high total dissolved solids up to 2000 mg/L are found in shallow groundwaters in the Keta basin and the Accra plains and these coastal aquifers are particularly vulnerable to over pumping and saline intrusion [24]. High fluoride concentrations up to 5 mg/L are found in some groundwaters in northwest and north-eastern granitic and volcanic terrains [25], whilst elevated arsenic concentrations (up to 141 µg/L) are reported in the Birimian basement aquifers [26]. The most widespread issues is high iron, over 60 mg/L in some instances, affecting up to a third of boreholes drilled in Ghana [22]. The high iron is thought to originate from corrosive groundwaters reacting with borehole casing and other pump components. High nitrate and microbiological contamination of shallow groundwater sources in urban and rural settings is a widespread threat to drinking water quality [27].

2.2. Data

To assess domestic packaged water production, records were obtained of sachet and bottled water producers registered with the GSA nationally and with the FDA in Greater Accra region. GSA records covered the period December 2009 to October 2015 and were drawn from published lists of registered producers, e.g. [28], whilst the FDA provided records directly for currently registered producers only, as of June 2016. Imported volumes of unsweetened beverage waters and ice from 1996-2013 as reported by the Government of Ghana were also downloaded from the UN CommTrade database (http://comtrade.un.org/).

Data from the 2012-13 Ghana Living Standards Survey Round 6 (GLSS6) were used to assess the regional pattern of sachet consumption. The GLSS6 was designed to be nationally and regionally representative, sampling 1,200 enumeration areas (EAs) from within 10 regions, using probability-proportional-to-population size. Within each selected EA, 15 households were systematically selected, giving an overall sample size of 18,000 households. Selected households were then asked about packaged water purchases over six separate visits.

2.3. Data pre-processing and analysis

To map packaged water manufacturing, addresses or place-names for manufacturers from these sources were geocoded using the Google Maps Application Programming Interface (API), version 2. Where addresses or placenames could not be found using this API, they were geocoded using the MapQuest API to the OpenStreetMap global database via the *geocodeopen* tool in Stata v13. Manual searches in Google Maps were used subsequently to review any remaining place-names or addresses lacking coordinates. To assess whether there were differences in the geographic distribution of natural mineral water producers versus other packaged water producers, we performed separate kernel density estimation on the resultant geocoded locations for these two groups. We used a quartic kernel function [29] and a bandwidth derived from the standard and median distance to producer-weighted mean centre of the pooled locations.

In the Ghanaian GLSS6, packaged water expenditure and unit prices were recorded, so daily volumes purchased were calculated by dividing expenditure by the appropriate price. We then calculated the total volumes purchased by region in 2012-13 using the Stata *svy* set of commands to account for the multi-stage sample design. Total packaged water consumption by region was then compared to the number of GSA licences granted for packaged and natural mineral water

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respectively. We also compared total national packaged water consumption from the GLSS6 to imported water beverages, as reported through the UN COMTRADE database.

3. Results

3.1. Geocoding and characteristics of registered packaged water production

In total, there were 764 instances of manufacturers registering with the GSA. These instances related to 291 locations, of which 278 were geocoded using the Google Maps API and the remainder either via the MapQuest API or manually (Figure 1). All were geocoded to at least the city level and the majority to the town or neighbourhood level, with only 8 being geocoded to address level. The FDA records contained 180 manufacturers in 65 locations across Greater Accra Region. The locations were all geocoded with Google Maps API to town level or higher precision (Figure 1).

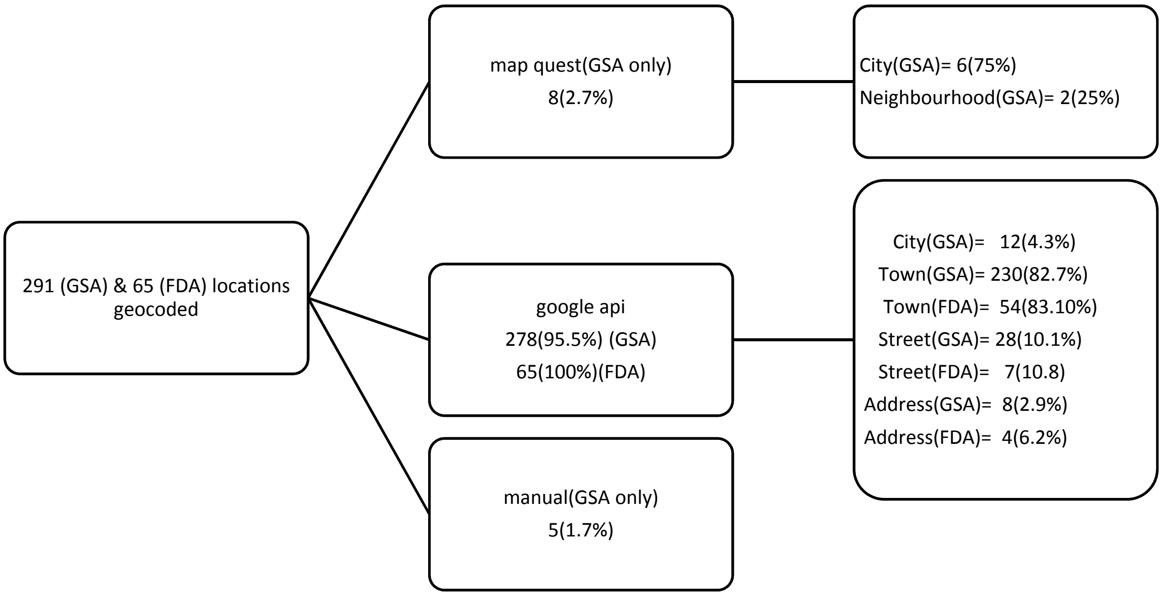


Figure 1. Flowchart, showing geocoding engines used and precision of geocoded locations for 764 records of packaged water manufacturers who registered: (a) nationwide with the Ghana Standards Authority (GSA) from 2009 to 2015; (b) who were registered with the Food and Drugs Authority (FDA) in Greater Accra region, as at June 2016

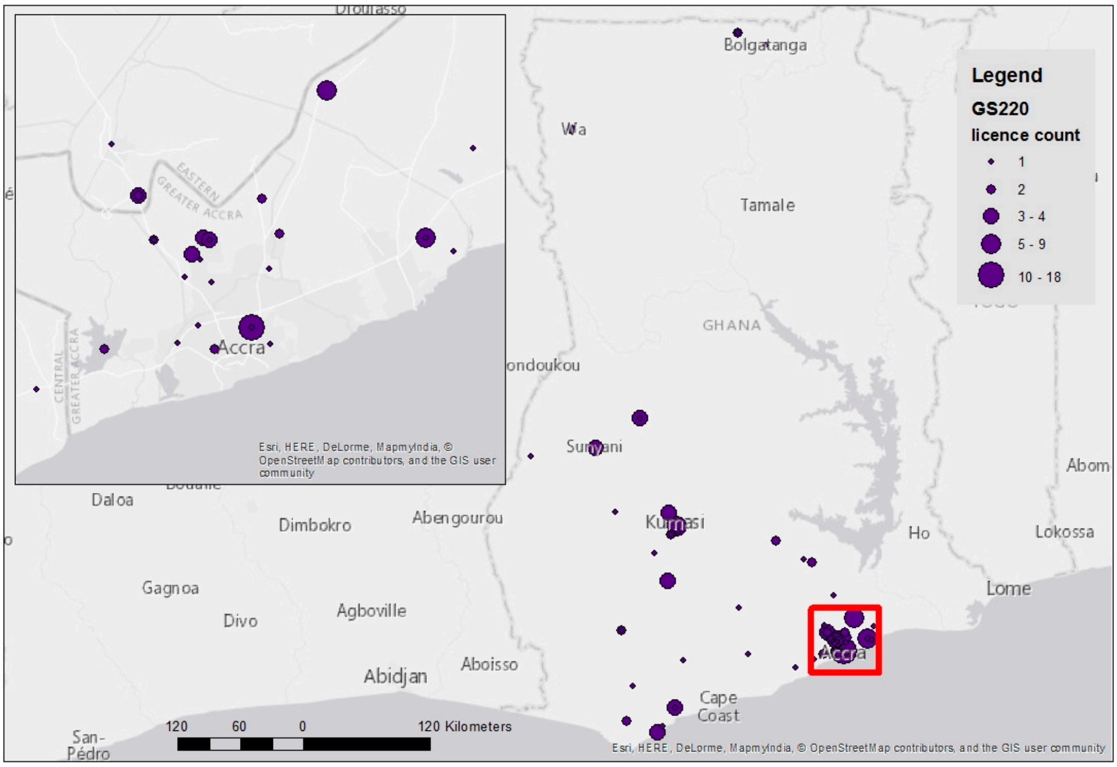
Most licences granted by the GSA were for production of bagged (sachet) water (Table 1), with the majority being granted licences under the packaged water rather than mineral water standard. As of June 2016, the FDA had similarly granted most licences (116; 64.4%) for packaged rather than mineral water.

Table 1. Characteristics of packaged water products registered with the Ghana Standards Authority, December 2009 to October 2015.

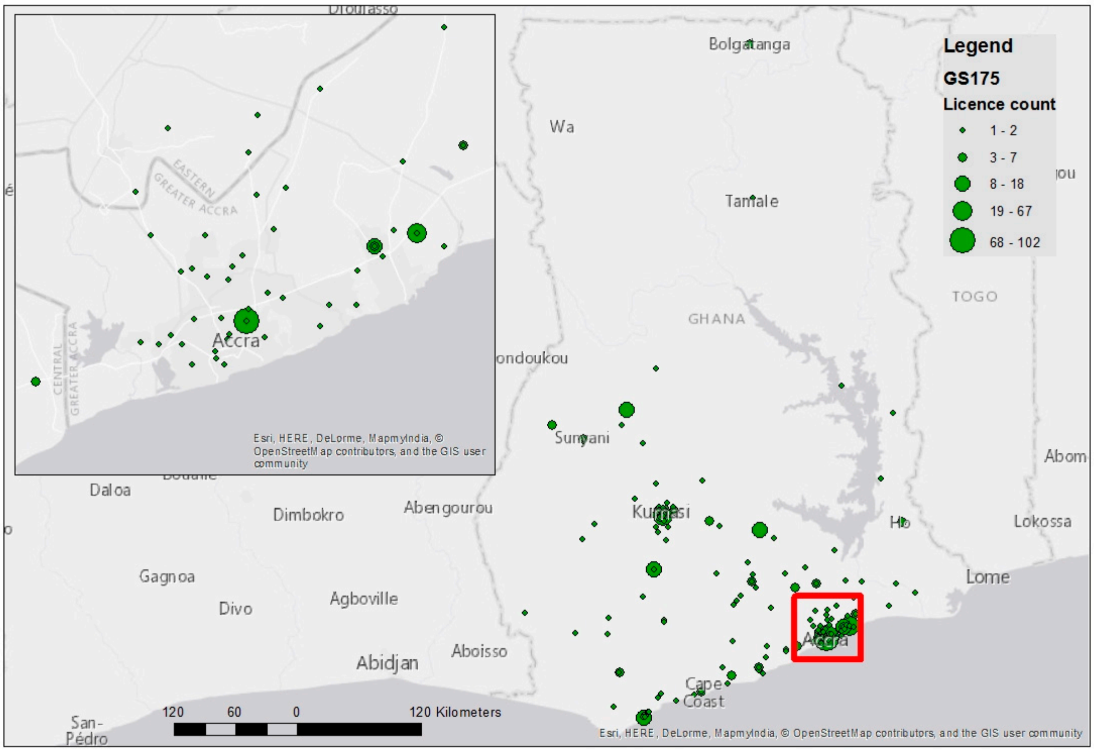
Product characteristic	No. of GSA licences (%)
Year of producer registration	
Registration date not recorded	20(2.6)
2009 (December only)	12(1.6)
2010	131(17.1)
2011	151(19.8)
2012[1]	45(5.9)
2013	149(19.5)
2014	157(20.5)
2015 (January to October)	96(12.6)
2016	
Product registered	
Packaged water (bagged)	579(75.8)
Mineral water (bagged)	77(10.1)
Bottled water	62(8.1)
Both bagged and bottled water	23(3.0)
Dispenser drinking water	19(2.5)
Ice cubes	1(0.1)
Region of production	
Ashanti	173(22.6)
Brong-Ahafo	30(3.9)
Central	51(6.7)
Eastern	63(8.2)
Greater Accra	334(43.7)
Upper East	7(0.9)
Volta	14(1.8)
Western	67(8.8)
Upper West	3(0.4)
Northern	1(0.1)
Not specified / geocoded	18(2.4)
Standard	
Mineral water (GS220)	145(19.0)
Packaged water (GS175)	619(81.0)
Total	764

3.2. Spatial patterns of registered packaged water production

Figure 2 shows the spatial distribution of licences granted by the GSA for natural mineral water packaged drinking-water products from 2009 to 2015. For both types of product, registered manufacturing is concentrated around Accra and Kumasi, Ghana's two main urban centres. This distribution also reflects large numbers of producer addresses that could only be imprecisely geocoded to the town or city level. The majority of GSA licences granted were in the Ashanti and Greater Accra regions containing these two cities. However, there are some geographic differences between natural mineral water and packaged water production. In Accra (inset map), for example, there are more natural mineral water producers to the north of the city along the border with Eastern Province.



(a)



(**b**)

Figure 2. Number of licences granted between December 2009 and October 2015 by the Ghana Standards Authority for production of (a) natural mineral water and (b) packaged drinking-water.

Figure 3 shows the spatial distribution of FDA licences active as of June, 2016 within Greater Accra. Similar to the GSA records, mineral water production is somewhat more concentrated to the north of Accra city relative to packaged water production.

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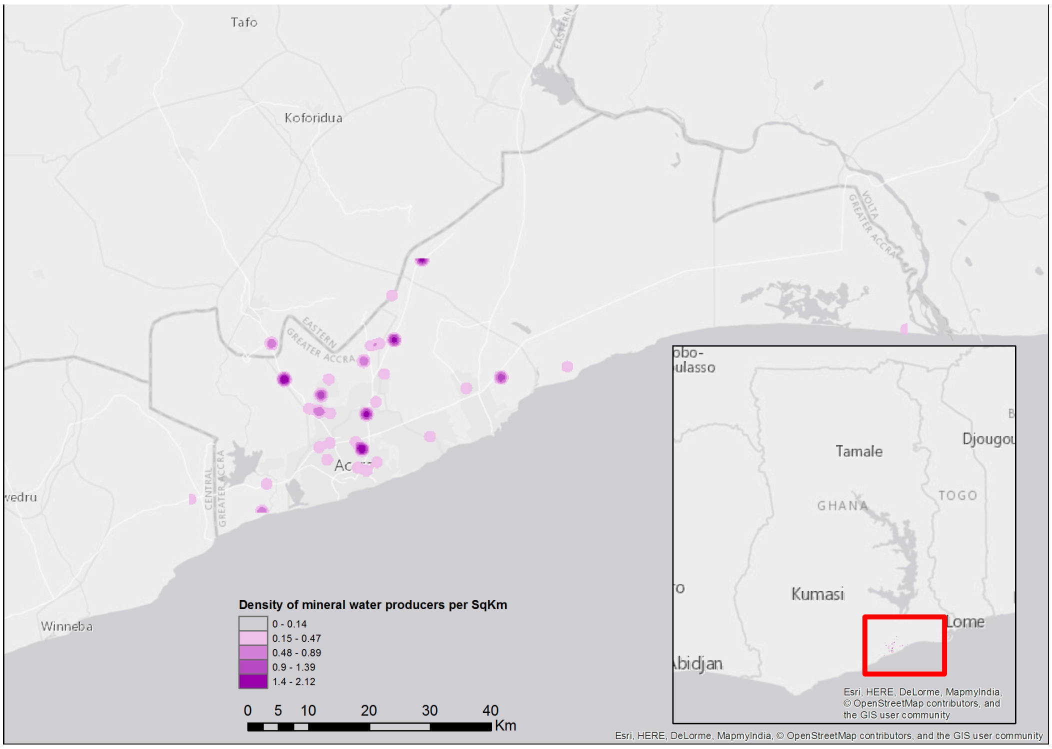
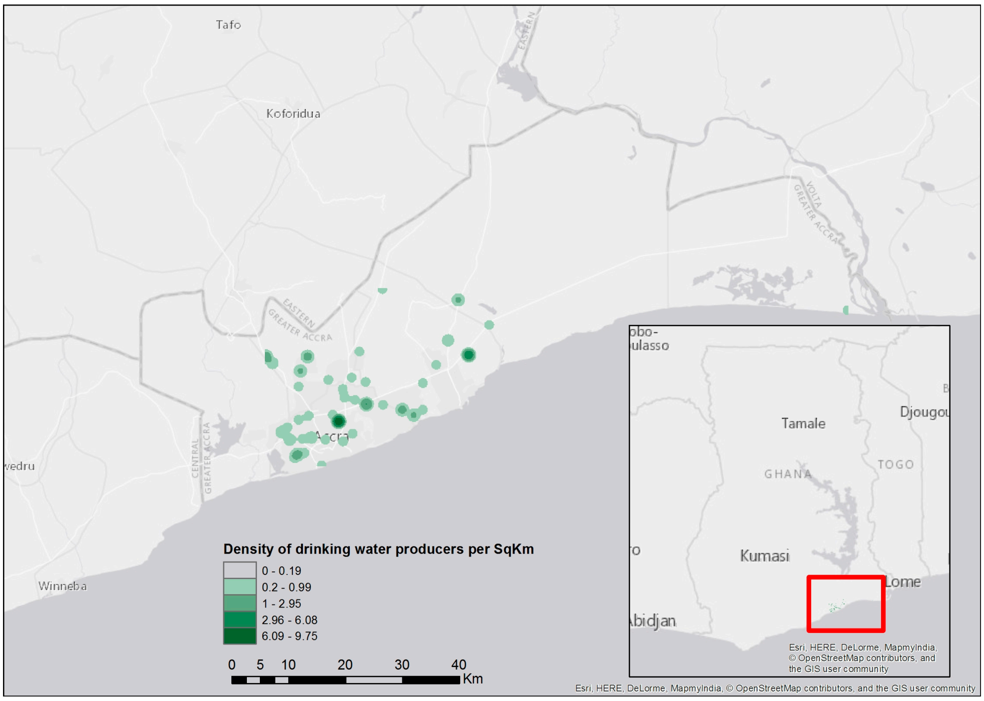


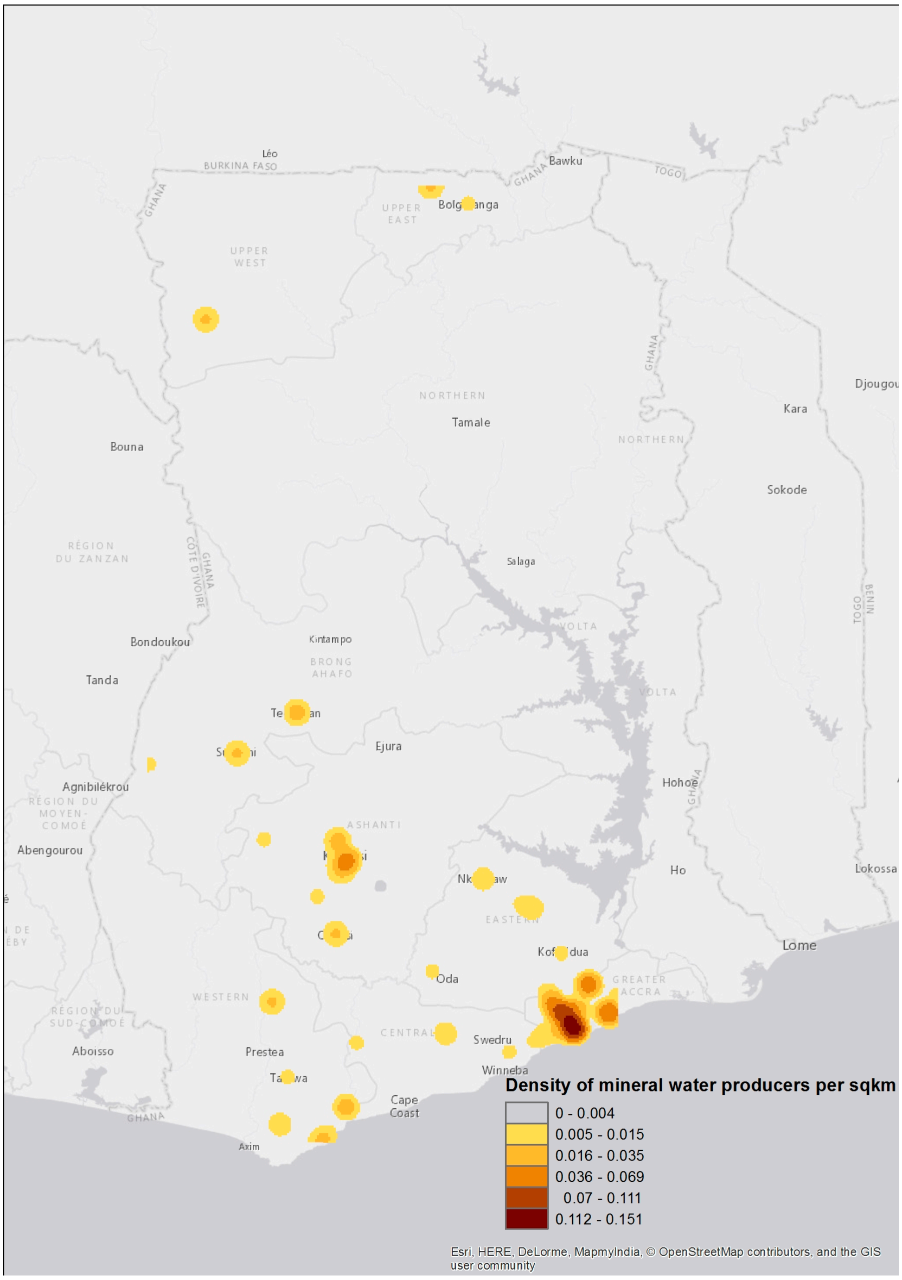
(a)



(b)

Figure 3. Density of licences granted within Greater Accra region as of June 2016 by the Food and Drugs Authority for production of (a) natural mineral water and (b) packaged drinking-water.

Figure 4 shows the density of natural mineral water producer licences versus other packaged water licences based on GSA records for 2009-2015. The natural mineral water producers, many of whom produce bottled water, were more heavily concentrated around the major urban centres such as Accra, Kumasi and Sunyani. Six of the ten regional capitals in Ghana had high counts of packaged water producers, as did other industrialised municipalities such as Techiman and Nkawkaw.



(a)

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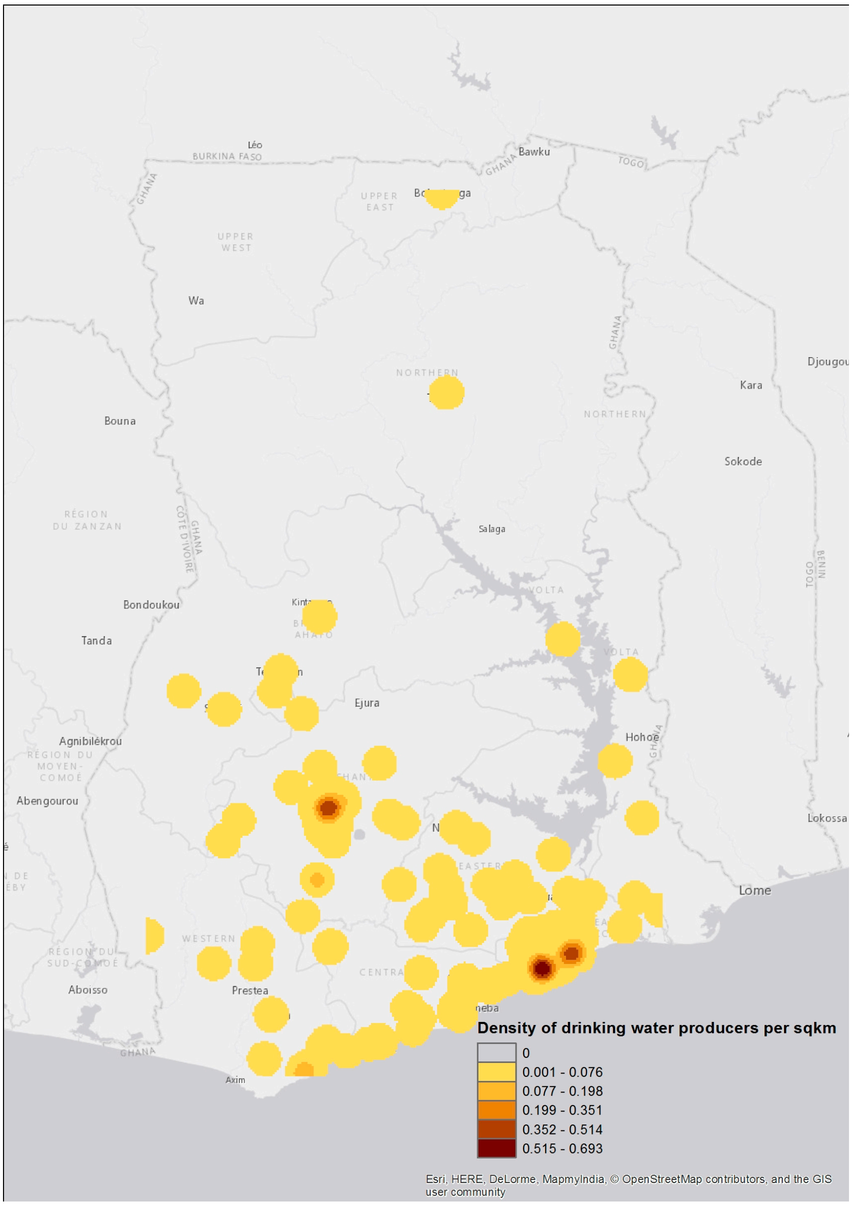

(**b**)

Figure 4. Density of Ghana Standards Authority producer licences, 2009-2015 for (a) natural mineral waters and (b) other forms of packaged water including tapwaters.

Figure 5 shows the number of GSA packaged water licences in relation to sachet consumption (as estimated from the 2012-13 GLSS6 survey data) by region. Both production and consumption were concentrated in Greater Accra and Ashanti regions and were highly correlated.

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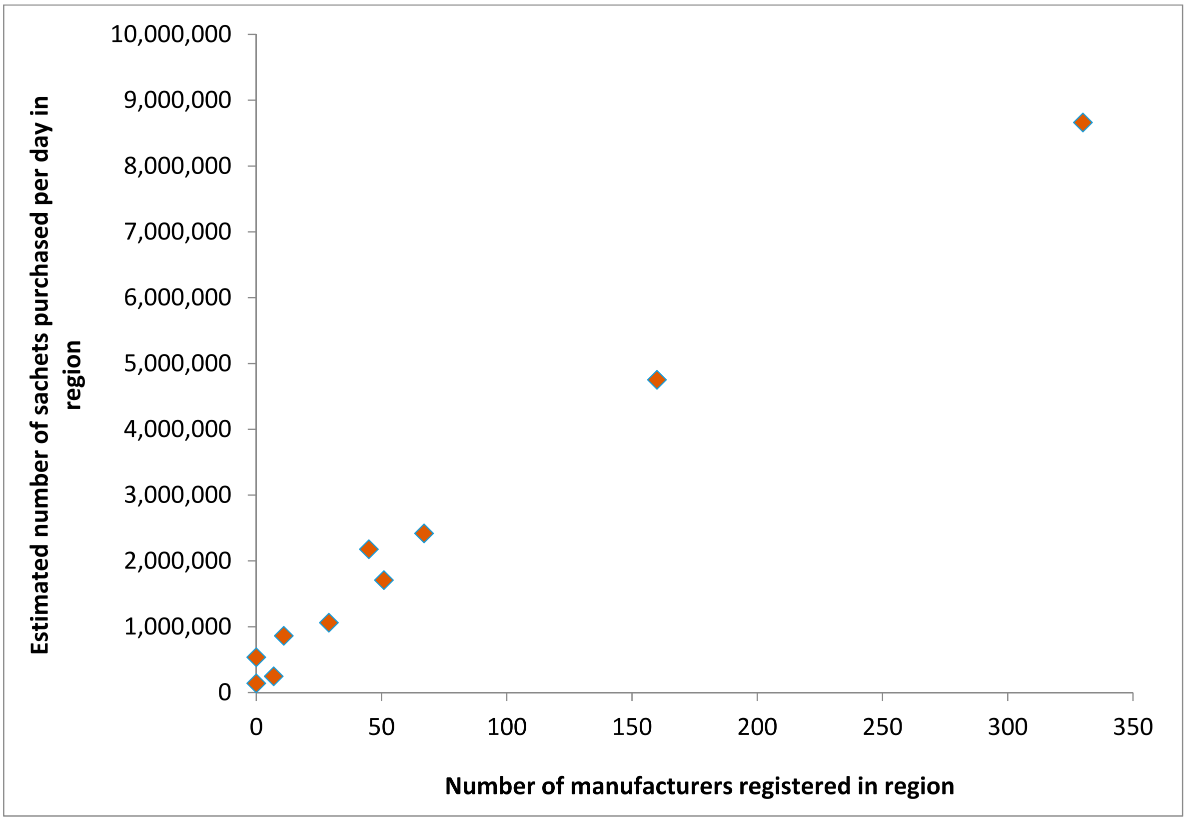

Figure 5. Estimated daily sachet consumption in 2012-13 versus number of Ghana Standards Authority producer licences granted from 2009 to 2015 by region.

3.3. Imported beverage waters

Figure 6 shows the volume of unsweetened beverage waters and ice imported into Ghana from 1996 to 2013. Imported volumes were greatest from 2006 to 2009, but fell thereafter. The GLSS6 survey data suggested Ghanaian households consumed over 11 million litres of sachet water daily in 2012-13 (Figure 5), so these imports met only a very small fraction of this demand (0.01% in 2012; 0.02% in 2013).

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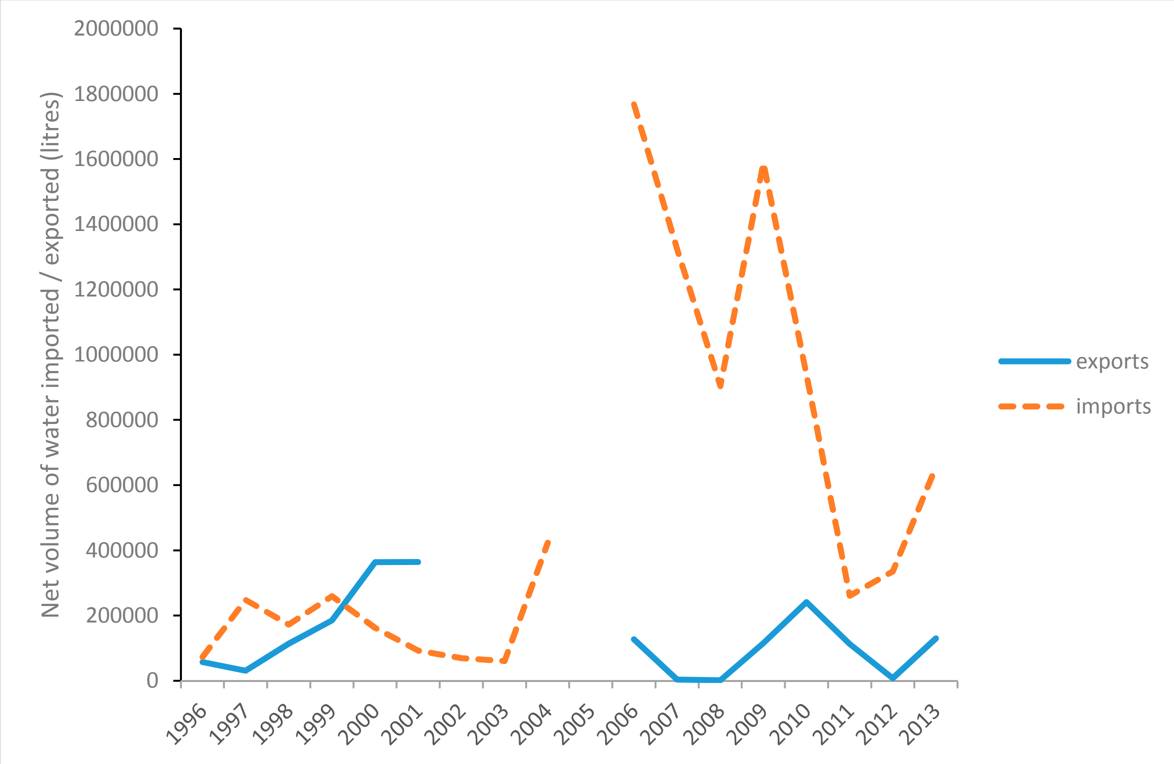

Figure 6. Annual volumes of imported and exported unsweetened beverage waters and ice, 1996-2013, as reported by the Government of Ghana (source: DESA/UNSD, United Nations COMTRADE database).

4. Discussion

Although urban packaged water consumption in low and middle income countries is growing, there is little research on packaged water production and its implications for water resource management in such countries. Our study provides evidence on packaged water production in Ghana, where growth of packaged water consumption has been particularly rapid. We find that demand for packaged water is overwhelmingly met (99.98%) through domestic production (Figure 6) rather than imports and that registered production of both natural mineral water and other packaged water is closely aligned with consumption at regional level (Figure 5). This contrasts with the USA, where natural mineral waters are reportedly transported long distances [11]. In the USA in 2013, UN COMTRADE data suggest a much higher proportion (680,156 litres/year or 1.48%) of a reported 46 billion litres of packaged water consumed [5] was met through imports. Given the need for Ghanaian producers to sell packaged water at low prices, this finding is plausible and implies lower energy costs of packaged water transportation in LMICs relative to high income countries. In contrast to the growing water footprint from urban piped utilities [3], Figure 4 suggests that regulated packaged water production takes place close to the urban centres where packaged water is consumed.

The spatial distribution of packaged water production confirms earlier reports that groundwater abstraction for packaged water production is concentrated in the Densu Basin [30], which includes the capital, Accra. In 2005, based on abstraction licences and inspection of industrial premises, the WRC estimated that major packaged water producers were among several industries abstracting up to 1,000,000m3/year in the basin [31]. A granite-gneiss complex underlies 90% of the Densu Basin, having negligible primary porosity and groundwater is found in the overlying weathered regolith or in fractures within the deeper basement rocks. 4% of the northern part of the Basin comprises sandstone, tuffs, quartzite and breccia of the Birimian formation, whilst the southern portion (6%) is underlain by the Togo formations comprising sandstone, quartizite, shale and schist. Both the

Birimian and Togo formations have generally higher primary porosity and transmissivity and higher borehole yields compared to the granite complex [20,23]. Aquifer vulnerability within basement rocks which underlie the Basin is high, since the shallow weathered regolith in the granite-gneiss complex, which dominates the Basin, is particularly vulnerable to pollution and over-abstraction due to low storage and variable yields. Overall groundwater in the Basin is weakly acidic, with mineralization/salinity increasing from the north towards the coastal Togo formations [32]. This could lead to water quality and borehole functionality challenges, including potentially chemically aggressive, acidic and low Specific Electric Conductivity (SEC) waters (<100 µS cm^{-1}) in the northern Basin, high SEC Na-Cl waters (2-10 mS cm^{-1}) which are also chemically aggressive to steel components and clearly of concern from a water quality perspective.

High nitrate and chloride, above WHO guideline values, are reported for many boreholes and wells within the central and lower Basin, which has extensive agricultural land use and urbanization [33]. There is little published data on microbiological contamination in groundwater in the Basin, though high borehole turbidity has been widely observed across the Basin (e.g. [34]), which strongly suggests faecal contamination of water could affect any sachet producers reliant on shallow wells and poorly constructed boreholes. Fluoride concentrations are typically below WHO guideline concentrations within the Basin, though 9% of sites were found to be >1.5 mg/L in a recent Basin-wide study [34]. Excess total iron concentrations from both geogenic sources and borehole casing, and to a lesser extent manganese, are reported across the basin, in part due to the acidic groundwater and low dissolved oxygen [35,36]. This has important implications for borehole design and functionality, and may impact on the quality of groundwater abstracted for sachet water production vendors.

Given calls for cross-sector linkages in groundwater management [37], there is scope to connect packaged water regulation with integrated groundwater resource management, for example through sharing of data on licences granted for beverage production by the GSA and FDA with groundwater abstraction records held by the WRC. This analysis also provides some insights into how any future increases in piped water tariffs for packaged water producers [19] could affect the spatial distribution of this industry. Such tariff rises would likely incentivise packaged water production from productive groundwaters with high drilling success rates, located close to the major centres of demand in Kumasi and Accra. However, given reported localized variation in borehole drilling success rates within hydrogeological units and sub-units [22], there is a considerable financial risk to producers who invest in borehole drilling, without suitable hydrogeological investigations, to avoid piped water rationing and increased utility tariffs.

Our findings are affected by several sources of uncertainty. Our analysis is dependent on the completeness and accuracy of the GSA and FDA producer registers. However, smaller-scale, unregistered sachet producers known as 'abalowes' are known to operate in Ghana [9] and such unregistered production is not captured in our analysis. Given that unregistered producers typically sell sachets at discounted prices [9], such producers are likely to be located close to urban centres of demand, to reduce transport costs. Some producers registered to the packaged water standard may also abstract groundwaters in addition to abstraction by natural mineral water producers, but it is not possible to differentiate this group based on regulatory databases. In common with many developing countries, Ghana lacks an address referencing system for precise geocoding [38]. Furthermore, whilst regulators record manufacturing facility locations as well as registered business addresses, there is potential for the two to be confused. The town-level precision of geocoded producer addresses and coarse spatial resolution of some of the hydrogeological map layers used may thus have affected our assessment of the density of packaged water abstraction. Our examination of the spatial pattern of packaged water production and consumption did not consider the distribution sector of the supply chain. It is thus possible that packaged water is transported long distances to markets, despite the proximity of production facilities to major urban centres.

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These limitations relating to the content of regulatory databases highlight potential knowledge gaps that could be addressed through field visits to producer premises and interviews with those working in the industry. The actual distribution channels used by producers could be explored by tracing supply chain entities backwards from interviews with retailers. Subsequent follow-up interviews with the distributors and producers identified would enable greater understanding of production processes among unregistered producers and the extent of groundwater use and treatment by regulated producers not registered under the mineral water standard. Such work would also enable more precise georeferencing of production facilities and thereby greater insights into groundwater abstraction, safety and their management. The approach taken here could be applied in other countries with registers of regulated packaged water producers, such as Nigeria, where the National Agency for Food and Drug Administration holds similar records of certified producers [39,40].

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References

1. United Cities and Local Governments. *Basic services for all in an urbanizing world: Third global report of united cities and local governments on local democracy and decentralization. Gold iii.*; Barcelona, 2013; p 433.
2. UN-Habitat. *Urbanization and development - emerging futures: World cities report 2016*; United Nations Human Settlement Programme: Nairobi, Kenya, 2016; p 262.
3. Showers, K.B. Water scarcity and urban africa: An overview of urban-rural water linkages. *World Development* **2002**, *30*, 621-648.
4. Li, E.; Endter-Wada, J.; Li, S. Characterizing and contextualizing the water challenges of megacities. *Journal of the American Water Resources Association* **2015**, *51*, 589-613.
5. Rodwan, J. Bottled water 2013: Sustaining vitality - us and international developments and statistics. *Bottled Water Reporter* 2014, p 11.
6. Stoler, J.; Fink, G.; Weeks, J.R.; Otoo, R.A.; Ampofo, J.A.; Hill, A.G. When urban taps run dry: Sachet water consumption and health effects in low income neighborhoods of accra, ghana. *Health & Place* **2012**, *18*, 250-262.
7. Kassenga, G.R. The health-related microbiological quality of bottled drinking water solid in dar es salaam, tanzania. *Journal of Water and Health* **2007**, *5*, 179-185.
8. Bordalo, A.A.; Machado, A. Water bags as a potential vehicle for transmitting disease in a west african capital, bissau. *International Health* **2015**, *7*, 42-48.
9. Stoler, J.; Weeks, J.R.; Fink, G. Sachet drinking water in ghana's accra-tema metropolitan area: Past, present, and future. *Journal of Water Sanitation and Hygiene for Development* **2012**, *2*, 223-240.
10. Fisher, M.B.; Williams, A.R.; Jalloh, M.F.; Saquee, G.; Bain, R.E.S.; Bartram, J.K. Microbiological and chemical quality of packaged sachet water and household stored drinking water in freetown, sierra leone. *Plos One* **2015**, *10*.
11. Gleick, P.H.; Cooley, H.S. Energy implications of bottled water. *Environmental Research Letters* **2009**, *4*.

12. Stoler, J. Improved but unsustainable: Accounting for sachet water in post-2015 goals for global safe water. *Tropical Medicine & International Health* **2012**, *17*, 1506-1508.
13. Ghana Statistical Service (GSS); Ghana Health Service (GHS); ICF International. *Ghana demographic and health survey 2014*; Rockville, Maryland, USA, 2015; p 530.
14. Ghana Statistical Service (GSS); ghana Health Service (GHS); ICF International. *Ghana demographic and health survey 2008*; Accra, Ghana, 2009; p 512.
15. Ghana Standards Authority. *Water quality - specification for natural mineral water*; GS 220: 2005; Accra, 2005; p 9.
16. Ghana Standards Authority. *Water quality - specification for drinking-water*; Accra, 2009; p 23.
17. Water Resources Commission. Drilling licence and groundwater development regulations. In *LI1827*, Commission., W.R., Ed. Water Resources Commission: Accra, 2006; Vol. LI1827, p 15.
18. Ahimah, J.K.; Ofosu, S.A. Evaluation of the quality of sachet water vended in the new juaben municipality of ghana. *International Journal of Water Resources and Environmental Engineering* **2012**, *4*, 5.
19. Orgeira, N.; Wright, J.; Fink, G.; Aryeetey, G.; Dzodzomenyo, M.; Hill, A. The sachet water industry in ghana: Why understanding the production and regulatory system is important. *Urban Water Journal* **in review**.
20. MacDonald, A.M.; Calow, R.C.; Andrews, A.; Appiah, S. *Groundwater management in drought prone areas of africa, northern ghana – inception report*; British Geological Survey: Nottingham, UK, 1996; p 63.
21. Kortatsi, B.K. Groundwater utilization in ghana. In *Future groundwater resources at risk*, International Association of Hydrological Sciences: Helsinki, 1994; Vol. 222, pp 149-156.
22. Gyau-Boakye, P.; Kankam-Yeboah, K.; Darko, P.K.; Dapaah-Siakwan, S.; Duah, A.A. Groundwater as a vital resource for rural development: Example from ghana. In *Applied groundwater studies in africa*, Adelana, S.M.A.; MacDonald, A.M., Eds. CRC Press / Balkema: London, 2008; pp 149-169.
23. Dapaah-Siakwan, S.; Gyan-Boakye, P. Hydrogeologic framework and borehole yields in ghana. *Hydrogeology Journal* **2000**, *8*, 405-416.
24. Kortatsi, B.K. Hydrochemical characterization of groundwater in the accra plains of ghana. *Environmental Geology* **2006**, *50*, 299-311.
25. Apambire, W.B.; Boyle, D.R.; Michel, F.A. Geochemistry, genesis, and health implications of fluoriferous groundwaters in the upper regions of ghana. *Environmental Geology* **1997**, *33*, 13-24.
26. Smedley, P.L. Arsenic in rural groundwater in ghana. *Journal of African Earth Sciences* **1996**, *22*, 459-470.
27. Gibson, K.E.; Opryszko, M.C.; Schissler, J.T.; Guo, Y.Y.; Schwab, K.J. Evaluation of human enteric viruses in surface water and drinking water resources in southern ghana. *American Journal of Tropical Medicine and Hygiene* **2011**, *84*, 20-29.
28. Ghana Standards Authority. *List of products certified in february 2015*; Accra, 2015; p 5.
29. Silverman, B.W. *Density estimation for statistics and data analysis*. Chapman and Hall: New York, 1986.
30. Obuobie, E.; Boubacar, B. Ghana. In *Groundwater availability and use in sub-saharan africa: A review of 15 countries*, Pavelic, P.; Giordano, M.; Keraita, B.; Ramesh, V.; Rao, T., Eds. International Water Management Institute: Colombo, Sri Lanka, 2012; pp 42-62.
31. Water Resources Commission. *Densu river basin: Integrated water resources management plan*; Water Resources Commission: Accra, Ghana, 2007; p 90.
32. Dickson, A.; Abass, G.; Tetteh, T.A.; Richmond, F.; Piotr, M. Hydrochemical evolution and groundwater flow in the densu river basin, ghana. *Journal of Water Resource and Protection* **2011**, *3*, 4.

33. Gibrilla, A.; Osae, S.; Akiti, T.; Adomako, D.; Ganyaglo, S.; Bam, E.P.; Hadisu, A. Origin of dissolved ions in groundwater in the northern densu river basin of ghana using stable isotopes of ^{18}o and ^{2}h. *Journal of Water Resource and Protection* **2010**, *2*, 10.
34. Amoako, J.; Karikari, A.Y.; Ansa-Asare, O.D. Physico-chemical quality of boreholes in densu basin of ghana. *Applied Water Science* **2011**, *1*, 8.
35. Pelig-Ba, K. *On an investigation of the water quality problem on borehole ap216 at oyibi*; Water Resources Research Institute: Accra, Ghana, 1989; p 20.
36. British Geological Survey. *Groundwater quality: Ghana*; British Geological Survey: Nottingham, 2001; p 4.
37. Foster, S.; Ait-Kadi, M. Integrated water resources management (iwrm): How does groundwater fit in? *Hydrogeology Journal* **2012**, *20*, 415-418.
38. Goldberg, D.W.; Wilson, J.; Knoblock, C. From text to geographic coordinates: The current state of geocoding. *Journal of the Urban and Regional Information Systems Association* **2007**, *19*, 14.
39. National Agency for Food and Drug Administration and Control. Registered food products. http://www.nafdac.gov.ng/index.php/product-registration/registered-food-products (10/11/2015),
40. Olaoye, O.A.; Onilude, A.A. Assessment of microbiological quality of sachet-packaged drinking water in western nigeria and its public health significance. *Public Health* **2009**, *123*, 729-734.