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Framework for WASH Sector Data Improvements in Data-Poor Environments, Applied to Accra, Ghana

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Abstract: Improvements in water, sanitation and hygiene (WASH) service provision are hampered by limited open data availability. This paper presents a data integration framework, collects the data and develops a material flow model, which aids data-based policy and infrastructure development for the WASH sector. This model provides a robust quantitative mapping of the complete anthropogenic WASH flow-cycle: from raw water intake to water use, wastewater and excreta generation, discharge and treatment. This approach integrates various available sources using a process-chain bottom-up engineering approach to improve the quality of WASH planning. The data integration framework and the modelling methodology are applied to the Greater Accra Metropolitan Area (GAMA), Ghana. The highest level of understanding of the GAMA WASH sector is achieved, promoting scenario testing for future WASH developments. The results show 96% of the population had access to improved safe water in 2010 if sachet and bottled water was included, but only 67% if excluded. Additionally, 66% of 338,000 m^3 per day of generated wastewater is unsafely disposed locally, with 23% entering open drains, and 11% sewage pipes, indicating poor sanitation coverage. Total treated wastewater is <0.5% in 2014, with only 18% of 43,000 m^3 per day treatment capacity operational. The combined data sets are made available to support research and sustainable development activities.

Keywords: anthropogenic WASH mapping; WASH planning tool; Accra WASH sector characterization; open data

1. Introduction

According to the WHO and UNICEF in 2015, 2.4 billion people (33% of the global population) lacked access to improved sanitation facilities and 663 million people (9% of the global population) lacked improved drinking water sources [1–3]. In developing countries, the proportion of people lacking access to improved sanitation and drinking water is substantially higher. For example, in Sub-Saharan Africa, 70% and 32% of the population lacked improved sanitation and drinking water sources, respectively [1]. These deficiencies in the water, sanitation and hygiene (WASH) sector impose tremendous financial, health and environmental costs on developing countries and their inhabitants [4,5]. A key challenge for improving WASH insufficiencies in developing countries lays in the lack of data describing the local WASH situation, and consequently the inability for fact-based decision-making and policy implementation. This data poverty is often encountered in the form of data availability only at the aggregate level, with inadequate information available at the decentralised levels. Moreover, data may not be fully up-to-date. Other data quality issues include the scattered nature of datasets without temporal or spatial integration, and specifically for the WASH sector, lack of input-output integration from raw water to wastewater discharge. For example, for a review on urine and faeces excretion literature, please see Supplementary Material D. This results in the inability to tackle water leakage and evaluate designs of new water and sanitation systems tailored to the local context. Additionally, there is a need for an integrated and reliable resource-flow methodology that can provide a structured and objective process to characterize urban WASH sectors in developing countries [6,7]. Moreover, this methodology should also pinpoint key areas for improvements and identify optimal improvement strategies via scenario testing.

To overcome these challenges, we developed a framework for data integration and a robust and comprehensive bottom-up methodology for describing anthropogenic water and sanitation material flows, considering the complete cycle from raw water intake to water use, wastewater and excreta generation, to discharge and treatment. This approach allowed us to describe the current WASH status quo at a district level and to model and evaluate future scenarios (e.g., for infrastructure upgrading) to support decision makers. Additionally, progress on local water and sanitation targets as well as needs, infrastructure and system change can also be monitored using this framework.

The framework and descriptive modelling approach were applied to the Greater Accra Metropolitan Area (GAMA), the capital city region of Ghana. GAMA is a rapidly growing metropolitan region with 4 million inhabitants, where efforts to improve the WASH situation have yielded mixed results [8–10]. A limited number of recent studies jointly provide an overview of the water and sanitation situation and data availability in GAMA, including institutional stakeholder descriptions, and WASH financing analyses [11–16]. However, applicability for urban planning is, in this case, limited by the absence of an integration of various data sources to generate a comprehensive baseline assessment of urban water flows from raw water to wastewater treatment and discharge. Moreover, there is a need for a robust and comprehensive methodology for WASH flow-cycle mapping and WASH sector improvements via scenario testing. Therefore, GAMA was an ideal location for applying such a descriptive and decision-making aiding framework and modelling tool. The first objective of the case study was to fill this data integration gap by creating an integrated flow picture of water and sanitation in GAMA, via material flow analysis using raw data from existing studies, local publications and authorities. The second objective was to define a set of standardized metrics usable for further research, future updates, and scenario studies of improvements in GAMA water and sanitation flows, of which some can also be applied to urban water flow studies of other cities.

2. Materials and Methods

2.1. Modelling Framework Development

The study design is based on a literature data review and bottom-up material flow analysis approach. In a bottom-up approach, the individual base elements of the system are specified in detail and combined using first-principle physical and engineering rationale (e.g., conservation of mass and energy) to obtain a higher-level understanding of a system. Using a bottom-up approach, the input and output flows can be determined, which describe the overall system.

The datasets are compared, integrated, and used either to calculate parameters or as input variables in material conversion steps. A conversion step x = 1, 2, 3, . . . , n, is described by a set of flows j = 1, 2, 3, . . . , n which can be an input I_(x,j), or output O_(x,j), and calculated using one or more variables and parameters. In addition to standard flow estimates, spatial distributions for the city-region districts k = 1, 2, 3, . . . , n were calculated so as to reflect spatial differences.

The system boundaries and conversion steps are chosen to depict the entire urban water and sanitation system, from raw-water intake to final discharge of untreated and treated wastewater. An overview of the 9 steps and 28 flows quantified as part of the study can be found in Figure 1 below. Since all water and sanitation flows are mapped, a complete description of the flows is obtained.

The nine conversion steps are then translated into a series of 34 material flow equations, which are described in the next sections with parameters listed in Table 1 below, alongside related variables and evaluated parameters. In Section 2.2, the methodology to obtain or calculate variable data and parameters is described for a specific area, including the amount of human urine and faeces generated in the context of developing countries. This framework specifies what data needed to be collected, and this can be repeated for other case studies.

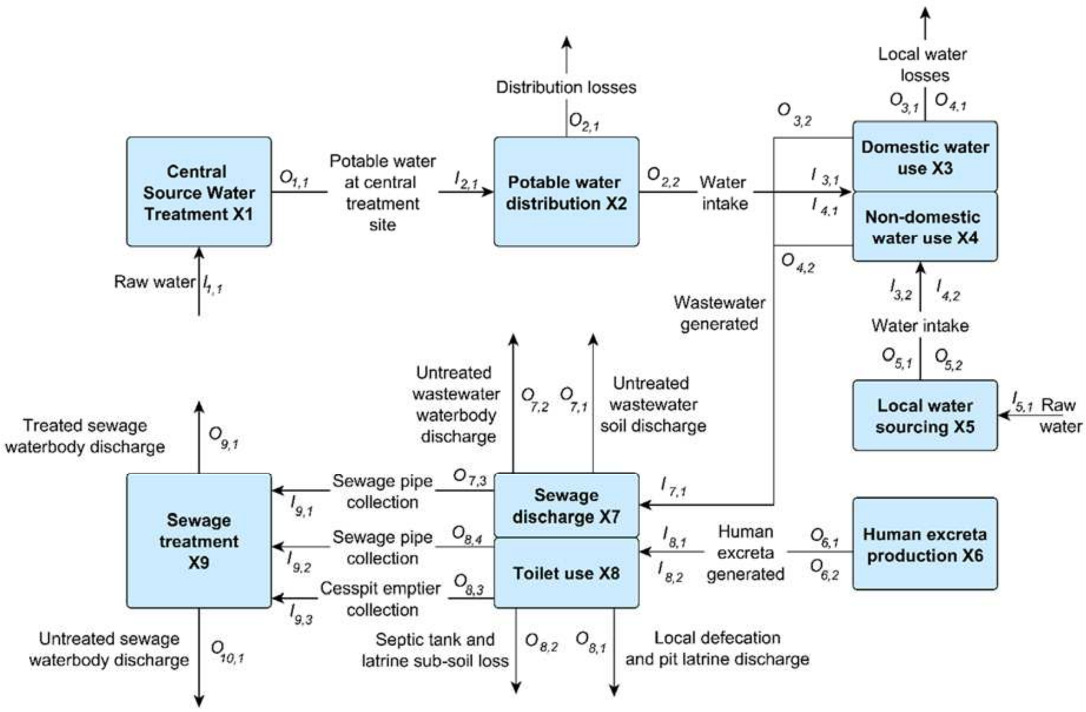

Figure 1. Overview of Water, Sanitation and Hygiene (WASH) flow calculations made in the study using mass-balance principles.

2.1.1. Centralized Source Water Treatment

The estimates for raw to potable water were based derived from literature values on raw water treatment capacity, W, and treated water values at the plant sites, so as to derive the source water output value from central treatment plants, Equation (1). The parameter value ∝ for source water treatment plant efficiency was estimated to be 0.85 based on the difference between capacity and actual treated output.

$$O_{1,1} = \propto W_1 \quad (1)$$

It was also assumed that there are no losses in the conversion from raw water to potable water at a central treatment site, such that raw water input equals potable water output, Equation (2), to estimate water abstraction.

$$I_{1,1} = O_{1,1} \quad (2)$$

2.1.2. Potable Water Distribution

The spatial distribution of central water treated supply was estimated using a three-step procedure. First, the total water lost in the pipe line system was established using Equation (3) for distribution losses and Equation (4) for water intake after distribution.

$$O_{2,1,k} = \phi_k \beta I_{2,1,k} \quad (3)$$

$$O_{2,2} = I_{2,1} - \beta I_{2,1} \quad (4)$$

The distribution losses were established based on inputs I, a pipe loss parameter β representing leaked water, and the distribution of central output to each area ϕ_k with index $k = 1, 2, ..., n$. The total aggregated supplied values were allocated to districts based on the calculated spatial distribution parameter ϕ for each district k, from the distribution of population members in piped areas per district including proportional reduction for the percentage of supply days (see online Supplementary Materials C). It was also assumed that the potable water input into distribution was equivalent to output from the central source water treatment plants, Equation (5).

$$I_{2,1} = O_{1,1} \quad (5)$$

The value for physical losses from pipeline system leakages was from the literature found to be 27% of treated water volume [16]. The value relates solely to leakage estimates, as opposed to Non-Revenue Water (NRW) which takes into account all unaccounted for water including non-paid usage.

2.1.3. Domestic Water Use

Total water use for domestic purposes was established via bottom-up analysis. The population is divided into socio-economic, $m = 1, 2, \ldots, n$ and age groups $p = 1, 2, \ldots, n$ to differentiate between water user types. The total water use is based on the multiplication of a parameter, γ, denoting water consumption in liters per capita for a socio-economic group, with the number of people P in a socio-economic group, resulting in Equation (6). It was further assumed that local losses occurred at a rate of δ at household sites resulting in Equation (7), converting centrally distributed piped water $I_{3,1}$ into water losses $O_{3,1}$. Thereby water available to households (and thereby outputs from households) from centralised water sources become Equation (8), and total available water including local water sourcing is expressed as Equation (9).

$$I_{3,1} + I_{3,2} = \gamma_m \sum_p P_{m,p} \quad (6)$$

$$O_{3,1} = \delta I_{3,1} \quad (7)$$

$$O_{3,2} = I_{3,1} - O_{3,1} \quad (8)$$

$$I_{3,1} + I_{4,1} = O_{2,2} \quad (9)$$

To obtain socio-economic groups occupation and employment values were translated into income groupings of low-medium-high income and related to non-drinking water sourcing access per household income category using sequential association, resulting in 30 groups per district, based on the ranking of private pipe access > public tap/stand pipe > protected spring or well or rainfall > tanker/vendor supply > unprotected spring or well or waterbodies in relation to income categories. Subsequently, groups with piped water access were split into rationed and continuous supply using supply rationing proportions to obtain the population P_m per socio-economic group values for Equation (6).

2.1.4. Non-Domestic Water Use

The total water use for non-domestic purposes was established using Equation (10). The parameter ε denotes the proportion of central distributed flows $I_{4,1}$ for non-domestic purposes, which with the addition of locally sourced water $I_{4,2}$, and output losses $O_{4,2}$, so as to obtain total non-domestic water use and outputs $O_{4,1}$. The parameter ε is differentiated for three sectors of the economy $n = 1, 2, \ldots, n$ and was based on values of 21%, 11%, and 13% water use share from total GWCL central pipe water supplied by commercial, industrial, and institutional sectors, respectively [16]. Similarly, to domestic water use, a local water loss ratio was assumed using parameter ζ to obtain water consumed and output from non-domestic users Equation (11). As a result, total non-domestic waste water generation $O_{4,2}$ can be estimated from water influx $I_{4,1}$ minus local loss outputs $O_{4,1}$ resulting in Equation (12).

$$O_{4,1} + O_{4,2} = \varepsilon_n I_{4,1} + I_{4,2} \tag{10}$$

$$O_{4,1} = \zeta_n (I_{4,1} + I_{4,2}) \tag{11}$$

$$O_{4,2} = I_{4,1} - O_{4,1} \tag{12}$$

The used water value can be translated to generated wastewater by taking into account on-site losses, such as from evaporation, local leakage, or incorporation into products. Such losses have been estimated to vary between 10% and 40% in urban water systems [17]. In the absence of indicative data, a loss value of 10% was assumed for both the parameter δ to calculate Equation (7) and parameter ζ to calculate Equation (11) for domestic and non-domestic losses, respectively.

2.1.5. Local Water Sourcing

The values for local water sourcing by decentralised means, such as boreholes, springs, wells and water bodies, were indirectly estimated since technology capacity data is not available. The domestic usage was derived from literature value D for each water source type $O = 1, 2, \ldots, n$, such that $O_{5,1} = D_o$ Equation (13). Company sourcing was determined from the list of licensed users in the water use register of the Water Resources Commission [18]. The number of companies sourcing water locally, N_n, was multiplied by a parameter for the amount sourced η, resulting in Equation (14). Total local water sourced inputs are equal to both non-domestic and domestic water outputs Equation (15).

$$O_{5,1} = D_o \tag{13}$$

$$O_{5,2} = \eta_n N_n \tag{14}$$

$$I_{5,1} = O_{5,1} + O_{5,2} \tag{15}$$

2.1.6. Human Excreta Production

The amount of urine and faeces generated was based on population members $P_{m,p}$ by age group $p = 1, 2, \ldots, n$ per district $m = 1, 2, \ldots, n$. The values were multiplied by the parameter ϑ denoting litres of urine excreted per age group resulting in Equation (16), to obtain Urine output $O_{6,1}$. Similarly for excreta the parameter κ was used denoting faeces excreted per day per age group resulting in Equation (17). It was further assumed that there were no losses between human excreta production and toilet inputs yielding Equations (18) and (19).

$$O_{6,1} = \vartheta_p \sum_m P_{m,p} \tag{16}$$

$$O_{6,2} = \kappa_p \sum_m P_{m,p} \tag{17}$$

$$I_{8,1} = O_{6,1} \tag{18}$$

$$I_{8,2} = O_{6,2} \tag{19}$$

The values used for parameter ϑ were 1.16 L and 0.8 L of urine excreted per day for groups of 15+ and 0–14 years, respectively. And for parameter κ values of 0.33 and 0.13 kg of faeces excreted per day for the 15+ and 0–14 year age groups were used, respectively. The parameter values were derived from a literature review of 15 studies (see online Supplementary Materials A).

2.1.7. Sewage Discharge at Collection Point

The calculated wastewater values were translated into discharge into local terrains, open drains, or sewage pipes based on a proportion of wastewater discharged λ per discharge route $q = 1, 2, 3$ for generated wastewater. Three discharge routes were assumed $q = 1$ for local soils, $q = 2$ for open drains, and $q = 3$ for sewage pipes, resulting in three equations Equations (20)–(22). Proportions were established from liquid waste disposal census data (see online Supplementary Materials C). The assumptions were made that sewage piped wastewater is routed towards treatment systems, open drain discharge is disposed into waterbodies, and local terrain discharge enters soils.

$$O_{7,1} = \lambda_{q=1} I_{7,1} \tag{20}$$

$$O_{7,2} = \lambda_{q=2} I_{7,1} \tag{21}$$

$$O_{7,3} = \lambda_{q=3} I_{7,1} \tag{22}$$

2.1.8. Toilet Use

The discharge of human excreta $I_{8,3}$ starts with the sum of urine and faeces inputs Equation (23). First, the proportion of inputs to outputs in terms of toilet types μ_r were established based on $r = 1$ for open defecation, $r = 2$ for pan and bucket latrines, $r = 3$, for private water closets, $r = 4$ for pit latrines and septic tanks, and $r = 5$ for public toilets. A combined output route for open defecation and pan and bucket latrines Equation (24), was made, since these are not connected to sewage systems. Also a combined output route was made for private water closets and public toilets Equation (25), as a proportion of these are connected to the centralised sewage system. The third route is for pit latrines, which are emptied by cesspit tanker vehicles.

$$I_{8,3} = I_{8,1} + I_{8,2} \tag{23}$$

$$O_{8,1} = (\mu_1 + \mu_2) I_{8,3} \tag{24}$$

$$O_{8,4} = \lambda_r (\mu_3 + \mu_5) I_{8,3} \tag{25}$$

Leakage losses into the sub-soil were estimated using Equation (26). The equation takes the loss proportion based on a private systems subsoil leakage rate ξ, and a public systems leakage rate ν, and multiplies it with the total excreta discharge $I_{8,3}$ accounting for the proportion routed to private toilets not connected to central sewage systems $(1 - \lambda_r)\mu_3$, the proportion of pit latrines μ_4, and the proportion of public toilets not connected to sewage systems $(1 - \lambda_r)\mu_5$, with the parameter λ_r denoting the proportion of water closets and public toilets connected to sewage systems. It was assumed that the human excreta that was not leaked was collected by cesspit emptier vehicles for further treatment or disposal Equation (27).

$$O_{8,2} = (\xi((1 - \lambda_r)\mu_3 + \mu_4) + \nu(1 - \lambda_r)\mu_5) I_{8,3} \tag{26}$$

$$O_{8,3} = ((1 - \xi)((1 - \lambda_r)\mu_3 + \mu_4) + (1 - \nu)(1 - \lambda_r)\mu_5) I_{8,3} \tag{27}$$

The equations takes into account that in case of pit latrine or septic tanks systems discharge, it was taken into account that a large liquid share will drain into the sub-surface due to bottom latrine porosity and septic drain field discharge. The sub-soil drainage rate was assumed different for public and private toilet systems because public systems have better structures which are more efficiently enclosed and emptied within weeks to months, whilst private systems typically have more porous structures and are emptied once every five to ten years. Values were established at 87% leakage for sub-soil leakage from private systems ξ, and 50% for leakage from public systems ν, based on literature values [19–25].

2.1.9. Sewage Treatment

The proportion of sewage treated in centralized treatment plants was established in two ways. First, the proportion of wastewater treated in sewage plants, and proportion of human excreta treated in sewage plants was established, from the three input routes cesspit emptier collection Equation (28), centralised piped intake of human excreta Equation (29), and for centralized piped intake of wastewater Equation (30).

$$I_{9,3} = O_{8,3} \tag{28}$$

$$I_{9,2} = O_{8,4} \tag{29}$$

$$I_{9,1} = O_{7,3} \tag{30}$$

Thereby taking into account the proportion ϱ of wastewater which is centrally treated, and σ, the proportion of human excreta that is centrally treated, this results in the amount of centrally treated Sewage Equation (31). The residual sewage is not treated and disposed of at cesspit emptier truck dump sites, or by direct discharge into the sea or other water bodies, as represented by Equation (32). These values should match up with the top-down calculation of sewage treated in centralised waste water treatment plants, based on operational sewage treatment capacity S_s, and the sewage treatment plant efficiency υ_s, for each technology $s = 1, 2, \ldots, n$. Thereby the treatment output should equate to Equation (33). Finally, the sum of treated and untreated discharged outputs should be equivalent to inputs from the three input routes cesspit emptiers, centralised piped human excreta intake, and centralised piped wastewater intake Equation (34).

$$O_{9,1} = \sigma(I_{9,1} + I_{9,3}) + \varrho I_{9,2} \tag{31}$$

$$O_{9,2} = (1 - \sigma)(I_{9,1} + I_{9,3}) + (1 - \varrho)I_{9,2} \tag{32}$$

$$O_{9,1} = \upsilon_s S_s(\sigma(I_{9,1} + I_{9,3}) + \varrho I_{9,2}) \tag{33}$$

$$O_{9,1} + O_{9,2} = I_{9,1} + I_{9,2} + I_{9,3} \tag{34}$$

The treatment capacity of sewage plants per technology was evaluated by creating an inventory of treatment plants, starting with a survey carried out in 2011–2012 on the operational status of all sewage treatment plants (STPs) in GAMA [26], which for this paper was reviewed and updated with newer studies and local news report updates as referenced in the results.

Table 1. Overview of variables and parameters established in the study.

Conversion Description		Equation No.	Variables Description	Parameters Description	Parameters Established	Uncertainty	See Section
1	Source water treatment	(1) (2)	W_l, raw water treatment capacity by technology	∝, source water treatment plant efficiency	∝ = 0.85	Low—typical for maintained plants	(2.1.1, 2.2.2)
2	Potable water distribution	(3) (4) (5)		β, pipe loss parameter ϕ, spatial distribution parameter with proportion of supply per area k	β = 0.27	High—no measured information, inferred value	(2.1.2, 2.2.3)
					ϕ = 0 to 0.66	Low—measured values for proportion delivery to areas	(Supplementary Material C)
3	Domestic water use	(6) (7) (8) (9)	P, population members per socio-economic m and age group p	γ, water consumption in litres per capita by socio-economic group m	γ = 32 to 138	Medium—estimates from triangulation of GAMA case studies	(2.1.3, 2.2.4)
				δ, local water losses at household site	δ = 0.10	Medium—single estimates-inferred value	(2.1.3, 2.2.4)
4	Non-domestic water use	(10) (11)		ε, proportion of distributed water used by non-domestic users by sector n	ε = 0.27, 0.11, 0.13	Medium—estimates from Ghana Water Company Limited	(2.1.4, 2.2.4)
		(12)		ζ, local water losses at non-domestic sites by sector n	ζ = 0.10	Medium—single estimates-inferred values	(2.1.4, 2.2.4)
5	Local water sourcing	(13)	D_o, local domestic water sourcing capacity by source type o				(2.1.5)
		(14) (15)	N_n, number of companies sourcing water locally per sector n	η, amount of water sourced per company in sector n	η = 1000	High—Top-down approximate estimate	(2.1.5, 2.2.4)
6	Human excreta production	(16) (18)	P, population members per socio-economic m and age group p	ϑ, amount of urine excreted per unit time i.e., litres per day per person for 15+ and 0–14 year age groups p	ϑ = 1.16, 0.8	Low—based on 15+ studies literature survey	(2.1.6, 2.2.5) (Supplementary Material A)
		(17) (19)		κ, amount of faeces excreted per unit time i.e., kilograms per day per person for 15+ and 0–14 year age groups p	κ = 0.33, 0.13	Low—based on 15+ studies literature survey	(2.1.6, 2.2.5) (Supplementary Material A)
7	Sewage discharge at collection point	(20) (21) (22)		λ_q, proportion of wastewater discharged onto local soils q = 1, into open drains q = 2, and into sewage pipes q = 3	$\lambda_{q=1}$ = 0.43 to 0.93 $\lambda_{q=2}$ = 0.02 to 0.30 $\lambda_{q=3}$ = 0.01 to 0.40	Low—census data + inferred calculation value	(2.1.7, 2.2.6) (Supplementary Material C)
8	Toilet use	(23) (24) (25)		μ_r, population proportion practicing open defaecation r = 1, using pan and bucket latrines r = 2, private w.c. r = 3, pit latrines r = 4, and public toilets r = 5	$\mu_{r=1}$ = 0.04 to 0.25 $\mu_{r=2}$ = 0.00 to 0.04 $\mu_{r=3}$ = 0.09 to 0.53 $\mu_{r=4}$ = 0.02 to 0.40 $\mu_{r=5}$ = 0.06 to 0.64	Low—census data + inferred calculation value	(2.1.8, 2.2.6) (Supplementary Material C)
		(26)		$\lambda_{r=1}$, proportion of w.c. and public toilets connected to sewage system			(2.1.8)
		(27)		ξ, sub-soil leakage from privately used septic tanks and pit latrines	ξ = 0.87	Low—multi-site studies with leakage measurements	(2.1.8, 2.2.6)
				ν, sub-soil leakage from publicly used septic tanks and pit latrines	ν = 0.50	Low—multi-site studies with leakage measurements	(2.1.8, 2.2.6)

Table 1. *Cont.*

Conversion Description		Equation No.	Variables Description	Parameters Description	Parameters Established	Uncertainty	See Section
9	Sewage treatment systems	(28), (29), (30)	S_s, operational sewage treatment capacity by technology s	ρ, proportion of wastewater treated in sewage plants	ρ = < 0.01	Low—triangulated study estimates & inferred values	(2.1.9, 2.2.7) (3.6)
		(31)		σ, proportion of human excreta treated in sewage plants	σ = 0.0		(2.1.9, 2.2.7) (3.6)
		(32)		υ, sewage treatment plant efficiency by technology s	υ = 0.12 to 0.85	Low—typical for maintained plants	(2.1.9, 2.2.7) (3.6)
		(33)					
		(34)					

2.2. *Application to the Greater Accra Metropolitan Area*

The study subject GAMA was defined on the basis of the administrative districts governed by assemblies with decentralized power by the Government of Ghana since 1993 [27]. The geographic boundary definition of GAMA as a city region used in this paper was defined by local stakeholders using the Metropolitan and Municipal District Assembly (MMDA) structures in the country [10]; for details, see Table S1 in Supplementary Material C. The definition includes 15 districts, with the Accra and Tema Metropolitan Districts as the most populous and home to the majority of economic activity. The used spatial outline of MMDAs in GAMA is shown in Figure 2, and the historic boundary development of the MMDAs since 1988 can be found in the online Supplementary Material A. The year 2010 was selected as the year of analysis as this is the last year with baseline data from the Ghanaian Census; nevertheless, more recent figures were included when available.

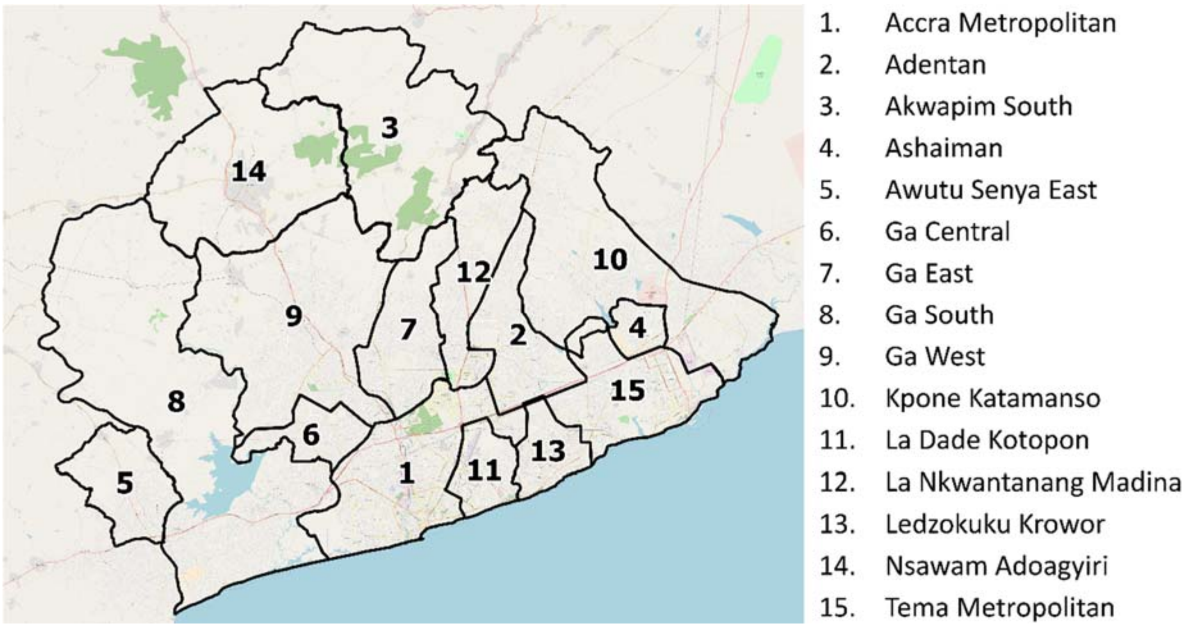

Figure 2. Boundaries of Greater Accra Metropolitan Area (GAMA) administrative regions from 2012 onwards.

2.2.1. Data Collection and Integration

The data required for WASH descriptive modelling as specified by the framework was sourced from documentation and from local authorities and water company officers. For data collection from documentation, several hundred literature studies, reports, news articles, and media reports were screened, out of which key datasets were incorporated into the study, in order to provide the most comprehensive quantification feasible within the limited data availability. The data screening criteria included: (1) time—data post 2008 was considered, (2) location—data relevant to GAMA was taken into account; (3) system boundaries—data with clearly defined system boundaries and units was preferred. The flow assessment was limited to the year 2010, primarily due to availability of household infrastructure use data from the Ghana Statistical Service [28–42]. If data from recent years were available, these were incorporated into the study. Moreover, as part of the study, contact was sought with local officers in GAMA at the Ghana Water Company Limited (GWCL) to update water treatment, pipeline system, and rationing data (GWCL, Managing Director Frederick Christian Lokko, personal communication, 19 November 2015). In addition to WASH flow data, surface water quality measurements were collected and integrated from the literature to provide for a summary of known datasets in this domain. The data were collected and integrated in MS Excel spreadsheets and in

QGIS [43] for spatial mapping purposes. The calculations were carried out in MS Excel for each of the 15 MMDAs, and subsequently aggregated to provide for the total GAMA estimates.

2.2.2. Raw Water to Source Water

The estimates for raw to potable water were derived from literature values on raw water treatment capacity and treated water values at the plant sites. The three central water treatment sites, (see Table 2), operating in GAMA informed the treatment capacity value W in Equation (1).

Historic figures for treated potable water supplied into the centralised distribution network were taken from [15,44,45] and complemented with 2014 plus 2015 values provided by GWCL. The parameter value $\propto$ for source water treatment plant efficiency was estimated to be 0.85 based on the difference between capacity and actual treated output.

The values for local water sourcing by decentralised means, such as boreholes, springs, wells and water bodies, were indirectly estimated since technology capacity could not be located. The domestic usage was derived from total bottom-up use estimates (see Supplementary Material C), and company sourcing was determined from the list of licensed users in the water use register of the Water Resources Commission [18]. The number of companies sourcing water locally, N_n, as per Equation (14), was thereby estimated to be 7 within the GAMA region. The parameter for the amount-sourced η was conservatively estimated at 1000 m^3 per day for each company.

Table 2. Overview of potable water treatment plants in GAMA.

Treatment Plant Sites	Water Source	Technology *	Year of Opening	Year of Expansion	Capacity in 2010 (m^3 per day)	Capacity in 2015 (m^3 per day)	Source of Data
Weija	Weija lake	Conventional chemical water treatment	1951	1978, 1984, 2002, 2009	245,484	245,484	[44–49]
Kpong	Volta river	Conventional chemical water treatment	1963	1965, 1995, 2015	220,454	434,454	[44,45,50–53]
Teshie	Sea	Desalination	2015	-	-	60,000	[54]

* Conventional technologies are defined following the American Water Works Association (AWWA) guidelines.

2.2.3. Source Water Distribution

The spatial distribution of central water treated supplies was estimated using a three-step procedure. First, the total water lost in the pipeline system was established using the pipe loss parameter β and Equations (3) and (4). The value for physical losses from the pipeline system leakages was from the literature and found to be 27% of treated water volume [16]. The value relates solely to leakage estimates, as opposed to Non-Revenue Water (NRW), which takes into account all unaccounted-for water including non-paid usage. Second, the spatial areas and population therein with continuous piped supply and 2+ days of rationed supply per week were calculated including the percentage of days with no supply. The spatial maps and allocation (see Figure 3) were created on the basis of a piped area and a rationing scheme map obtained from GWCL, and census population data [28–42]. The rationing scheme in place is imposed on approximately 63% of the area with central pipe supply. Finally, the total aggregated supplied values were allocated to districts based on the calculated spatial distribution parameter ϕ for each district k, from the distribution of population members in piped areas per district including proportional reduction for the percentage of supply days (see online Supplementary Material C).

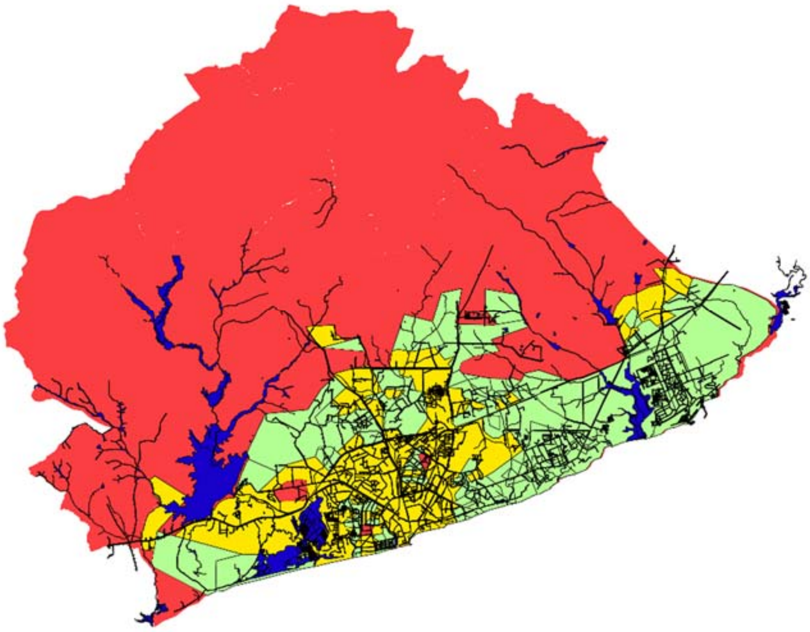

Figure 3. Zones in GAMA supplied by the pipe and rationing scheme as of August 2015 (areas with no access to pipe supply (red), areas with continuous pipe supply (blue), areas with rationed supply (yellow), water bodies (turquoise), and the pipe network (dark lines)). Source of data: Ghana Water Company Limited (GWCL), Accra, Ghana, map data © OpenStreetMap contributors.

2.2.4. Potable Water Use and Local Sourcing

The total water use for non-domestic purposes was established via the parameter ε for proportion of central distributed flows used for non-domestic purposes. The parameter was based on values of 21%, 11%, and 13% water use share from total GWCL central pipe water supplied by commercial, industrial, and institutional sectors, respectively [16]. Total water use for domestic purposes was established via bottom-up analysis.

Firstly, socio-economic groups were established per district using population numbers for employment status, occupation, and non-drinking water sourcing [28–42]. The occupation and employment values were translated into income groupings of low-medium-high income and related to non-drinking water sourcing access per household income category. The method was sequential association, resulting in 30 groups per district, based on the ranking of private pipe access > public tap/stand pipe > protected spring or well or rainfall > tanker/vendor supply > unprotected spring or well or waterbodies in relation to income categories. Subsequently, groups with piped water access were split into rationed and continuous supply using supply rationing proportions (Supplementary Material C) to obtain the population P_m per socio-economic group values for Equation (6).

Secondly, to achieve the demand data, the number of people in each group was multiplied by a water consumption per capita value, taking into account the income status and supply type. The values used for the parameter γ, water consumption per capita by socio-economic group, are summarised in Table 3 as obtained from four literature studies [55,56].

Thirdly, per capita use values per socio-economic group were multiplied by population numbers and aggregated to the district level to obtain total water use and sourcing categories including decentralised, improved protected, unimproved decentralised, and tanker/vendor-based pipe supply. Decentralised pipe-based supply was calculated by subtracting central pipe supply delivered (Section 2.2.3) from total domestic pipe supply as calculated, including correction for supply to non-domestic customers.

Table 3. Water consumption in litres per capita per day by income, sourcing condition and source type. Source of data: [55–58].

Sourcing Condition	Source Type	Low Income	Medium Income	High Income
Continuous piped water access	Piped water source	66	90	138
Good intermittent piped water access (80%+ time available)	Piped water source Secondary source	56 0	83 0	110 28
Poor intermittent piped water access (<50% time available)	Piped water source Secondary source	43 0	54 0	75 15
No piped water access/decentralised source	Secondary decentralised source	32	53	53

2.2.5. Wastewater and Human Excreta Generation

The used water value can be translated into generated wastewater by taking into account on-site losses, such as from evaporation, local leakage, or incorporation into products. Such losses have been estimated to vary between 10% and 40% in urban water systems [17]. In the absence of indicative data, a loss value of 10% was assumed for both the parameter δ in Equation (7) and parameter ζ in Equation (11) for domestic and non-domestic losses, respectively.

The amount of urine and faeces generated was based on population members by age group $P_{m,p}$ per district. The values were multiplied by the parameter ϑ values of 1.16 L and 0.8 L of urine excreted per day for groups of 15+ and 0–14 years, respectively, and by the parameter κ values of 0.33 and 0.13 kg of faeces excreted per day for the 15+ and 0–14 year age groups, respectively. The parameter values were derived from a literature review of 15 studies (see online Supplementary Material A).

2.2.6. Sanitation and Sewage Collection

The calculated wastewater values were translated into discharge into local terrains, open drains, or sewage pipes. The proportions per discharge route λ_q for generated wastewater for Equations (21)–(23) were established from liquid waste disposal census data [28–42] (see online Supplementary Material C). The assumptions were made that sewage piped wastewater is routed towards treatment systems, open drain discharge is disposed into waterbodies, and local terrain discharge enters soils.

The discharge of human excreta was informed by the parameter μ_r describing the proportion of toilet types used by the population with data from [28–42] (see online Supplementary Material C). The excreta routed into water closet (W.C.) was split into two groups: W.C. connected to sewage systems, and W.C. connected to septic tanks, expressed via proportions using the parameter λ_q based on liquid waste disposal data [28–42]. In the case of pit latrine or septic tanks systems discharge, it was taken into account that a large liquid share will drain into the sub-surface due to bottom latrine porosity and septic drain field discharge. The sub-soil drainage rate was assumed different for public and private toilet systems, because public systems have better structures which are more efficiently enclosed and contained, and emptied within weeks to months, whilst private systems typically have more porous leak-prone structures and are emptied once every five to ten years. Values were established at 87% leakage for sub-soil leakage from private systems ξ, and 50% for leakage from public systems ν, based on literature values [19,21,23].

2.2.7. Sewage Treatment

The treatment of sewage was calculated by creating an inventory of treatment plants, their technology and capacity. The main dataset was taken from a survey carried out in 2011–2012 on the operational status of all sewage treatment plants (STPs) in GAMA [26], which, for this publication, was reviewed and updated with newer studies and local news report updates as referenced in the results.

3. Results: Water, Sanitation and Hygiene Data for the Greater Accra Metropolitan Area in Ghana

The complete year 2010 analysis results for the GAMA are presented in Figures 4 and 5 as Sankey diagrams below, from raw water to wastewater discharge, and from human excreta generation to discharge, respectively. The results for individual components and districts are presented in detail in Sections 3.1–3.6 below. An overview of parameters established to carry out the material flow analysis is provided in Table 1, as described in Section 2.1. The areas in GAMA supplied by the pipe and rationing scheme as of August 2015 are shown in Figure 3. The evolution of total central water treatment capacity in GAMA from 1980 to 2015 is displayed in Figure S1 in Supplementary Material B. The domestic water use in the districts of GAMA in 2010 is shown in Figure S2 in Supplementary Material B. The wastewater and human excreta generation estimates in GAMA per district for 2010 by sink are provided in Figure S3 in Supplementary Material B. The proportions of wastewater and human excreta ending up in the environment and collected via sewage pipes and cesspit-tankers are illustrated in Figure S4 in Supplementary Material B. Figures S1–S4 are available in Supplementary Material B.

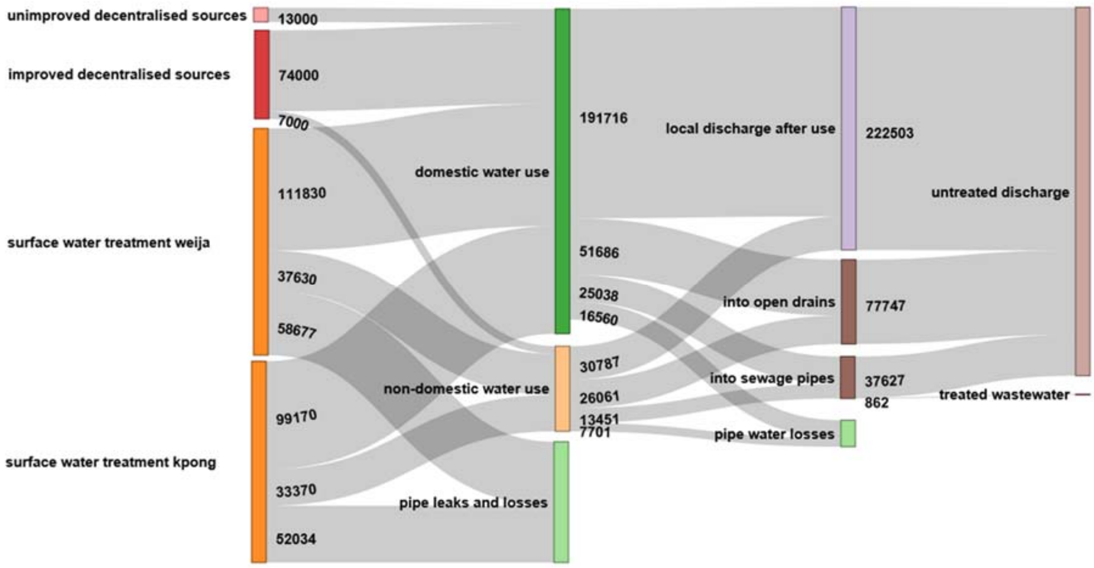

Figure 4. Sankey diagram from 2010 GAMA raw water treatment to final wastewater discharge flows in m^3 per day.

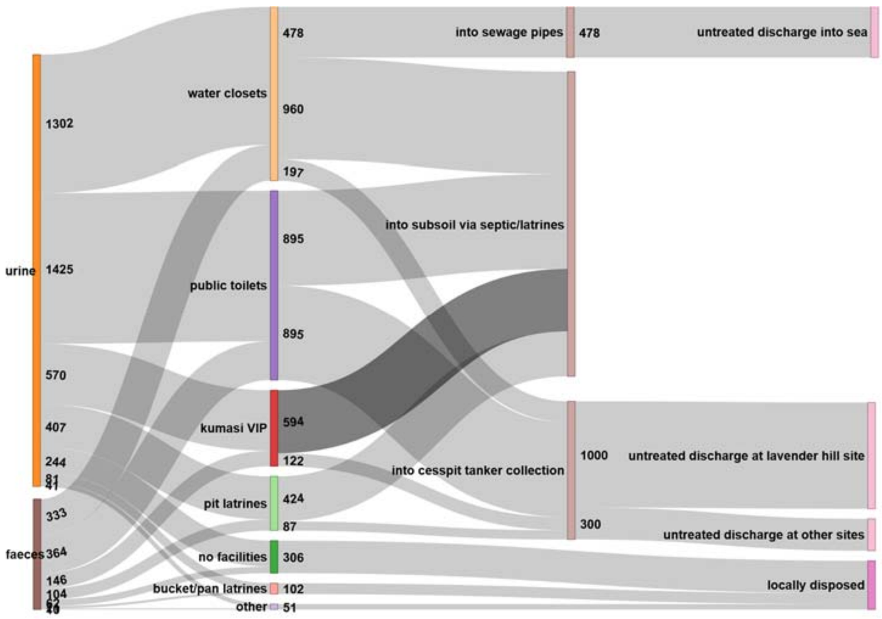

Figure 5. Sankey diagram from 2010 GAMA human excreta generation to final discharge flows in m^3 per day. A Kumasi Ventilated Improved Pit (VIP) is designed with two pits versus a single-pit VIP.

3.1. Central Source Water Treatment and Distribution

The calculated 1980–2015 GAMA central water treatment capacity is shown below in Figure 6A, as well as total estimated water supply to GAMA residents from 1980 to 2015 (Figure 6B), and the 2010 distribution per district (Figure 6A). The results showed that total water supplied increased by 40% from 2010 to 2015, or from 285 to 374 m^3 per day, due to expansions at Kpong treatment and the Teshie desalination plant opening. In total, the central pipe network supplied ~66% of the population with potable water in 2010, and approximately 50% utilised it as their main drinking water source. The ~16% difference is plausibly explained by diminished water quality due to ageing metal pipes introducing rust, occasional soil plus faecal contamination from burst pipes, and general distrust of pipe-supplied water from previous contamination incidents [59–61]. The outcome of the 2014/2015 supply expansion on water access is not clear, beyond that it appears to have significantly improved the water rationing situation that was imposed by GWCL [53].

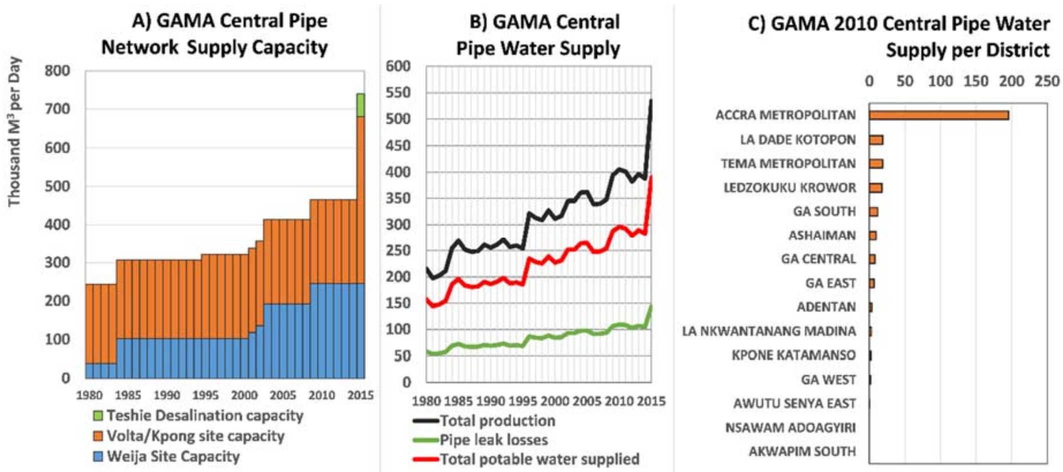

Figure 6. Centrally supplied water in GAMA. (**A**) Total central water treatment capacity in GAMA in m^3 from 1980 to 2015. (**B**) Total water produced, lost from leaks, and supplied to customers. (**C**) Estimated distribution of water supplied per district for 2010.

3.2. Decentralised Water Sourcing

To augment central piped supplies, several thousand improved decentralised sources of water have been developed including boreholes, pump and tube-wells, improved wells and improved springs. Often, boreholes are connected to local small town pipe supply systems supplying several hundred to thousands of people. Altogether, these sources were estimated to supply 24% of households in GAMA with non-drinking water in 2010, and 16% utilised such sources for drinking water [28–42]. The large majority of decentralised supplies are established in the districts: Ga West, Ga East, Ga South, Nsawam Adoagyiri, Akwapim South, Kpone Katamanso and La-Nkwantanang-Madina. In addition, unprotected local decentralised sources are used including springs, wells, rivers, ponds, and canals, from which 4% and 1% of the population obtained their 2010 non-drinking and drinking water supply, respectively [28–42]. Finally, tanker/vendor suppliers of potable water operate in the city-region. The tankers/vendors typically obtain water from GWCL's pipe system and transport it to non-access or rationed areas. They provide non-drinking and drinking water to 6% and 3% of the GAMA population, respectively [28–42].

Since the late 1990s, the use of sachet water has grown considerably, as the small 250–500 mL plastic bags are a conveniently available source of drinking water [14]. Several hundred small to large filling companies of sachet waters have sprung into existence, which supplied sachets to a total of 29% of households in 2010 as a main drinking water source [28–42]. Bottled water only served 1% of the population for their drinking water. If sachets and bottled water would be of consistently supplied at high water quality and counted as improved water sources, a total of 96% of the population had access to improved safe water in 2010, otherwise only 67% had improved safe water access in 2010.

3.3. Domestic and Non-Domestic Water Consumption

Total domestic water use from all sources was calculated at 298 thousand m^3 per day, of which 211 thousand m^3 was from the central GWCL pipe system, 74 thousand m^3 from improved decentralised sources, and 13 thousand m^3 from unimproved decentralised sources. An overview per district is shown in Figure 7 including central pipe, improved decentralised, and unprotected decentralised sources. Total non-domestic supplies were estimated at 77 thousand m^3 per day in 2010.

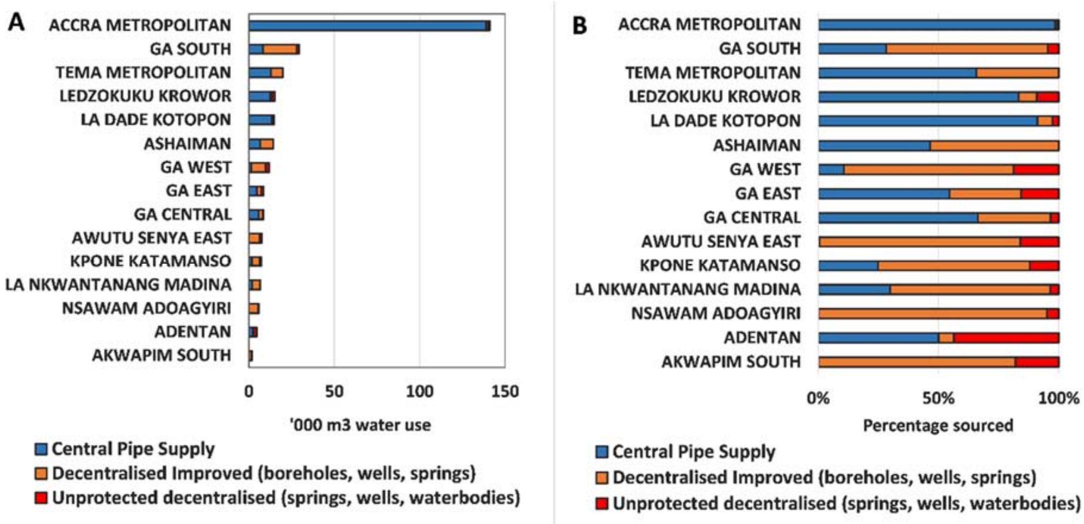

Figure 7. Total domestic water use estimate in GAMA per district for 2010 by supply source. (**A**) Water sourcing in the districts of GAMA by water source type in m^3. (**B**) The water source types for each district as shares of total water use per district.

3.4. Waste Water and Human Excreta Generation

The total amount of wastewater generated was estimated at 338 thousand m^3 per day in 2010, of which 268 thousand m^3 was from the domestic origin. Values for human excreta were estimated at a total amount of 4070 m^3 of urine and 1040 m^3 of faeces generated per day. An overview of the wastewater, urine, and faeces generated per district is shown below in Figure 8.

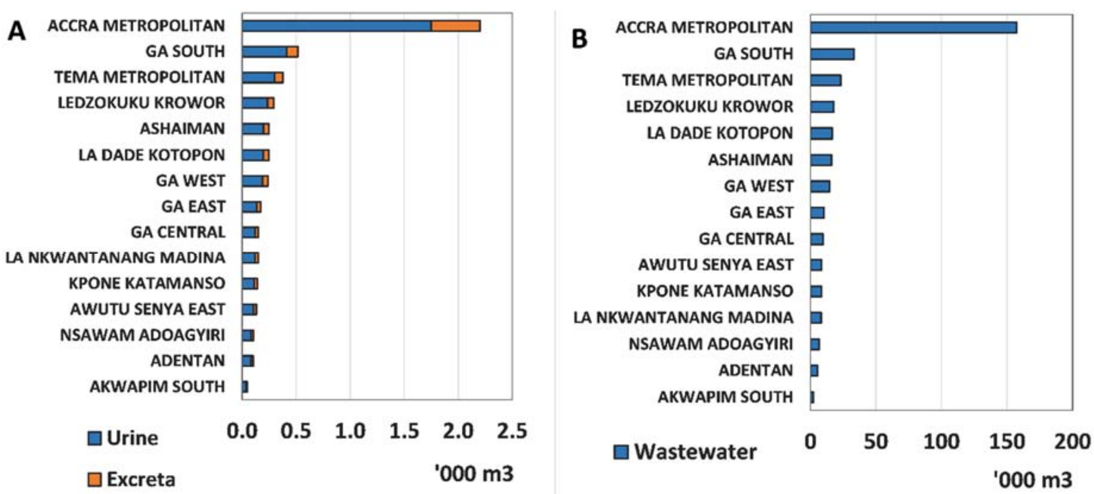

Figure 8. Total wastewater and human excreta (feces and urine) generation estimates in GAMA per district for 2010 by sink. (**A**) Feces and urine generated per district of GAMA in thousands of m^3. (**B**) Wastewater generated per district of GAMA in thousands of m^3.

3.5. Wastewater and Sanitation Collection

The generated wastewater mainly ends up in open-drains connected to local lagoons and the sea, with less than 5% of households and buildings connected to a sewer system [62]. The two main sewage systems in GAMA are established in the Accra Metropolitan and Tema Metropolitan Districts, with a few minor systems in existence at the site of University of Ghana Legon, hotels and large companies.

On the basis of sewerage figures, an estimated 222 thousand m^3 of wastewater generated in 2015 is discharged directly into the environment, 78 thousand m^3 into open-drains, and 38 thousand m^3 into a sewage pipe network. In terms of sanitation, 91% of human excreta or 4642 m^3 per day is estimated to end up in a variety of toilets systems, and 9% or 468 m^3 per day is directly discharged into the environment via either open defaecation or the use of bucket/pan latrines. However, there is a large variation between districts, as shown in the breakdown of toilet usage for GAMA in Table 4 below [28–42]. Moreover, a large proportion of the population frequents public toilets which are usually 16 or 32 seater types of various make-up (e.g., W.C., improved pit latrines). Total improved toilet access in GAMA was estimated at 81% with a variation from 54% to 93% between districts. Data on public toilets installed is sparse, but generally, the hygienic standards of these toilets are low: in a survey study of four neighbourhoods, it was found that between 17% and 80% of public toilets are equipped with handwashing stations, and in 40% to 88% of public toilets, faecal matter is visibly present [63].

The numbers of private and public W.C. connected to the sewage systems are a minority. Total excreta entering W.C. is estimated at 1620 m^3 per day, of which 478 m^3 enters sewage pipes with the majority flowing into septic tanks. The primary collection is thereby carried out via cesspit-tankers, which suck human excreta out of pit latrines and septic tanks. A total estimate of 4165 m^3 per day of excreta enters septic tanks and pit latrine systems, out of which 2854 m^3 leaks into the sub-soil due to the porous latrine bottom and septic-tank field discharge. The remaining 1298 m^3 of excreta is collected via cesspit-emptier services, which, in 2010, were primarily emptied untreated at the 'Lavender Hill' site into the sea. The collected excreta values are similar to reported values by the approximately 125 cesspit-tankers in use in GAMA [62,64]. Cesspit-tankers transport human excreta to the disposal site, which can be either treatment facility or the environment (e.g., lagoon or sea). Proportional values for human excreta and wastewater discharge route per district can be found in Figure 9 below.

Table 4. Toilet use proportions in GAMA districts as per the 2010 population census. Source of data: [28–42].

GAMA District	No Facilities	W.C.	Pit Latrine	Kumasi VIP	Bucket/Pan	Public Toilet	Other	Improved Toilet Access
ACCRA METROPOLITAN	2.5%	33.0%	4.3%	13.8%	4.0%	41.9%	0.5%	88.7%
ADENTAN	23.5%	32.2%	12.7%	14.7%	0.3%	16.4%	0.2%	63.3%
AKWAPIM SOUTH	8.8%	9.5%	24.2%	15.8%	0.7%	40.6%	0.4%	65.9%
ASHAIMAN	4.0%	11.7%	2.7%	17.5%	0.3%	63.5%	0.3%	92.7%
AWUTU SENYA EAST	15.4%	9.2%	23.1%	11.8%	0.5%	39.5%	0.5%	60.5%
GA CENTRAL	4.9%	27.4%	40.3%	20.8%	0.2%	6.1%	0.4%	54.2%
GA EAST	7.3%	42.6%	22.7%	12.2%	0.2%	14.3%	0.6%	69.1%
GA SOUTH	13.5%	26.6%	24.0%	13.2%	0.2%	22.0%	0.6%	61.8%
GA WEST	6.2%	29.7%	28.9%	22.6%	0.1%	11.9%	0.6%	64.2%
KPONE KATAMANSO	23.9%	26.1%	7.5%	14.4%	0.2%	27.1%	0.8%	67.6%
LA DADE KOTOPON	4.0%	42.5%	1.5%	4.5%	2.3%	44.4%	0.7%	91.4%
LA NKWANTANANG MADINA	6.7%	38.8%	13.2%	23.4%	0.1%	17.2%	0.7%	79.4%
LEDZOKUKU KROWOR	7.8%	25.7%	5.1%	19.1%	3.7%	38.0%	0.6%	82.9%
NSAWAM ADOAGYIRI	3.6%	17.7%	9.8%	17.0%	0.7%	51.1%	0.2%	85.8%
TEMA METROPOLITAN	9.5%	53.1%	2.1%	3.5%	0.2%	30.8%	0.9%	87.4%
GAMA	6.0%	32.0%	10.0%	14.0%	2.0%	35.0%	1.0%	80.7%

Table notes: Improved toilet access is the sum of water closet (W.C.), Kumasi VIP, and Public Toilets. W.C. is a flush toilet connected to a sewer or septic tank.

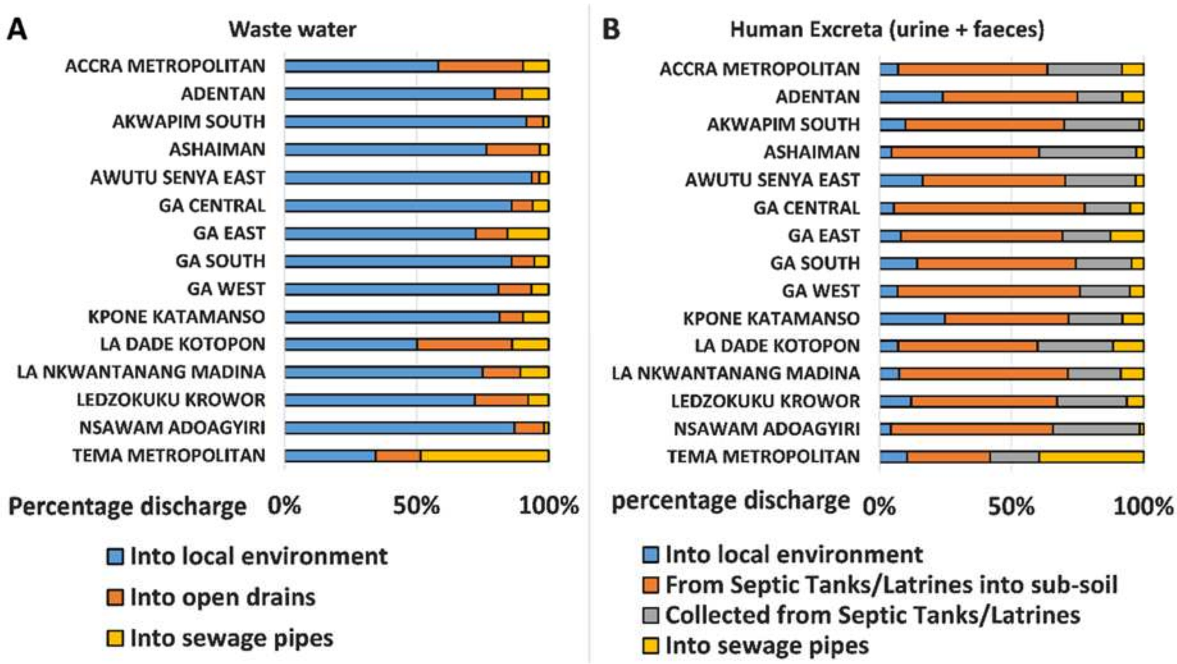

Figure 9. Proportion of wastewater and human excreta ending up in the environment and collected via sewage pipes and cesspit-tankers. (**A**) Share of wastewater per GAMA district discarded into the local environment, open drains or sewage pipes. (**B**) Share of human excreta (urine and faeces) per GAMA district disposed into the local environment, flown into sewage pipes, collected from septic tanks and pit latrines by tanker trucks, and leaked from septic tanks and pit latrines into the sub-soil.

3.6. Waste Water Treatment Capacity

The analysis found that the majority of STPs in GAMA are currently no longer operational due to historic breakdowns, in agreement with previous reports [65]. As a consequence, any sewage routed into the central pipe systems in Acrra Metropolitan Area and Tema Districts is discharged untreated into the sea below the Korle Lagoon and into the Sakumo lagoon, respectively [62]. The total amount of treated liquid waste in 2010 based on treatment capacity, as described below, was negligible at <0.01% for wastewater and human excreta. Since then, the situation has improved slightly with, as of 2014, a total of 0.5% of wastewater and 8% of human excreta estimated to have been treated.

In total, four larger public treatment plants have been built since 1997 with a joint capacity of 43 thousand m^3, of which two were operational in 2016:

- **Slamson Ghana Korle Lagoon cesspit treatment** (built in 2013): this polymer separation and drying-based STP with a 400 m^3 per day capacity is operational and will be expanded to 1200 m^3 per day capacity in the Danish International Development Agency (DANIDA)-funded Lavender Hill Project [64,66];
- **Jamestown/Korle Lagoon sewerage plant** (built in 2000): this upflow anaerobic sludge blanket (UASB) technology-based STP with a 16,120 m^3 per day capacity broke down in 2004 due to a malfunctioning intake pump, potentially caused by inflow of industrial discharge and storm water beyond design specifications [67]. The sewage from the AMA central pipe system is, as a consequence, not treated but directly pumped into the sea at the Korle Lagoon. The plant has been under rehabilitation since 2011, but according to the contractor, work halted in 2013 due to missing payments [68];
- **Tema septage central sewer** (built in 1997): this aerated lagoon-based STP with seven treatment ponds and a 20,000 m^3 per day capacity broke down in 2000, allegedly due to looting and lack of electricity cables replacement, with degradation now to the point of plant overgrowth in treatment

basins [69–71]. The sewage from the TEMA central pipe system is in consequence directly pumped into the Sakumo Lagoon;

- **University of Ghana Legon Sewerage** (built in 2011): this operational waste stabilisation pond-based STP has a 6424 m^3 per day capacity, but in 2013/2014, it functioned at only 12% of design capacity due to limited inflows [62].

The other existing significant larger STPs are mostly privately owned, for example, at the La Palm Royal Beach Hotel, Golden Tulip Hotel, and Nestle Ghana, with a joint service capacity of 750 m^3 per day. A small number of smaller plants have also been built, of which a total estimated 112 m^3 per day capacity is still operational, as dozens of older smaller plants have significantly degraded or have been removed [26].

4. Discussion

The study provides an integrated framework for aiding policymaking, using a bottom-up approach based on material balances. It provides a comprehensive overview of key macro aspects of the WASH system for an urban environment, and to the knowledge of the authors, specifically for the case study of GAMA, it is the first bottom-up analysis based on mass balances, drawing from both literature and locally provided data and information. The WASH material flow methodology as outlined herein is a prerequisite for carrying out scenario analyses, because it provides a sound quantitative basis to rapidly examine the current status of water and sanitation flows, including validation via mass balances to reduce the plausibility of errors. Moreover, this physical flow-based bottom-up analysis combined with accurate WASH sector supply and demand data, provides a robust and unique platform for evaluating future scenarios to improve the urban WASH sector.

The quality of results is reliant on parameter accuracy. Data for the parameter on leakage in the pipe system was found to be limited with only rough estimates of pipe loss values based on the difference between the quantity of water sold and water treated. Additional analyses on physical loss from pipe leakages and improvements in order to reduce non-revenue water would be beneficial, as also indicated by the GWCL. A second area with limited data available was water use in non-domestic sectors, with only indirect estimates available from the GWCL. Data could be generated by carrying out company water use surveys, and by expanding water metering and meter maintenance within GWCL systems.

A large variation was found in parameters for water use per capita by socio-economic variables, income levels, the cost of water, and whether rationing is imposed. The challenge with the range of parameter values is that studies often only include potable water drawn from central pipe systems, and sourcing from other systems is not measured (Banafo, 2013; Lamptey, 2010). The values for rationing are therefore likely biased to lower values, since it can be expected that, when piped supplies are rationed, the population will source water from tankers/vendors or local systems. An exception is the study of [58], but here, only continuous to intermittently well supplied households were analysed. The key aspect of importance that deserves more analysis was found to be the difference between public flat rates and public variable rates, as set by the Public Utilities Regulation Commission (PURC), and private charges for water, which are typically ten to fifteen higher then public rates [72].

The key limitation in the study is the availability of more recent household data than 2010 to provide for a more up-to-date analysis. In particular, figures on household use of non-drinking and drinking water sources, toilets types, and liquid waste discharge were not available. The consequence is that it is difficult to analyse whether improved water and sanitation flows are on track at the level of households per district. A more frequent sub-survey, ideally in line with medium-term development plans of 2014, 2018, and 2022 in GAMA districts, could solve this planning deficit.

Another challenge is the interpretation of key indicators, such as access to improved sources of water, as these depend on definitions, e.g., which sources are included or excluded. In particular, the use of sachet water is key since in the WHO and United Nations (UN) definition it is not to be counted as improved. One reason is that water quality of sachets has been found to vary significantly, with occasionally elevated bacterial levels and faecal coliform counts [14]. Notwithstanding, the availability of water sachets in GAMA presents one important improvement in recent times relative to no sachets.

Accra provides a transferable and representative case study because the WASH development level and data availability is similar to other developing countries. Urban planning in many developing countries is limited by the absence of an updated data-driven integrated assessment of urban water flows from raw water to wastewater treatment and discharge. The modelling methodology presented here provides well-defined flow-cycle phases for describing WASH-related flows and performance metrics to accurately characterize WASH flow-cycle. The following eight flow-cycle phases were established in this modelling methodology: (1) central water treatment; (2) potable water distribution; (3) local water sourcing; (4) domestic and non-domestic water use; (5) wastewater generation and toilet use; (6) human excreta production; (7) sewage transport; and (8) sewage treatment. The eight life-cycle phases were established as a standardized set to enable calculations of water and wastewater flows from sourcing to disposal, including sanitation. In comparison to currently available methods, this set of eight WASH flow-cycle phases provides an improved understanding of key data input requirements for WASH planning. These flow-cycle phases can be applied to an entire city or to districts to map potable water treatment, toilets requirements, wastewater treatment, and transport infrastructure needs relative to the current situation. The results can be used to obtain: (1) more accurate mid- to long-term scenarios for infrastructure requirements, at all levels of governance within the urban environment; and (2) quantification of the costs and benefits of system efficiency improvements, such as pipe loss reductions, versus water treatment expansions.

To highlight the main characteristics described above, the following metrics were applied to describe the WASH map: (1) fresh water use in m^3, (2) wastewater generated in m^3, (3) urine and excreta generated in m^3, (4) proportion of adequately treated sewage in %. This bottom-up physical modelling methodology, consisting of well-defined flow-cycle phases and performance metrics, promotes the identification of the bottlenecks in WASH flows and WASH planning. In addition, this resource-flow modelling methodology also facilitates scenario testing to overcome these WASH flow and planning bottlenecks with minimal infrastructure material, energy, labour, time and financial investments and with maximal improvements in fresh water supply and wastewater treatment. In this way, optimal and efficient policies, prioritization and investments can be implemented to improve urban WASH sectors.

5. Conclusions

A data integration framework and a modelling methodology have been developed for obtaining a baseline understanding of water and sanitation systems in developing countries, where up-to-date district level data is not available. The framework and the model have been applied to GAMA, Ghana. For this application, data has been collected both from documents (e.g., journal articles, local studies and reports) and via personal communications from officials and local WASH service suppliers. The exact data needed was specified by the framework. Once all the data required by the framework was available, descriptive modelling calculations were performed based on the mass balance of water and sanitation flows.

On the basis of the flow data assessment, the WASH landscape has been mapped for GAMA and made available in one place for the first time. In this way, important insights have been gained on centralised raw water treatment, decentralised water sourcing, potable water rationing, improved water use, wastewater and excreta generation, toilet usage, toilet excreta collection, wastewater collection, and wastewater treatment. This framework and the corresponding modelling methodology offer a baseline understanding and open up avenues for improving the WASH sector in developing countries by repeating further data collection efforts guided by the steps and frameworks presented in this paper.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/9/1278/s1, Supplementary Material A (containing Table S1: Overview of change in GAMA administrative regions 1988–2012); Supplementary Material B (containing Figure S1: Total central water treatment capacity in GAMA in

m^3 from 1980–2015, Figure S2: Total domestic water use estimate in GAMA per district for 2010 by supply source, Figure S3: Total wastewater and human excreta generation estimate in GAMA per district for 2010 by sink, Figure S4: Proportion of wastewater and human excreta ending up in the environment and collected via sewage pipes and cesspit-tankers); Supplementary Material C (containing Table S2: Water consumption in litres per capita per day by income, water sourcing, and rationing from secondary sources plus estimates, Table S3: Proportion of population with central pipe access in rationed areas and with continuous supply and final % of central water distribution per district, Table S4: Proportion of wastewater discharged onto local soils $\lambda_{q=1}$, into open drains $\lambda_{q=2}$, and into sewage pipes $\lambda_{q=3}$, Table S5: Population proportion parameter values μ_r for use of toilet types and defaecation practices, Table S6: Toilet use proportions in GAMA districts as per the 2010 population census, Table S7: Parameters established for the material flow analysis.); Supplementary Material D (containing Table S8: Literature overview of studies on human urine excretion, Table S9: Literature overview of studies on human faeces excretion).

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