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Quantifying and analysing water trade-offs in the water-energy-food nexus: The case of Ghana

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ABSTRACT

Water, Energy and Food (WEF) are inextricably linked, and the Water-Energy-Food nexus (WEF nexus) provides a comprehensive framework for addressing the complex and intricate interconnections in the development of these invaluable resources. Quantifying the interconnections among energy, water, and food sectors is a preliminary step to integrated WEF systems modelling, which will further contribute to robust WEF security management. However, the use of the WEF nexus concepts and approaches to systematically evaluate WEF interlinkages and support the development of socially and politically relevant resource policies in Ghana has been limited. This study sets the pace in the development of WEF nexus research in Ghana to facilitate policy and decision-making in the WEF sectors in the country. The study aimed at quantifying the existing water trade-offs in the WEF nexus and also model the trade-offs considering basic development scenarios. The water intensities of food production and energy generation in Ghana were found to be 990 m^3/tonne and 2.05 m^3/kWh respectively. Scenario analysis was done to project future annual water requirements for food production, energy generation as well as socio-domestic WEF demands based on two possible development scenarios. The analysis predicts that with business as usual, the annual water requirements for food production and energy generation as well as domestic sustenance in Ghana would increase by 34% in 2030. However, technological advancements and innovation in the energy and food sectors could reduce annual water requirements by over 26% even when 100% access to electricity is achieved nationwide.

Introduction

There exist strong interconnections between the sustainability goals in the fields of water, energy, and food (WEF) security. Resources in the WEF sectors are inextricably and intrinsically interrelated such that actions or developments in any one of these sectors affect either one or both of the remaining sectors. These inextricable interlinkages lie at the core of sustainable economic, social and environmental development for any country. Energy is needed for the pumping, purification and distribution of freshwater, as well as for wastewater collection, transport and treatment. In the generation of energy, water is required to move turbines in hydropower plants; for cooling processes in thermal power generation; in the growing of crops and cellulose for biofuels, etc. Agriculture and other food production activities also require the use of water and energy at various levels. Agricultural irrigation requires the use of energy for pumping water to the fields while cattle and other farm animal farming requires the use of significant quantities of energy and water. Industrial production and processing of food likewise require substantial quantities of water and energy resources in its activities. Food has also been used as input materials in the production of biofuels for domestic as well as industrial uses (Fig. 1). These intrinsic interdependencies present a complex network of interconnections among water, energy and food resources. The WEF nexus provides a comprehensive conceptual framing and approach for addressing the complex and intricate interconnections in the development of these invaluable resources.

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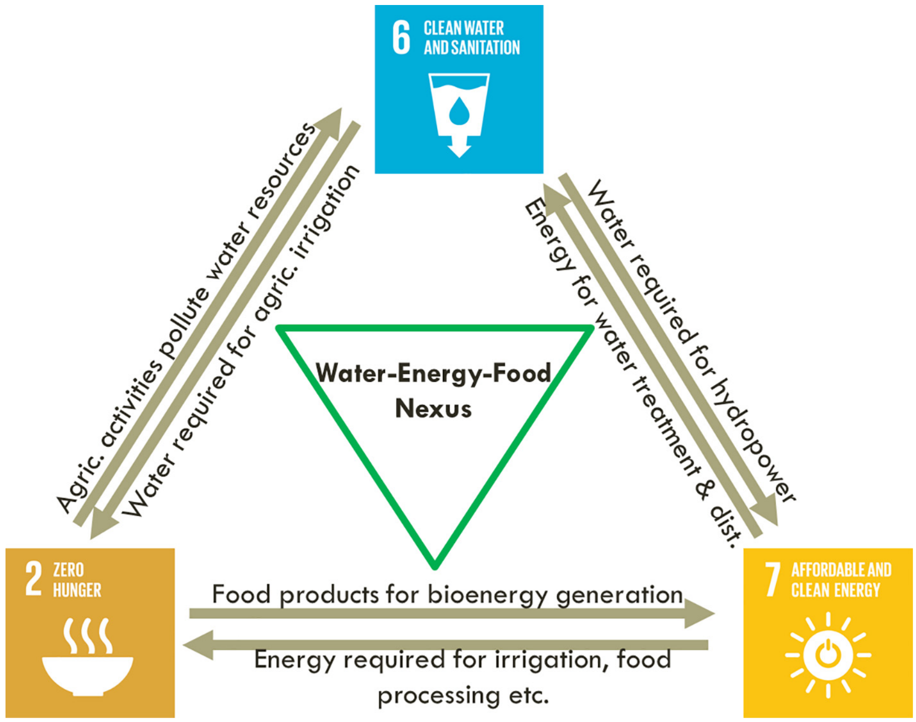

Fig. 1. Interlinkages between Sustainable Development Goals of water, energy and food.

The growth of populations, as well as the improvements in people's livelihoods, comes with increasing demands for WEF in good quantity and improved quality (Hussien et al., 2017). The increasing demands and usage of these resources further result in lots of wastage and inefficiencies in the WEF nexus. Planning and implementation of developmental projects without an in-depth understanding of the intricacies surrounding the nexus also results in imbalances in the allocation of resources and further culminates in poor resource management. Because of these interdependencies, decision-makers in WEF sectors face the major challenge of taking into account synergies, tensions and future trade between food, power, water and environment on various spatial and temporal scales (Lele et al., 2013).

As such, evaluation techniques and frameworks need to be developed to properly quantify the interdependencies between WEF nexus structures and the environment to recognize and assess the trade-offs and synergies between them (Simonovi, 2012). Although the nexus has resulted in many theoretical studies, only a subset of empirical research applied the WEF nexus to particular areas to show its capacity to structure assessment (Karnib, 2017a; Galaitsi et al., 2018). Quantifying interconnections between WEF is a preliminary step towards the embedded modelling of WEF systems, which will further add to the robust management of WEF security. Existing studies have calculated the impact on the three industries of multiple energy technologies (such as systems for generating electricity), water manufacturing and supply systems, and food products such as cereals, meat and beverages (Chang et al., 2016).

Planning of projects in the water, energy and agricultural (or food) sectors in Ghana is mostly done independently without recourse to the integrated or interconnected nature of these sectors. This culminates in poor policy and institutional frameworks for the agricultural, water and energy sectors. The resulting implication is the inefficient appropriation of resources in these three sectors. These weaknesses in planning and implementation of projects in the water, energy and food sectors may be a major reason for the appalling outcomes of water and agricultural development and management in Ghana and Africa at large (African Development Bank Group, 2010). Quantifying tradeoffs in the WEF nexus is an initial step to contributing to integrative WEF nexus modelling in the effective and efficient management of resources in the WEF sectors. Several studies have been conducted to assess the impacts of new and emerging technologies, climate scenarios as well as developments in WEF sectors, among others, on the WEF nexus at multiple levels, ranging from local (national, province, city, urban, rural) to global (Chang et al., 2016). This study sought to quantify the water trade-offs for food production and energy generation in the WEF nexus in Ghana. The study further sought to apply a quantitative assessment framework (Karnib, 2017c) for the analysis of trade-offs in the WEF nexus that allows for the determination of inter-sectoral usage and demands of resources and the comprehensive planning of future WEF developments in the Ghanaian context. The study thus analysed two possible future development scenarios in the WEF sectors at the national scale in Ghana.

Study area

Geographic and demographic background

The Republic of Ghana is located within latitudes 4° 44′ N and 11° 11′ N; and longitudes 3° 11′ W and 1° 11′ E in the western part of Africa. The country has a total land area of 238,533 square kilometres (km^2) (SRID, 2017) and 535 kilometres of coastline (Cotillon and Tappan, 2016). The nation extends approximately 670 km from north to south and has a total east–west expanse of approximately 560 km. It shares geographical boundaries westward with Côte d'Ivoire, northward with Burkina Faso, eastward with Togo, and southward with the Gulf of Guinea and the Atlantic Ocean. The topography, with slopes of less than 1%, is largely undulating and has low relief. Approximately 70% of the nation is susceptible to mild to serious sheet and gully erosion despite the gentle slopes (Frenken, 2005). Ghana's climate is warm and humid, with an estimated average annual rainfall of 1187 mm.

Ghana currently has sixteen (16) administrative regions with the administrative capital of the country being Accra. The 2018 population of Ghana was estimated at over 29.6 million people, with a population growth rate of 2.2% (The World Bank Group, 2019). The population of Ghana is mainly concentrated along the coast and in the major cities of Accra and Kumasi as well as the country's regional capitals. The country experiences a strong rural–urban drift from the north to the southern parts.

Water resources of Ghana

Ghana is blessed with significant water resources. Total internal renewable water resources for the country is estimated at nearly 5500 cubic metres per inhabitant annually (Mendes et al., 2014). The water potential of Ghana is split into surface and groundwater sources.

Surface water resources are primarily the result of three river systems draining Ghana, namely the basins of the Volta, Southwest and Coastal river systems. These river systems respectively account for 70%, 22% and 8% of the total land area of Ghana. These are further divided into five basins in Ghana, namely the Densu basin, the Ankobra basin, the Pra basin, the Tano basin and the Volta Basin. The Volta river system consists of the Red, Black and White Volta and the River Oti. The Bia, Pra and Ankobra Rivers make up the Southwest River system while the Coastal system is comprised of Todzei/Aka, Densu, Ayensu, Ochi-Nakwa and Ochi-Amissah rivers. Perhaps the most important feature of Ghana's surface water is Lake Volta, an artificial lake created by the Akosombo hydropower dam that stretches approximately 500 km north–south (Fig. 2).

Energy production in Ghana

Energy generation in Ghana dates back to the Gold Coast period when electricity supply was primarily from industrial-owned diesel generators such as those of factories, mines, and other institutions including hospitals and schools (Kumi, 2017). Ghana's energy sector was transformed with the completion of the Akosombo Hydroelectric Power Station, which also saw electricity exports to neighbouring nations including Togo, Burkina Faso and Benin.

Currently, Ghana relies on three hydropower generation plants (Akosombo, Kpong and Bui), thermal energy generation plants and, just recently, biomass energy sources (Energy Commission of Ghana, 2018). Energy generation statistics from the Energy Commission of Ghana put the country's electrical energy generation above 14,000 GWh as of 2017. Thermal energy accounted for 59.9% of all energy generated, hydropower about 39.9% and other renewables, such as biogas and solar, accounted for about 0.2% of total electrical energy generated in 2017 (Fig. 3). Hydropower and thermal were the only sources of electrical energy in Ghana until 2013 when the VRA introduced solar generation plants. Power generation through solar sources was 3 MW in 2013 and rose to 28 MW in 2017. Biogas (food) was only added to the national energy generation mix in 2017 and generated 0.04 MW and 0.08 MW in 2017 and 2018 respectively (Energy Commission of Ghana, 2018). Three interrelated organizations supervise the energy industry: the Ministry of Energy and Petroleum (Ministry), the Energy Commission (EC) and the Public Utilities Regulatory Commission (PURC), which is an autonomous regulator financed by the state.

Agriculture and food production in Ghana

Ghana has six climate-defined, natural vegetation-related and soil-influenced agro-ecological areas as presented in Table 1. In the forest, agricultural and coastal agro-ecological zones, the distribution of rainfall is bimodal, resulting in major and minor planting seasons annually. There is, however, unimodal distribution of rainfall in the remaining two agro-ecological areas, which provides for only one growing season. It is projected that the cultivable area in Ghana is 10 million ha, which is about 42% of the country's total area (Frenken, 2005).

Farming in Ghana is largely rain-fed, with small farms sizes dominating the agricultural industry and accounting for about 80 percent of total agricultural production in the country. Ghana is not self-sufficient in food production, and it has been hard to guarantee food accessibility in adequate amounts throughout the year (Frenken, 2005). Food is abundant during periods of good rain but insufficient storage facilities lead to the loss of perishable crops.

Approach and methodology

Scope of the assessment

This study focused on the quantification of the water trade-offs for energy generation and food production in the WEF nexus at the national scale in Ghana. This was relevant because the management of the power generation and food production sectors is at the national scale. Even though institutionalised agencies such as the Volta River Authority and Bui Power Authority handle the day-to-day management of their activities, the general policy direction of the energy sector comes from the central government. Likewise, the central government through the Ministry of Food and Agriculture (MoFA) and other agencies such as the Ghana Irrigation Development Authority (GIDA), etc handle the overall management and policy direction of the agricultural and food sector in the country. In this regard, the study considered the full spatial extent of the country. Temporally, the study relied on historical data from the year 2000 to 2017. Since the latest set of data available in both sectors was that of 2017, it was considered the current statistic in this assessment. The assessment covered all three sectors of the WEF nexus, though the specific focus was given to the water sector. Thus the assessment focused on quantifying the water use intensity by the food and energy sectors of the country.

Data sources

The study mostly relied on secondary data obtained from national sources in the WEF sectors. These included the Water Resources Commission (WRC), the Energy Commission, the Volta River Authority (VRA), GIDA irrigation schemes, etc. Table 2 provides further descriptions of the data used in the study.

Estimating water intensity for food production

The water intensity for food production for the GIDA-managed irrigation schemes in Ghana was estimated by dividing the total annual water abstraction by the scheme by the total annual food production of the scheme as illustrated in Eq. (1).

$$\text{Water intensity},\ I_f = \text{Water abstraction } (\text{m}^3)/\ \text{Annual food production (tonnes)} \ldots \quad (1)$$

Hence, the water intensity of food production (I_f), was estimated in cubic metres per tonne of food produced (m^3/tonne) as outlined in Eq. (1). The irrigation schemes considered here were mostly for the production of rice.

To estimate the water intensity for other major crops produced in the country, the same Eq. (1) was used. However, since most staple crops production in the country is rain-fed, the average annual rainfall received in the area where the crop is produced is multi-

Fig. 2. Map of Ghana showing various water resources. Source: https://www.mapofworld.com (2013).

plied by the total cropping area of the crop to estimate the annual water consumption of the crop. The resulting water use is then divided by the annual production (in tonnes) of the crop (Eq. (2)).

$$I_f^{\,x} = \frac{\text{Annual rainfall in cropping area} \times \text{Area of Crop (x)}}{\text{Total annual production of crop (x)}} \tag{2}$$

where $I_f^{\,x}$ is the water intensity of crop *x*.

Not all the rainfall on agricultural fields contributes to crop production or the growth of food crops. Significant losses arise from surface runoff, percolation into groundwater aquifers, evaporation, among others (Lee et al., 2006; Ren et al., 2017). However, the formulations used in this assessment are based on two (2) assumptions;

1. Water abstractions from an irrigation scheme and its applications in the agricultural fields are solely intended for agricultural purposes, and thus all losses are as results of its application on the field and could be said to be a part of the food production process.
2. Without any other source of irrigation water, amounts of rainfall received on any agricultural field are the only water source for irrigation of crops.
3. With the same amount of rainfall received on a definite agricultural field, food production or yield could vary depending on other factors such as soil fertility, pests or diseases, cropping pattern, type of seed, etc. (Muhammad-Lawal and Atte, 2006). The ability of the farmer to balance all these factors to ensure maximum yield and food production is, therefore, key to good agricultural or food production practices.

Although there are other methods of estimating crop water requirements including the Food and Agriculture Organisation (FAO) Penman-Monteith method and remote sensing techniques, which perhaps does a much better job of estimating the actual water needs of specific crops (Beyazgül et al., 2000; Trout and Johnson, 2007), this assessment primarily focused water intensity used for total annual food production in the country.

Estimating water intensity for energy generation

In estimating the (non-consumptive) water intensity of hydropower generation in Ghana, the annual water abstractions by each hydropower plant were divided by the total energy generated by the plant annually. The water intensity of energy generation in Ghana was estimated in cubic metres per kilowatt-hour of energy generated as shown in Eq. (3).

$$I_e = Water\ abstraction\ (m^3)/Energy\ generation\ (kWh) \tag{3}$$

where I_e is the water intensity of energy generation.

The water intensity of thermal energy generation was likewise estimated by dividing the annual freshwater use by the total energy generated.

Proposed conceptual framework for annual water requirements estimation

The proposed conceptual framework for the analysis of tradeoffs in this assessment is based on the work done by Karnib (2017c), which presents a quantitative WEF nexus Assessment

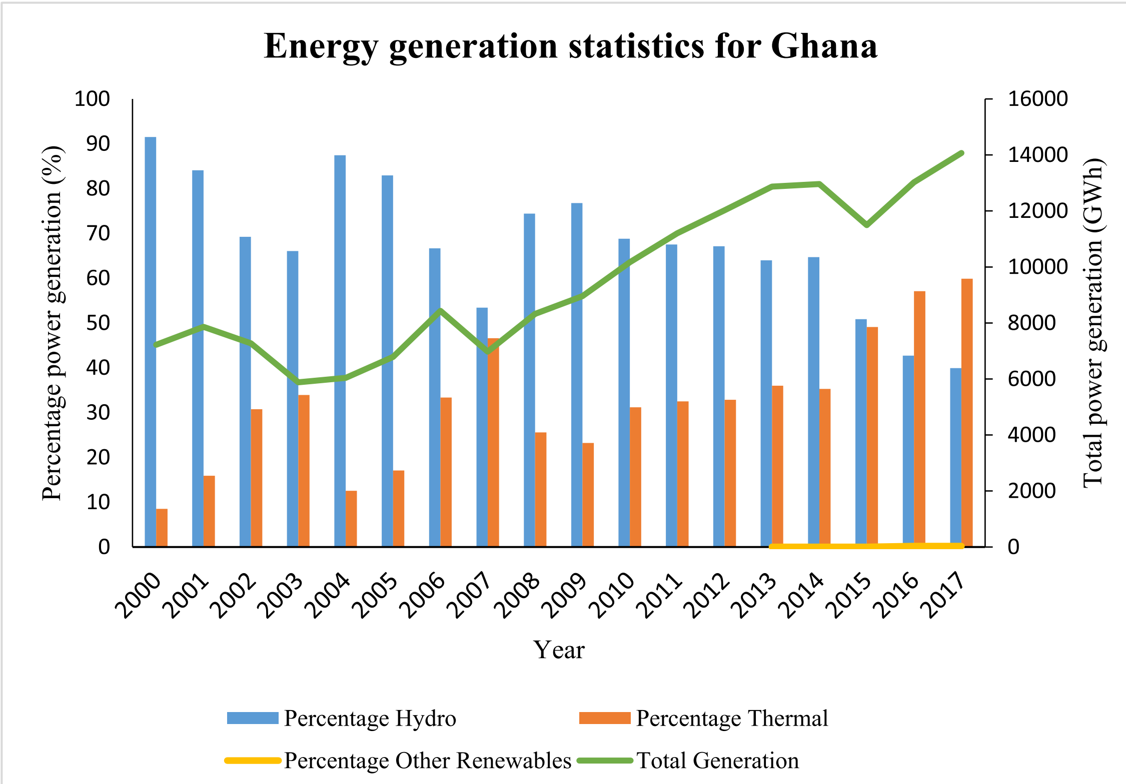

Fig. 3. Energy generation statistics for Ghana from 2000 to 2017.

Table 1
. Agro-ecological zones of Ghana and their characteristics.

Zone	Rainfall (mm/yr)	Portion of total area (%)	Length of the growing season (days)	Dominant land-use systems	Main food crops
Rain forest	2200	3	Major season: 150–160 Minor season: 100	forest, plantations	roots, plantain
Deciduous forest	1500	3	Major season: 150–160 Minor season: 90	forest, plantations	roots, plantain
Transition zone	1300	28		annual food and cash crops	maize, roots, plantain
Guinea savannah	1100	63	180–200	annual food and cash crops, livestock	sorghum, maize
Sudan savannah	1000	1	150–160	annual food crops, livestock	millet, sorghum, cowpea
Coastal savannah	800	2	Major season: 100–110 Minor season: 50	annual food crops	roots, maize

Source: Frenken (2005).

Framework to evaluate intersectoral quantitative use and resource demands and to prepare future W-E-F developments consistently and inclusively. Several nexus frameworks have been developed in efforts to help advance WEF nexus assessments at different scopes and levels, including MuSIASEM (Giampietro et al., 2009), Q-Nexus model (Karnib, 2017b), and several others are available (Biggs et al., 2015; Endo, 2017). However, these models or methodologies only cover partial aspects of the nexus and share the difficulty of investigating the WEF nexus quantitatively (Karnib, 2017c). The analysis of water trade-offs in the WEF nexus in Ghana was done at the national scale and was intended to model the annual water requirements for the sustenance of WEF security as well the basic socio-economic resource requirements for a country, state, province, etc. The framework is based on a resource balance of the WEF annual total quantities. The resource balance approach holds total annual WEF requirements to sustain the provision of services in the three sectors and to support domestic and basic socio-economic needs equal to the sum of the inter-sectoral resource use and annual socio-economic demands (Karnib, 2017c). This framework, therefore, comprises three main quantitative conceptual elements:

1. the inter-sectoral use quantities matrix (X)
2. the final demand quantities vector (Y)
3. the annual total WEF resources requirement quantities vector (Z), as shown in Eq. (4).

$$Xi + Yi = Zi \tag{4}$$

The WEF sectors are affected by ‘technological interveners’ and driven by factors such as climate change, etc. Such ‘interveners’ may include resource-efficient technologies, reuse and recycling of wastes in the systems, etc., that may reduce the intensities of such resources required to maintain services among the three sectors. ‘Drivers’ in the socio-economic demands for WEF resources may include climate and global environmental change, population

Table 2
Description and sources of data.

Description	Time Range (year)	Source, Year Obtained	WEF Sector/ Interaction	Spatial Extent
Food production and cropping area estimates	2000 to 2017	SRID-MoFA, 2019	Food	National
Water abstraction data	2005 to 2018	Water Resources Commission (WRC), 2019	All sectors, including some domestic.	National
Energy generation statistics	2000 to 2017	Energy Commission (EC), 2019	Energy	National, including all energy sources
Water abstraction and food production data	2011 to 2017	GIDA – Kpong Irrigation Scheme, 2019	Water for Food	Kpong Irrigation Scheme
Water abstraction estimates		GIDA – Tono Irrigation Scheme, 2019	Water for Food	Tono Irrigation Scheme
Hydropower water abstraction data	2000 to 2017	Volta River Authority, 2019	Water for Energy	Akosombo and Kpong Hydropower generation stations
Energy generation data	2000 to 2017	Volta River Authority, 2019	Energy	Akosombo and Kpong Hydropower generation stations
Freshwater consumption for thermal energy generation	2017	Volta River Authority, 2019	Water for Energy	VRA thermal power generation plants
Annual rainfall data	2000 to 2018	Ghana Meteorological Agency, 2019	Water	National: Agroecological Zones

or demographic change and changes in consumption patterns among others (Wakeford, 2017). Fig. 4 presents a model of the proposed conceptual framework showing how the 'drivers' and 'interveners' impact the WEF nexus.

The proposed nexus framework can be modified to include other economic sectors, and to balance the present, past or any future year, and at any assessment level, be it provincial, national, regional or global. The effects of any projected change due to 'drivers' and/or 'interveners' on the WEF nexus could be assessed using the framework.

Detailed estimation and scenario analysis methodology

WEF nexus interlinkages matrix

A nine-element matrix, representing the complete interlinkages or inter-relationship between resources in the WEF nexus is enumerated as follows:

1. water for energy
2. water for food
3. energy for water
4. energy for energy
5. energy for food
6. food for water
7. food for energy, and
8. food for food.

By denoting $X^{i\text{-}j}$ to be the total i^{th} resource requirement in the j^{th} resources services, we can represent the interlinkages between the WEF nexus by a three by three (3 × 3) matrix as illustrated as follows;

	Water (w)	Energy (e)	Food (f)
Water (w)	$X^{w\text{-}w}$	$X^{w\text{-}e}$	$X^{w\text{-}f}$
Energy (e)	$X^{e\text{-}w}$	$X^{e\text{-}e}$	$X^{e\text{-}f}$
Food (f)	$X^{f\text{-}w}$	$X^{f\text{-}e}$	$X^{f\text{-}f}$

Let 'x^j' be the total j^{th} resource services generated. Dividing the total i^{th} resource requirement in the j^{th} resource services, $X^{i\text{-}j}$ by the total j^{th} resource services generated introduces a new resource intensity coefficient, $I^{i\text{-}j}$.

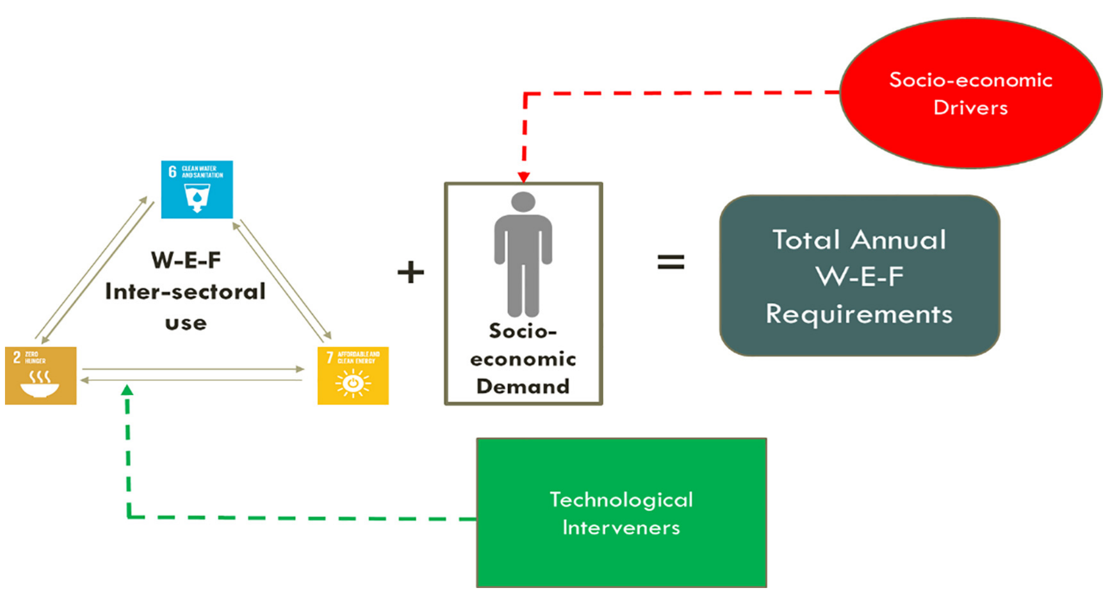

Fig. 4. A proposed conceptual model for the WEF nexus. (modified from Karnib, 2017c).

Thus; $I^{i-j} = \frac{X^{i-j}}{x^j}$ and

$X^{i-j} = (I^{i-j})(x^j)$

The new interlinkages matrix is thus rewritten as;

$$X = \begin{bmatrix} I^{w-w} \& I^{w-e} \& I^{w-f} \\ I^{e-w} \& I^{e-e} \& I^{e-f} \\ I^{f-w} \& I^{f-e} \& I^{f-f} \end{bmatrix} \begin{bmatrix} x^w \\ x^e \\ x^f \end{bmatrix}$$

Final socio-economic demand quantities vector

The final socio-economic demand for WEF resources could be expressed in terms of a quantities vector as;

$$Y = \begin{bmatrix} \textit{Annual water demand} \\ \textit{Annual energy demand} \\ \textit{Annual food demand} \end{bmatrix}$$

Denoting Y^i as the total socio-economic demand and y^i as the annual per capita demand for the i^{th} WEF resource, a new variable, denoted 'P', is introduced which represents the total population that use the source as explained in the equations below;

$P = \frac{Y^i}{y^i}$; and.$Y^i = P \times y^i$

The final socio-economic demand quantities could, therefore, be rewritten as;

$$Y = P \begin{bmatrix} y^w \\ y^e \\ y^f \end{bmatrix}$$

Annual WEF resource requirements

The total annual WEF requirements, as outlined in the conceptual framework, can be expressed as a quantities vector and is the summation of the inter-sectoral use matrix and the socio-economic demands vector. The final WEF requirements vector Z is given by;

$Z = \begin{bmatrix} Z^w \\ Z^e \\ Z^f \end{bmatrix}$; Where Z^w, Z^e and Z^f are total annual resource requirements to maintain WEF inter-sectoral services and domestic socio-economic demands.

The final model of the assessment framework is therefore given by the following mathematical equation;

$$\begin{bmatrix} I^{w-w} \& I^{w-e} \& I^{w-f} \\ I^{e-w} \& I^{e-e} \& I^{e-f} \\ I^{f-w} \& I^{f-e} \& I^{f-f} \end{bmatrix} \begin{bmatrix} x^w \\ x^e \\ x^f \end{bmatrix} + P \begin{bmatrix} y^w \\ y^e \\ y^f \end{bmatrix} = \begin{bmatrix} Z^w \\ Z^e \\ Z^f \end{bmatrix} \quad (5)$$

Final socio-economic requirements play a main role in the evaluation owing to population growth, urbanization, changing lifestyles and diets and climate change. The suggested model can allow decision-makers and policymakers in the WEF sectors of national economies to estimate the outputs in the WEF industries needed to meet any final WEF resource requirement vector.

Application to the study area

The study focused on two of the nine-element interlinkages matrix presented in 3.6, thus:

1. water for energy, and
2. water for food.

The final model for the assessment in this study was thus modified into Eq. (6) as follows:

$$\left[I^{w-w} \& I^{w-e} \& I^{w-f} \right] \begin{bmatrix} x^w \\ x^e \\ x^f \end{bmatrix} + P[y^w] = [Z^w] \quad (6)$$

where I^{w-w} (resource intensity coefficient of water for water) is zero.

This proposed model was applied to Ghana to assess annual water demands for energy generation and food production; thus water for energy and water for food; as well as the domestic socio-economic demands for WEF at the national scale. The current resource requirements for the year 2019 was estimated using the model framework.

Scenario analysis

Future projections based on two possible development scenarios were made to estimate annual water requirements or trade-offs for energy generation and food production, as well as domestic water demands until the year 2030. The scenarios were formulated to assess the impact of population growth, changes in domestic per capita WEF demands and technological innovation in the energy and agricultural sectors on the annual freshwater requirements for socio-domestic sustenance, food production and energy generation in the country. The analyses make future projections based on historical trends and linear scaling to estimate total annual freshwater requirements in the country. The scenario analyses use the 2019 annual water requirements estimated in this assessment (Fig. 5) as baseline data. The scenarios were formulated by making informed assumptions about the development of the WEF sectors based on information available in the literature (Energy Commission of Ghana, 2018; Kumi 2017; Ministry of Energy, 2019; MoFA, 2017). The assumptions made up inputs for modelling the impacts on freshwater requirements into the future.

Scenario 1: reference scenario (business as usual)

This scenario assumes business as usual, maintaining that current per capita domestic demands for resources in the WEF nexus remain unchanged into the future and that current WEF inter-sectoral use intensities also remain the same. The scenario assesses the effect of the current rate of population growth on demand for water for food production and energy generation as well as domestic demands for WEF resources in the country.

The reference scenario or Business As Usual (BAU) considers total annual water requirements based on current situations in the food (agricultural) and energy sectors in Ghana. The scenario maintained the current population growth rate of 2.19%, the current rate of increase of access to electricity of 3.48% (Kumi, 2017) and the current growth of food production of 8.4% (MoFA, 2017) in Ghana. The scenario sought to assess the impact of population growth on the total annual requirement for water in energy and food production, as well as domestic activities.

Scenario 2: Technological advancement & improved living conditions (innovation)

Another development scenario for this analysis, 'Innovation', assumes an improvement in the living conditions, and advances in technology, which brings about reduced WEF inter-sectoral use intensities and improved WEF services. The scenario assumes that technological advancements result in a yearly reduction of 2.5% in WEF inter-sectoral use intensities, and an improvement in the provision of WEF services resulting in a 2.5% increase in per capita resource demand annually. The scenario further assumes 100% access to electricity from 2020.

The scenario, 'Innovation', sought to model and assess the impact of technological interventions on total annual water requirements as in the case of the first scenario. The scenario considered improvements in living standards resulting in increased

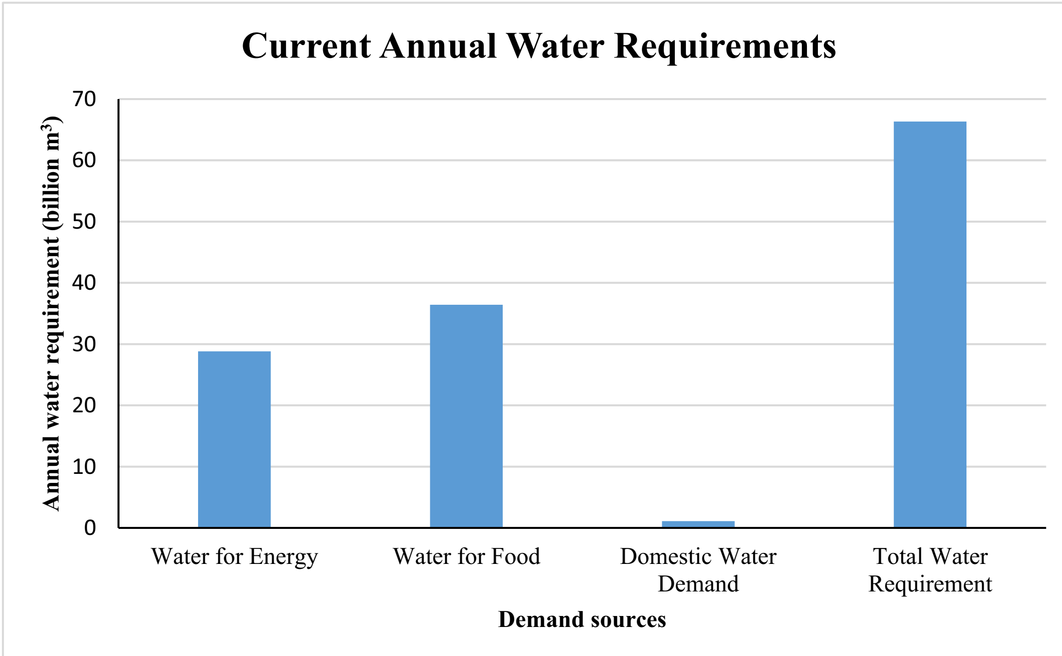

Fig. 5. Annual water requirements in Ghana.

per capita demand for resources in the WEF nexus. The impacts of the application of technological advancements in the nexus are also modelled in this scenario. Scenario 2 also assumes 100% electricity access in the country in 2020 as suggested by Kumi (2017).

Results and discussion

Water intensity for food production

Table 3 presents the water intensity of major food crops as well as agricultural irrigation types in Ghana. These estimates represent consumptive agricultural freshwater uses, consumptive freshwater uses for energy generation from thermal plants and 'supposedly' non-consumptive hydropower energy generation uses.

The consumptive agricultural water use in Ghana increases with increased agricultural production. The water-food nexus mainly applies to the water-use-intensity or water footprint of agricultural production (Chang et al., 2016). This assessment considers the water use intensity for food production in Ghana. Sorghum recorded the highest water footprint with 5803 cubic metres per tonne produced, followed by cassava with 4913 cubic metres per tonne of cassava produced. Generally, foods produced in the northern sector; millet, sorghum, cowpea and soya beans; recorded very high water footprints. This could be attributed to the relatively dry lands and dry atmospheres in the northern sector of the country (Quaye, 2008). The least water intensity per tonne of food crop production in Ghana was recorded for yam, which uses an estimated 295 cubic metres per tonne of yam produced. The water footprint of rice, which is mostly irrigated, was found to be 3706 cubic metres per tonne. Chang et al. (2016) report a water footprint of 1.7 cubic metres per kilogram (m^3/kg) of rice produced, comparatively lower than the water footprint recorded for Ghana in this assessment. All cereals (rice, millet, maize, sorghum, cowpea and soya bean) produced in the country have water footprints of more than 2000 cubic metres per tonne (Table 3).

This is significantly higher compared to the water footprints of cereal crops in China, which uses less than 1700 m^3 of water on average to produce a ton of cereal (Chang et al., 2016). This can be due to inefficient irrigation systems leading to high transmission losses in the transport of water to the irrigation fields. Initiatives to promote water efficiency for agriculture in Ghana should

Table 3
Water intensity of food production in Ghana.

Crop	Cropped area (hectares)*	Description	Formulation used for estimation	Unit	Water intensity
Maize	970,290	Mainly rain-fed	Eq. (2)	m^3/tonne	2981
Millet	239,342	Mostly rain-fed	Eq. (2)	m^3/tonne	2932
Sorghum	156,662	Mostly irrigated, with some rain-fed	Eqs. (1) and (2)	m^3/tonne	5803
Rice	223,513	Irrigated	Eq. (1)	m^3/tonne	3706
Cassava	925,617	Rain-fed	Eq. (2)	m^3/tonne	4913
Yam	492,981	Rain-fed	Eq. (2)	m^3/tonne	295
Cocoyam	204,240	Rain-fed	Eq. (2)	m^3/tonne	364
Plantain	363,395	Rain-fed	Eq. (2)	m^3/tonne	898
Groundnut	320,313	Mainly rain-fed	Eq. (2)	m^3/tonne	518
Cowpea	153,912	Mainly rain-fed	Eq. (2)	m^3/tonne	4498
Soyabean	101,695	Mainly rain-fed	Eq. (2)	m^3/tonne	4440
Rain-fed agriculture		Mean intensity of rain-fed agric.		m^3/tonne	688
Irrigated agriculture		Mean intensity of irrigated agric.		m^3/tonne	3706
Mean water intensity of total food production				**m^3/tonne**	**990**

*Cropping area of major food crops in Ghana (Source: Statistics, Research and Information Directorate (SRID), MoFA, 2018).

include attempts in one or more of the following categories: formulating long-term water policies and associated strategies, improving water productivity, encouraging water availability, controlling agricultural pollution, reforming institutions and governance, increasing the involvement of stakeholders, etc. (FAO, 2008).

Irrigated rice production in Ghana uses more water than rainfed agriculture in the country (Table 3). Rice production alone, from estimates in this assessment, would account for over 1.4 billion m^3 of water abstraction and consumption in the country annually. This calls for more water-efficient irrigation systems, drought-resistant crops, etc. On average, Ghana requires 990 cubic metres of water to produce a tonne of food as shown in Table 3, accounting for over 20 billion cubic metres of freshwater consumed in the country.

Water intensity for energy generation

Table 4 provides estimates of the consumptive and non-consumptive freshwater uses for energy generation categorised by the energy supply source.

The assessment in this study did not include freshwater losses due to water impoundments for hydropower generation. Hence, the water footprint for hydropower generation and that of total energy generation in Ghana as outlined in this study does not account for evaporation losses from hydropower dams. Consumptive water uses of hydropower generation mainly result from evapotranspiration losses attributed to the storage of huge quantities of water in large reservoirs for the generation of energy (Mekonnen and Hoekstra, 2011). In their study assessing the evaporation losses associated with hydropower generation, Mekonnen and Hoekstra (2011) found that the Akosombo and Kpong hydropower dams collectively had the highest consumptive water footprint among all the dams assessed globally. The Akosombo and Kpong hydropower dams together recorded a water footprint of 3 million m^3 for each Gigawatt of energy generated (Mekonnen and Hoekstra, 2011). Thus, evapotranspiration generally accounts for the majority of the freshwater losses in the Volta River Basin in Ghana.

The Bui, Akosombo and Kpong dams are all along the same river stretch, the Volta River, which is a transboundary river basin in the West Africa sub-region, comprising the Black Volta, the White Volta, the Oti River and other minor tributaries. Ghana is at the downstream end of the basin and shares this all-important river basin with six (6) other countries in the sub-region. The Black Volta, which flows through the Bui Dam for electricity generation, joins the White Volta downstream and then flows through the Akosombo Dam to be used for electricity generation purposes. These flows then join the Kpong Dam, which is a 'run-of-the-river' hydropower dam relying on the tailwater from the Akosombo Dam to generate electricity to complement power generation from the two major hydropower plants (Akosombo and Bui) in Ghana. As illustrated in Table 4, the hydropower plant with the highest non-consumptive water intensity was found to be the Kpong Dam (35 m^3/kWh), followed by the Akosombo Dam (6.69 m^3/kWh) and then the Bui Dam (1.37 m^3/kWh) with maximum head levels of 11.75 m, 75.59 m and 88 m respectively. With hydropower currently accounting for almost 40% of the country's electricity supply, the mean water withdrawal for hydropower generation was found to be 5.08 m^3/kWh. This accounts for the total non-consumptive water withdrawal for hydropower generation in the country. These flows, amounting to about 28.6 billion m^3 of freshwater resources are lost annually to the sea after its use at the Kpong Dam as there are no measures or strategies put in place to reclaim these flows for other purposes. This accounts for more than 90% of all freshwater uses for energy generation in the country. The FAO (1997) estimated that total annual freshwater flows into the sea were in excess of 38 km^3, which far exceeded the total annual irrigation water requirements of 28.5 km^3 for the whole Volta Basin (FAO, 1997). It is therefore important to consider water requirements for hydropower generation in national WEF nexus analysis as it provides relevant information on the various freshwater uses in the country. Most hydropower plants in the world, including those in Ghana, share dams and reservoirs with irrigation schemes, water treatment and distribution plants and/or aquaculture farms, all of which compete for immediate uses. Paying particular attention to the water intensities of all competing users will allow for more efficient water allocation and proper management of reservoirs.

In thermal power plants, water is circulated continually in a closed loop where it is heated into high-pressure steam to drive a turbine and generate electricity and then cool down the water. Relatively speaking, this closed-loop method uses hardly any water that requires only a tiny quantity of make-up. The cooling of the closed-loop water needs and consumes the essential portion of the complete use of thermal water (Larsen et al., 2016). The cooling of the closed-loop in thermal energy generation is mostly done with ocean water in Ghana. Water use in thermal energy generation is consumptive (Holmes and Chivas, 2015). The processes in thermal energy generation that require freshwater uses include water for injection, boiled/feedwater make-up, cooling tower make-up, process water for fuel treatment and service water. All these services require small quantities of water and the freshwater component used in these services in thermal energy generation in Ghana was found to be 0.03 m^3/kWh (Table 4).

The mean water requirement for energy generation in Ghana, both consumptive and non-consumptive, was found to be 2.05 m^3/kWh, with less than 5% being for consumptive uses. Though these figures represent largely non-consumptive hydropower uses, there is the need to explore other innovative and cost-effective ways of reusing the huge amounts of freshwater resources lost to the sea annually resulting from hydropower generation in the country. Though there are significant technical difficulties in reusing flows from hydropower dams, with good engineering these enormous freshwater resources could be used for greening purposes and mechanised agricultural irrigation along the Ada and other coastal plains in the country.

Table 4
Water intensity of energy generation in Ghana.

Energy source	Description	Formulation used for estimation	Unit	Water intensity
Bui Hydropower	Non-consumptive	Eq. (3)	m^3/kWh	1.37
Akosombo Hydropower	Non-consumptive	Eq. (3)	m^3/kWh	6.69
Kpong Hydropower	Non-consumptive	Eq. (3)	m^3/kWh	35.00
Mean water withdrawal for hydropower generation	Non-consumptive		m^3/kWh	5.08
Water intensity for thermal energy generation	Consumptive	Eq. (3)	m^3/kWh	0.03
Mean water requirement of total energy generation			**m^3/kWh**	**2.05**

Current water demands

Fig. 5 presents the current annual water requirements for energy generation, food production and domestic socio-economic uses in Ghana. About 42% (28 billion m^3) of all water abstractions in 2019 were for non-consumptive hydropower generation which returned to the system for reuse, with consumptive freshwater abstraction for thermal energy generation accounting for less than 1%. Water withdrawals, including consumptive uses, for food production accounted for over 57% of all freshwater abstractions, with total freshwater abstractions amounting to over 66 billion cubic meters. This is consistent with findings from other assessments in similar contexts where water withdrawals for food production were reported to be the largest freshwater user in the WEF nexus (Chang et al., 2016; Karnib, 2017b; Karnib, 2017c; Karnib and Alameh, 2020; Udias et al., 2018; Yang et al., 2018). Freshwater abstractions for domestic socio-economic uses accounted for less than 2% of the total annual freshwater abstractions. The cyclical use of water by the three hydropower plants, where water is withdrawn for power generation and returned to the system to be used by other plants allows for synergy in the energy generation sector. This allows water to be recycled in the system. However, it is unfortunate that huge amounts of freshwater resources are allowed to flow into the ocean after use for hydropower generation by the Kpong Dam.

Agriculture accounted for the most consumptive water use in this assessment. All consumptive freshwater uses considered in this study; water for thermal energy generation, water for food production and domestic water uses; accounted for over 37 billion cubic meters. Out of this, over 95% is for food production alone, with domestic water use and thermal energy generation accounting for 3% and below 2% respectively.

Future water demand projections under scenario analysis

Domestic resource requirements

Under the reference scenario (BAU), domestic demands for water, energy and food increase by 26.9%, 58.6% and 26.9% respectively by the year 2030 (Figs. 6 and 7). These demand increases are consistent with the projections of IEA (2012). Under the reference scenario, Ghana can achieve universal access to electricity in the year 2023. Domestic demands for water, energy and food under 'Innovation' increases by 54.8%, 93.5% and 54.8% respectively, with universal electricity access from 2020 (Kumi, 2017). The improvement in living standards undoubtedly accounts for significant increases in resource requirements in the WEF nexus (OECD, 2012). The scenario 'Innovation' results in higher resource demands in the WEF nexus by over 21% across all three sectors.

Annual water requirements

Total annual water requirements for food and energy production and domestic supply increased by 34.2% in 2030 under BAU (Fig. 8). This huge increase is the result of increasing population causing effectual increases in the water abstraction for agriculture and domestic supplies as well as energy to meet the growing demands (OECD, 2012; IEA, 2017). The analysis also demonstrates that rising demand results primarily from food production and the generation of electricity. Although Ghana is enriched with enormous freshwater resources, freshwater pollution mostly resulting from illegal artisanal mining has been a major problem in the country (Danyo, and Osei-Bonsu, 2016; Aboka et al., 2018; Kuffour et al., 2018). This poses significant threats to Ghana's ability to meet such rising annual freshwater requirements. The exploration of alternative and innovative solutions in freshwater use and allocation is vital to achieving sustainable development in the water sector.

The second scenario, 'Innovation', projects a 26.1% reduction in total annual water requirements (Fig. 8). This scenario projects increased domestic demands for WEF by about 55% for both water and food, and over 93% for electricity or energy by 2030. Notwithstanding the enormous increases in demand for WEF resources at the household level, the huge reduction in total freshwater requirements to meet total WEF demand in the country could be attributed to significant investments in technological interveners in the WEF nexus that reduces the water intensity of energy and food production activities. Investments in technological advance-

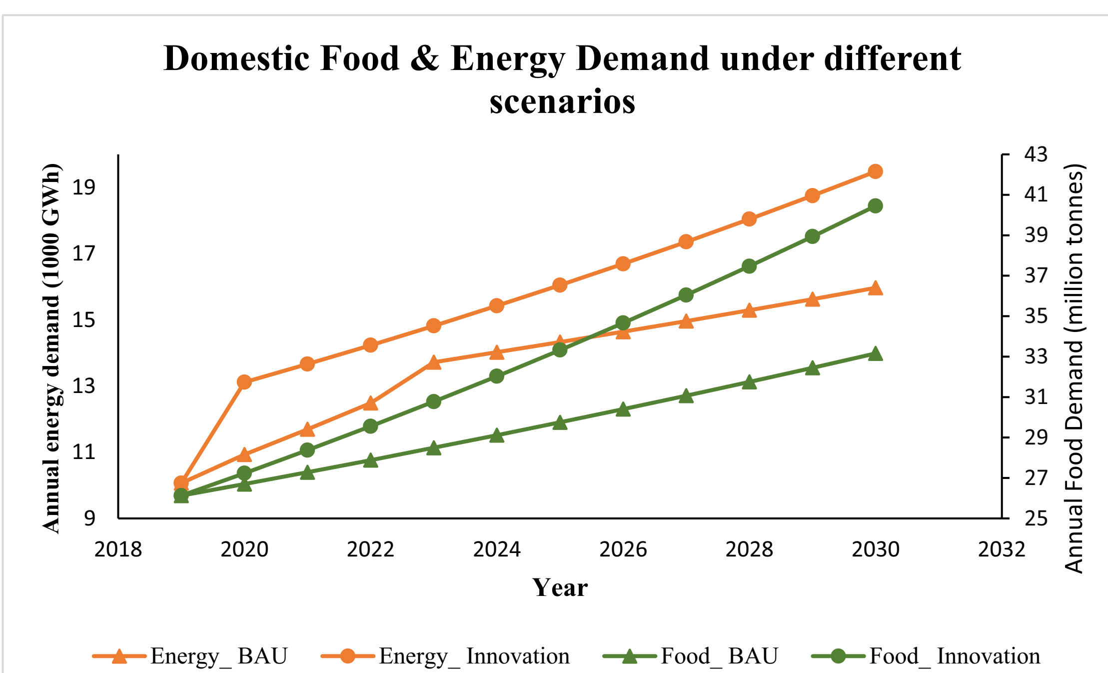

Fig. 6. Domestic food and energy demand in Ghana under different scenarios.

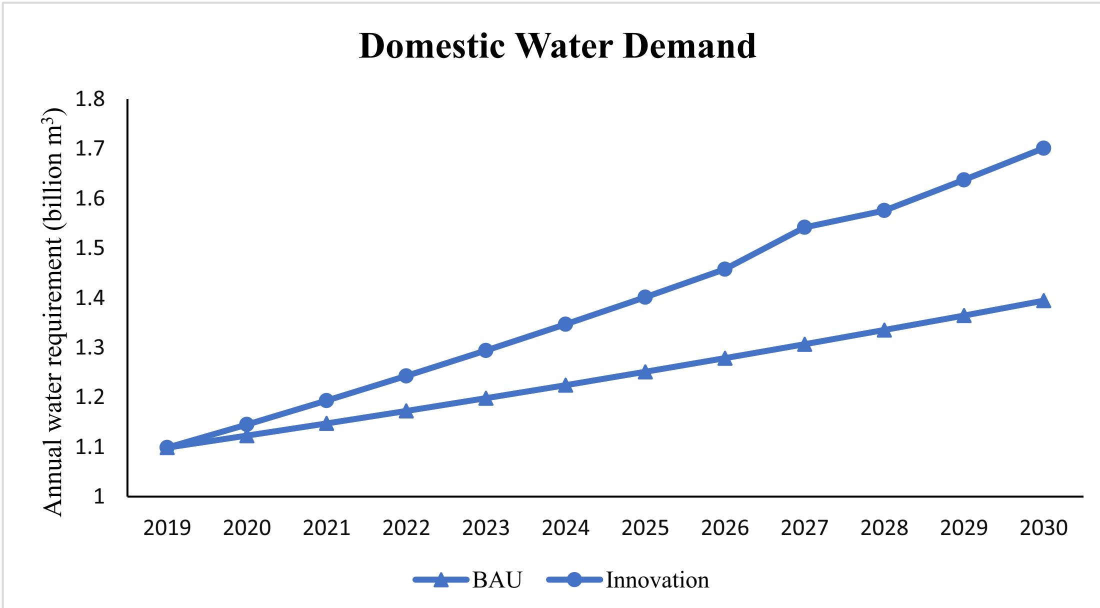

Fig. 7. Domestic water demand under different scenarios in Ghana.

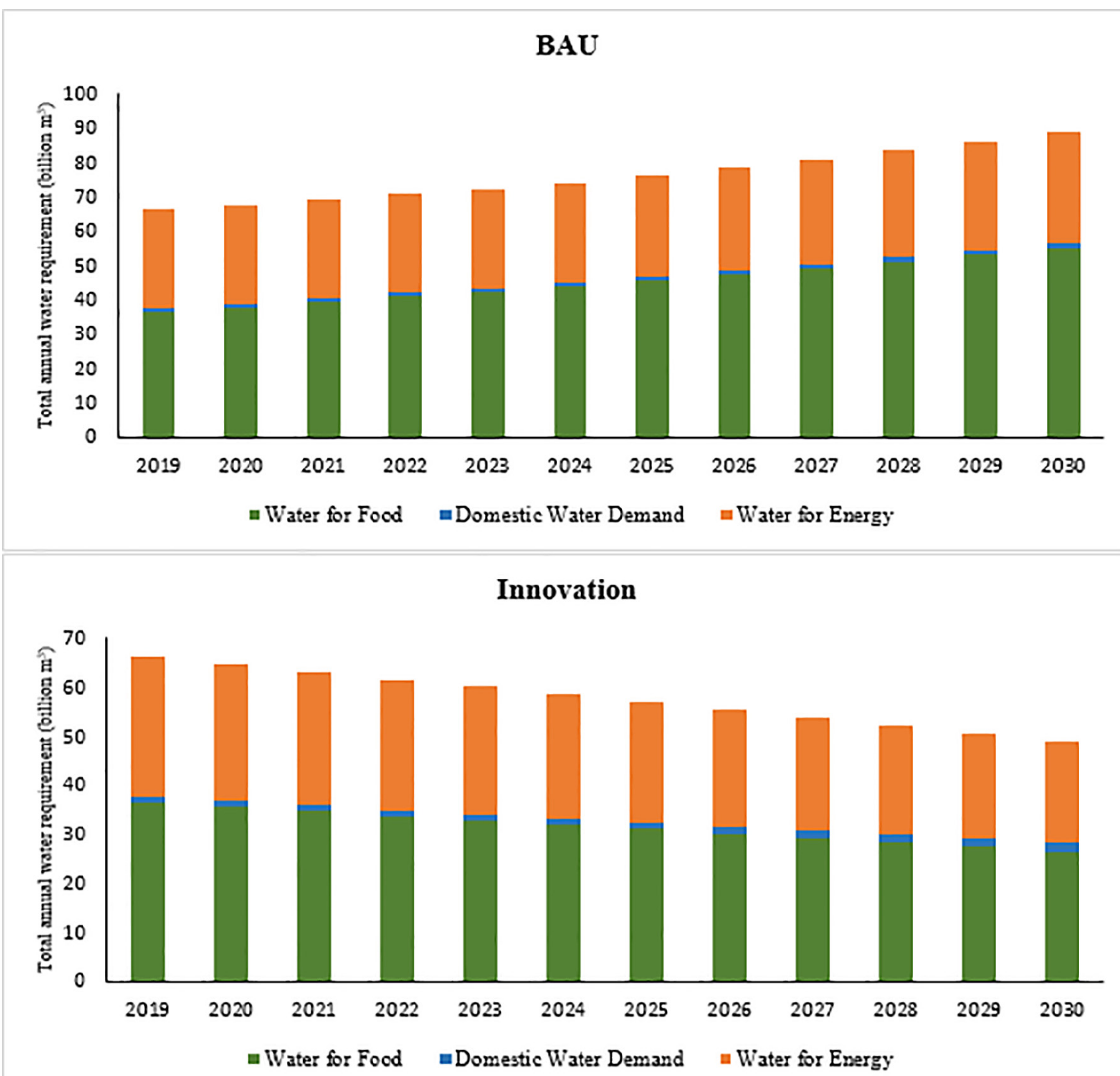

Fig. 8. Variation in total annual water requirements under different scenarios for Ghana.

ment in the agriculture industry to improve irrigation systems and the use of drought-resistant crops will result in a massive reduction in irrigation inefficiencies, thereby reducing irrigation water requirements in the agricultural sector. Additionally, by moving to more renewable energy sources such as solar and biomass which require very little or no freshwater in their generation, the water intensity of energy generation in the country will be greatly reduced.

This is feasible for Ghana, as the government of the Republic, through the Ministry of Energy, has launched an ambitious Renewable Energy Master Plan that seeks to make significant achievements in the energy sector by the year 2030 (Ministry of Energy, 2019). The Renewable Energy Master Plan aims to achieve the following by 2030:

- Increase the share of renewable energy in the national energy generation mix from 42.5 MW in 2015 to 1363.63 MW (with a total of 1094.63 MW of grid linked installations);
- Reduce reliance on biomass as the primary fuel for apps in thermal energy;
- Provide decentralized electrification in 1000 off-grid societies based on renewable energy;
- Promote local content and local involvement in the renewable energy sector.

The Ministry of Food and Agriculture, through GIDA, has taken bold efforts to ensure water efficiency in the agricultural sector by constructing new and improved irrigation canal systems for irrigation schemes across the country as well as training farmers on efficient water allocation (MoFA, 2017). In relation to this, the vision indicated by MoFA is that "modernized agriculture culminating in a structurally transformed economy and evident in food security, employment opportunities and decreased poverty" will boost crop yields generated in the nation, considerably decreasing the water intensity of food production in the country.

A comparison of the variation in total annual water requirements in both scenarios shows huge increases in the water requirements for energy and food under the scenario 'BAU, whereas there are steady decreases in the water requirements for energy and food under the scenario 'Innovation' as shown in Fig. 8. The scenario analyses have shown that to achieve sustainability in the water sector, it is imperative to employ technological advancements and other innovative solutions to effectively the water intensity of various freshwater uses in the country.

Conclusion

The assessment found the water intensity for food production to be the largest consumptive water user in Ghana. Even though water abstraction for hydropower generation in Ghana is non-consumptive, has revealed that over 28 billion m^3 of freshwater resources are lost to the sea annually after its use for hydropower at the Kpong Dam. Future projections of annual freshwater requirements for energy generation, food production as well as socio-domestic WEF sustenance under two possible development scenarios showed that under the 'BAU' scenario, total annual water requirements increase by 34.2% by 2030. Under the scenario 'Innovation', however, total annual freshwater requirements are expected to reduce from the 2019 estimate by 26.1% by 2030. Based on the results of this study, the implementation of policies and the application of more technological advancement in the management of the WEF resources is highly recommended, as this would aid in combatting the negative impacts of population growth on demands for WEF resources.

Conflict of interest

The authors wish to declare no conflict of interests.

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CRediT authorship contribution statement

Emmanuel K. Opoku: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Kwaku A. Adjei:** Conceptualization, Supervision, Validation, Writing – review & editing, Funding acquisition. **Charles Gyamfi:** Validation, Writing – review & editing. **Christopher Vuu:** Visualization, Writing – review & editing. **Emmanuel K. Appiah-Adjei:** Writing – review & editing. **Samuel N. Odai:** Funding acquisition, Writing – review & editing. **Ebenezer K. Siabi:** Writing – review & editing.

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