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Bridging the data gap: using remote sensing and open-access data for assessing sustainable groundwater use in Kumasi, Ghana

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ABSTRACT

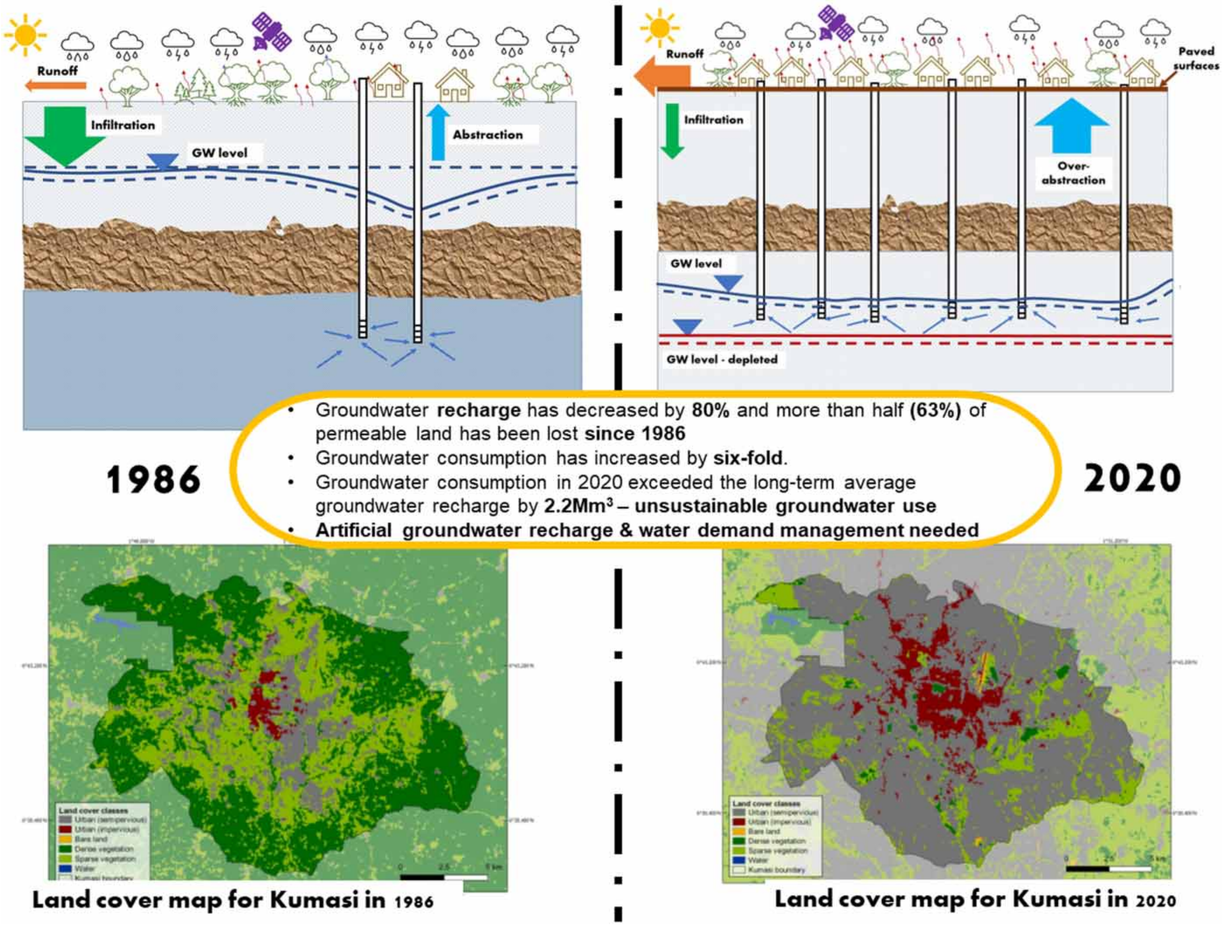
Groundwater use has significantly increased in the rapidly urbanising city of Kumasi, Ghana. But there is a lack of understanding of whether the groundwater system can sustain the growing demand in the future amidst climate change and rapid urbanisation. Using remote sensing datasets and a water balance approach, this study estimated the groundwater recharge and assessed how urbanisation has affected its groundwater sustainability. Sustainability is investigated by comparing multi-annual groundwater withdrawals to long-term average annual replenishment. Results show that while groundwater recharge has decreased by 80% from 1986 to 2020, mainly due to substantial (63%) loss of permeable land, groundwater consumption has seen a six-fold increase. Groundwater consumption in 2020 exceeded the long-term average groundwater recharge by 2.2Mm^3, suggesting that the current groundwater use trends are unsustainable for future groundwater availability. Under a 'business-as-usual' scenario, a four-fold increase in groundwater consumption is predicted by 2050 while climate change and land-cover changes may reduce groundwater recharge by 10% and 55% respectively. Practical measures such as promoting artificial groundwater replenishment approaches, adopting low-impact development and instituting demand management measures must be implemented in the Metropolis. This should be informed by further studies to ascertain the exact condition of the groundwater.

Key words: groundwater, Kumasi, remote sensing, sustainability, urbanisation, water consumption

HIGHLIGHTS

- Since 1986, groundwater use in Ghana's fastest-growing city, Kumasi, has increased by six-fold while recharge has dwindled by 8%.
- By mid-century, groundwater use can see a four-fold increase while climate change and land cover changes may reduce groundwater recharge by 10 and 55%, respectively.
- Promoting artificial groundwater recharge approaches in the Metropolis is key to ensuring the availability of groundwater for future generations.

GRAPHICAL ABSTRACT



- Groundwater **recharge** has decreased by **80%** and more than half **(63%)** of permeable land has been lost **since 1986**
- Groundwater consumption has increased by **six-fold**.
- Groundwater consumption in 2020 exceeded the long-term average groundwater recharge by **2.2Mm³ – unsustainable groundwater use**
- **Artificial groundwater recharge & water demand management needed**

INTRODUCTION

Today, a little more than half of the global population resides in urban areas, and by the middle of the century, this figure is expected to increase to more than two-thirds (68%) (UNDESA 2019). Nowhere is this growth as rapid as in Sub-Saharan Africa (SSA), where the urban population is expected to double within the next two decades (Foster *et al.* 2020). In SSA, urban growth is expected to be absorbed in large part by the outward expansion of metropolitan areas, namely in the form of informal settlements where access to basic services is inadequate (Dos Santos *et al.* 2017). The unparalleled growth is a great challenge for both sustainability of water resources and the capacity of existing infrastructure to deliver water to households. Additional challenges such as climate change, land use changes, poor sanitation, and mismanagement of urban water resources have added to the worsening quality and availability of water (Dos Santos *et al.* 2017). This, along with the increasing demand owing to population growth, emphasises the importance of sustainable management of water resources.

In Ghana, urbanisation rates have outpaced West Africa's with more than half (51%) of the population now living in urban areas (Abass 2020). The population and housing survey conducted in 2010 pegs the country's population growth rate at 2.5% with the city of Kumasi growing at twice the national growth rate – 5.5% (Ghana Statistical Service 2013a). Such rapid growth poses an enormous challenge for urban planning, water management, and sanitation services (Foster *et al.* 2020). Most of Kumasi's population relies on piped water, however, access dropped from 83% in 2000 to 75% in 2010 (World Bank Group 2015). This has been attributed to infrequent water flows, poor maintenance, and insufficient investments from the water sector to meet the increasing demand in new communities (World Bank Group 2015). To supplement this demand, residents have resorted to groundwater as an alternate source (Ewusi *et al.* 2016).

As reliance on groundwater increases and recharge reduces owing in part to land use changes, this could lead to over-exploitation of the resource (Foster *et al.* 2020). There is therefore the need to ensure sustainable groundwater use.

Ensuring groundwater sustainability should be based on robust understanding of the groundwater situation – inflows and outflows – using information from groundwater modelling and monitoring and requires hydrogeological expertise (Adelana *et al.* 2008; Gleeson *et al.* 2012). Over the years, hydrogeological assessments of Ghana have been carried out (Kortatsi 1994; O'Dochartaigh 2019). However, these national-scale assessments are coarse and fail to provide insight into local aquifer conditions. Due to the rapid growth of groundwater use in Kumasi, there is a need for a hydrogeological assessment of the Metropolis to determine the sustainability of groundwater for current and future uses. At present, no such assessments have been conducted and literature covering groundwater use and the hydrogeological situation is conspicuously missing. Available groundwater-related literature only covers groundwater quality assessments (Ewusi *et al.* 2016; Aboagye & Zume 2019) and *in-situ* data required for hydrogeological assessments, such as groundwater levels, are not available in Kumasi.

By utilising open-access data and remote sensing techniques, the study fills the data gap and provides a means of assessing groundwater sustainability in urban contexts where traditional hydrogeological data is unavailable. The aim of the study is to investigate whether current trends of groundwater usage are sustainable for the future based on using remotely sensed and open-access data. Sustainable groundwater use adopted in this study is from the indicator defined by Bierkens & Wada (2019), namely the prolonged (multi-annual) abstraction of groundwater from an aquifer cannot exceed quantities of average annual recharge. Therefore, it is based on estimates of annual groundwater abstraction and groundwater recharge. Remote sensing datasets, often used for purposes of rainfall monitoring and distinguishing land use categories (Meijerink *et al.* 2007), are used to bridge the scientific data gap in this study. GIS-based recharge calculations are carried out in Google Earth Engine (GEE), where such datasets are readily available. The method developed in this study can be used to assess groundwater sustainability in similar urban situations. The findings of this study are intended to provide a point of departure for further studies on the actual groundwater situation in the Metropolis. This will inform decision-makers and policymakers to implement practical strategies to enhance groundwater recharge and thus forestall groundwater depletion in the future.

METHODOLOGY

Study area

Kumasi is in the south-central Ashanti region of Ghana. The centrality of Kumasi has made it a national traversing point, fueling the growth of industries and commercial activities that have led to high national and international migration rates (Cobbinah & Amoako 2012). It accommodates nearly two-thirds of the region's population in an area of 254 km^2 (Cobbinah & Amoako 2012). The population census of 2010 by Ghana Statistical Service (2013a) determined that the city was experiencing a growth rate of 5.5% and had a population of 1.7 million. Following this growth rate, current projections indicate a population of well over 3 million (Figure 1).

Kumasi used to be known as the 'Garden City of West Africa' due to its abundant greenery (Ghana Statistical Service 2013b). However, due to urban expansion, physical and agricultural developments have taken place in important natural areas such as wetlands, flood plains, and rivers (Amoateng *et al.* 2018; Abass 2020). An earlier study by Cobbinah & Amoako (2012) estimated that 80% of the land in Kumasi was developed and that this development is expected to increase. The pressure from the city's expansions has caused alterations in the natural hydrologic conditions translating into frequent flood disasters, especially during the rainy season (Amoateng *et al.* 2018).

Kumasi lies in Ghana's moist, semi-humid climate zone experiencing two rainfall seasons annually (Amoateng *et al.* 2018). The major season occurs between March and July and the minor season between August/September and October, with an annual mean of 1,400 mm recorded between 1980 and 2012 (Ewusi *et al.* 2016). The hydrogeology in the region is characterised by weathered and fractured aquifer properties (O'Dochartaigh 2019). High aquifer yields are locally experienced due to the development of secondary porosity (Yeleliere *et al.* 2018). The depth of the aquifers in this complex ranges from 10 to 60 m (Gumma & Pavelic 2013; Yeleliere *et al.* 2018). The water table in the Kumasi Metropolis is shallower in the western part and increases towards the eastern part (Ofosu *et al.* 2014).

Groundwater recharge in Ghana is dominated by direct infiltration from precipitation through fractures and fault zones and through sandy portions of the weathered zone (Kortatsi 1994). During the rainy season, recharge can also occur through seepage from ephemeral stream channels (Kortatsi 1994). Per decade, Ghana experiences a total recharge of 970 mm ranging

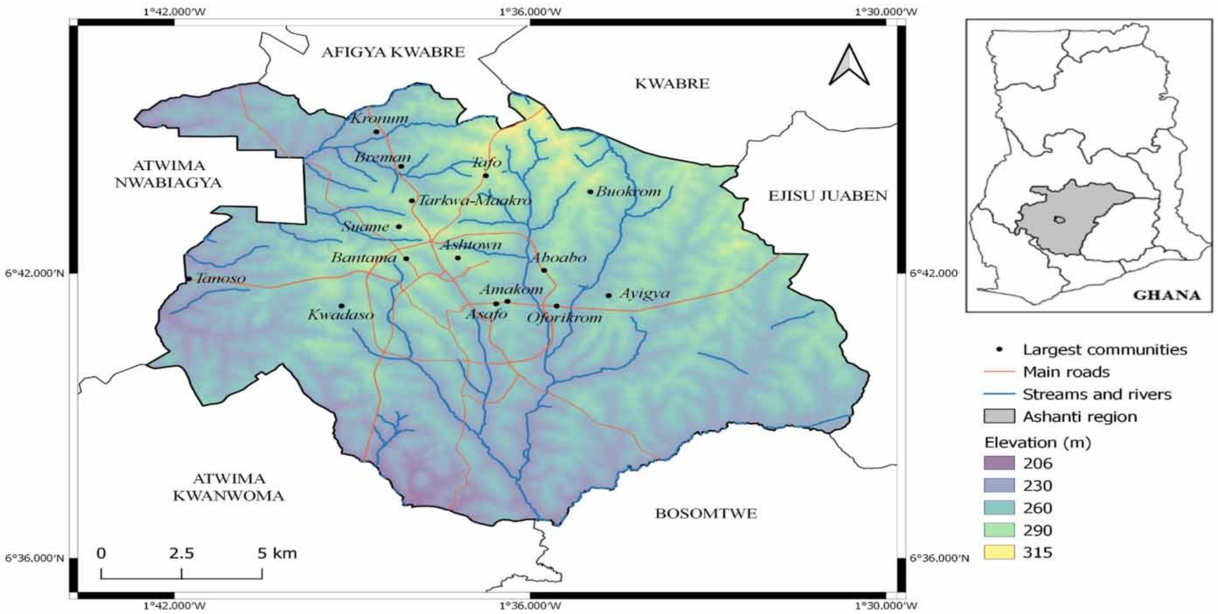


Figure 1 | Map of Kumasi showing location within Ghana, traversing roads, major streams and rivers, and largest communities within the city. Information was retrieved from Ghana Statistical Service (2013b) and the underlying SRTM elevation map.

between 340 and 2,800 mm depending highly on the climatic zone (MacDonald *et al.* 2021). As Kumasi is located in the semi-humid zone, recharge is expected to be around the average presented by MacDonald *et al.* (2021), approximately 1,500 mm/decade (150 mm/year). In a study conducted by Anornu *et al.* (2009), groundwater recharge was estimated to be 93–120 mm annually. Further investigations on groundwater recharge around the area are non-existent, giving the best estimate of groundwater recharge to be around 120 mm per year.

DATA COLLECTION AND ANALYSES

The approach used to assess sustainable groundwater use in Kumasi is shown in Figure 2. This study uses the sustainability indicator of 'physically sustainable groundwater use' as defined by Bierkens & Wada (2019):

> 'Prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities not exceeding the average annual replenishment'.

By estimating long-term average groundwater recharge and groundwater abstraction volumes in Kumasi, this sustainability definition can be applied to define the state of the groundwater resources. Due to the limited hydrogeological data available, using this approach made it possible to rely on remotely sensed and open-source data to determine the groundwater sustainability. The domestic abstraction component of sustainability is determined using consumption data from Kuma *et al.* (2010) and Ghana Statistical Service (2013a) containing survey results on population, percentage of households reliant on groundwater consumption, and per capita water demand. Non-domestic consumption is estimated from the results of a 2020 survey conducted in Kumasi for this study at 52 different locations. Survey questions revolved around groundwater abstraction rates of the facility, total usage period, and observations on water quality and low yields. The groundwater recharge component of sustainability is estimated using a simple water balance in Equation (1), requiring estimates of precipitation, runoff, and evapotranspiration. An overview of the methodology is shown in Figure 2.

Due to data scarcity in Kumasi, this study uses Earth Observation to estimate components of the water cycle to bridge the data gap. Precipitation datasets are readily available in GEE, runoff is estimated using remote sensing precipitation datasets and the Soil Conservation Service-Curve Number (SCS-CN) method, and evapotranspiration estimates are derived from remote sensing datasets. An overview of all datasets is presented in Table 1. Detailed descriptions of the methods used to determine each component are given in the following sections.

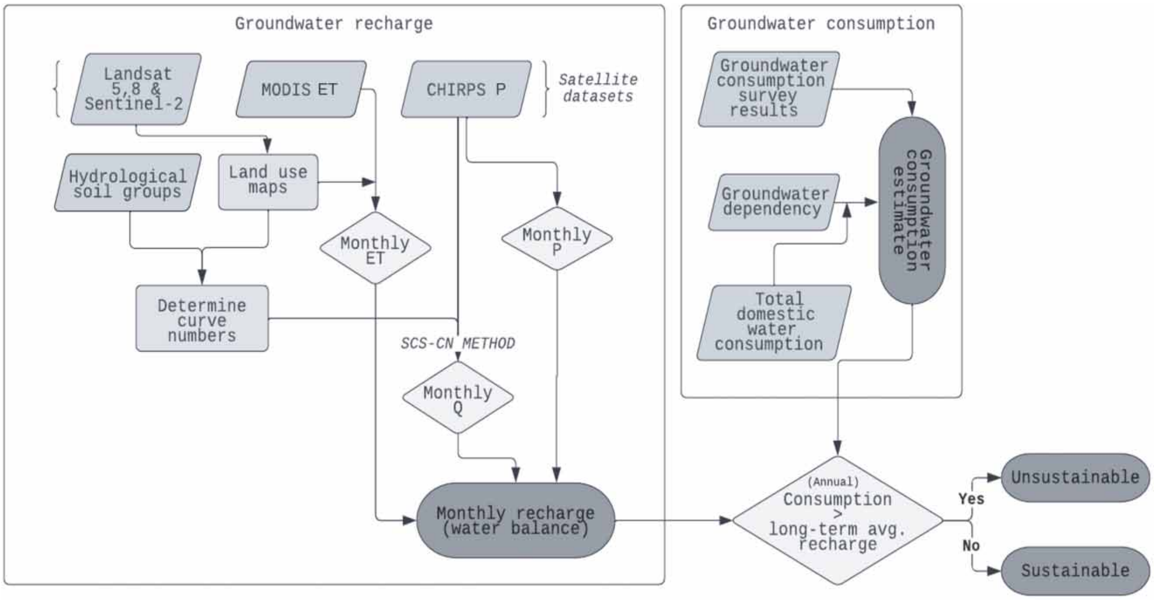


Figure 2 | Simplified overview of the methodology used to assess sustainable groundwater use in Kumasi. Q, runoff; P, precipitation; ET, evapotranspiration; SCS-CN, Soil Conservation Service-Curve Number.

Land cover classification

Urban cover alters direct natural recharge due to changes in the infiltration capacity (Lerner 1990). Pavement, concrete, and impermeable urban cover reduce the infiltration capacity, emphasising the importance of determining land cover for groundwater recharge estimates. In Kumasi, the increase in impermeable surfaces is expected to lead to reduced infiltration in the city.

Infiltration is estimated using the SCS-CN method, which requires distinguishing infiltration characteristics of surfaces including differentiating between urban areas, cultivated, and uncultivated agricultural lands (USDA 1986). Therefore, the distinction in this study is made by grouping land cover categories with similar infiltration properties. The five land cover categories are classified: impervious urban (urban with $<30\%$ open areas), semi-pervious urban (urban with $>30\%$ open areas), sparsely vegetated, densely vegetated, and water bodies. The distinct groups are chosen due to their similar CNs. The CN uncertainty ranges are investigated in the runoff estimates.

A supervised land cover classification was conducted in GEE using the Random Forest classifier with 100 trees to create land cover maps. In total, approximately 100 polygons were used as training data to train the classifier. Surface reflectance images used to carry out the classification were chosen from the first available satellite images in 1986–2020 using available datasets (Table 1). Due to heavy cloud cover in the area, cloud-free data throughout the years are limited. Moreover, data between 2000 and 2013 are limited due to a corrector failure in Landsat 7 since June 2003 (USGS 2021). These challenges, along with the lack of cloud-free data over Kumasi, have caused a gap in usable images for classification between 1986 and the late 2000s. Therefore, the final composites used for the land cover maps are retrieved from surface reflectance products of Sentinel-2A (2020 image), Landsat 8 (2013), and Landsat 5 (1986).

Water balance components

Recharge

Groundwater recharge was determined in GEE using the water balance principle. This method follows the studies of Szilagyi *et al.* (2011) and Anornu *et al.* (2009). In these studies, two assumptions are made: net groundwater flow and natural groundwater storage changes are assumed to be negligible when averaging over a longer time period (over 10 years). This assumption is adopted in this study, allowing for an estimate of recharge using long-term average forcing data. The water balance for short time periods is shown in Equation (2), where P is precipitation, Q is runoff, ET is evapotranspiration, GWR is the average annual recharge/discharge, ΔS_S and ΔS_G are the change in surface water storage and the change in groundwater storage,

Table 1 | Overview of datasets used for groundwater recharge estimations

Satellite datasets

Product	Availability	Provider	Resolution	Application
Landsat 7 ETM+ sensor (Surface Reflectance – Tier 1)	January 1999–Present	USGS	30 m	Land use classification
Landsat 5 ETM sensor (Surface Reflectance – Tier 1)	March 1984–May 2012	USGS	30 m	
Landsat 8 OLI/TIRS sensor	April 2013–Present	USGS	30 m	
Sentinel-2 MSI (MultiSpectral Instrument)	28 March 2017–Present	European Union/ESA/Copernicus	10 m for visible and NIR	
MODIS Evapotranspiration/Latent Heat Flux	January 2001–Present	NASA	500 m/8-day composite	Water balance
CHIRPS precipitation	January 1981–Present	USCB/CHG	0.05 arc degrees	

Non-satellite datasets

Variable	Value	Source	Application
Population (2010)	2.0 million	Ghana Statistical Service (2013b)	Groundwater consumption
Population growth rate in 2010	5.5	Ghana Statistical Service (2013b)	
Population (2020)	3.4 million	Projection using growth rate	
Total water consumption (m^3/person/d)	0.094	Kuma *et al.* (2010)	
Domestic groundwater consumption (%)	23.8	Summarised from Ghana Statistical Service (2013b)	
Drinking groundwater consumption (%)	19.2		
Area of Kumasi (sq. km)	241	Extent of Kumasi outline shapefile from download (Shapefiles of all districts in Ghana 2019)	Water balance

respectively. Averaging over several years $\Delta S_S \approx \Delta S_G \approx 0$, reducing the water balance to Equation (1):

$$\mathrm{P} = \mathrm{Q} + \mathrm{ET} + \mathrm{GWR} <-> \mathrm{GWR} = \mathrm{P} - \mathrm{Q} - \mathrm{ET} \tag{1}$$

$$\mathrm{P} = \mathrm{Q} + \mathrm{ET} + \mathrm{GWR} + \Delta \mathrm{S}_S + \Delta \mathrm{S}_G \tag{2}$$

Recharge was calculated per land use pixel (30 m resolution) on a monthly time step from 2001 to 2020 based on the monthly runoff, evapotranspiration, and precipitation results. This time period was chosen due to the overlap in satellite datasets, constricted by the availability of MODIS from 2001 onwards. An overview of datasets used for recharge is given in Table 1. The long-term average results refer to average monthly recharge estimates over the investigation period based on a weighted average over the city of Kumasi. This study does not investigate the impact of urban recharge components, such as water imports, and recharge from pipe leakages, in the water balance.

Precipitation

The Climate Hazards Infrared Precipitation with Stations (CHIRPS) dataset combines 0.05° resolution satellite imagery with *in-situ* data from stations and is available from 1981 providing a quasi-global daily rainfall dataset (Google Earth Engine 2020). Funk *et al.* (2015) explained that *in-situ* data is used to calibrate the Cold Cloud Duration (CCD) rainfall estimates for specific regions to give the best estimate. The combination of on-site and satellite data makes CHIRPS a reliable precipitation dataset when station data is not readily available. Daily and 5-day precipitation estimates from 2001 to the present are used for long-term recharge and runoff estimates, respectively.

Runoff

The SCS-CN method is used to estimate runoff on a 5-day time step for 1986, 2013, and 2020. This method has been applied by Wakode *et al.* (2018), Sisay *et al.* (2017), and Domfeh *et al.* (2015) to estimate runoff. It considers the distribution of soil type and land cover and can be applied to estimate runoff in small urban catchments (Wakode *et al.* 2018). The SCS-CN runoff equation is given in Equation (3) where Q is runoff depth, P is accumulated rainfall depth, I_a is the initial abstraction of water, and S is the potential maximum retention all in millimetres. The following equations are retrieved from the USDA (1986) manual on the SCS-CN method:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{3}$$

I_a includes all losses before runoff begins and is influenced by soil and cover parameters and can be related to S. The losses include interception, initial infiltration, surface depression storage, and evapotranspiration. The empirical relationship $I_a = 0.2S$ is commonly used. Substituting this relation in Equations (3) and (4) is achieved. Finally, retention can be calculated with the CN using Equation (5):

$$Q = \frac{(P - 0.2S)^2}{P - 0.8S} \tag{4}$$

$$S = 25.4\left(\frac{1{,}000}{\mathrm{CN}} - 10\right) \tag{5}$$

CNs are used to predict runoff and are determined by hydrologic soil group (HSG), land cover type, treatment, hydrologic condition, and antecedent moisture condition (AMC). Soil groups are divided into four HSGs according to their minimum infiltration rates. The AMC indicates the runoff potential before a storm event, accounting for the variation in CN for storm events (USDA 1986).

In this study, the CN is selected depending on the 5-day antecedent precipitation as defined by USDA (1986) and HSGs. Look-up tables from USDA (1986) are used to determine CNs for corresponding antecedent soil moisture conditions. HSGs are determined using available soil maps for Kumasi (Panagos *et al.* 2011; Amoateng *et al.* 2018) and soil properties defined by USDA (1986) in Supplementary Table A1. Equations (4) and (5) are applied on each land use class pixel in GEE to compute the CN and retention giving a spatial distribution of runoff.

Evapotranspiration

MODIS (MODerate Resolution Imaging Spectroradiometers) products provide information on vegetation dynamics and surface energy variations. One of the datasets derived from the MODIS products is evapotranspiration. The ET product provides terrestrial ecosystem ET on an 8-day (MOD16A2) and annual (MOD16A3) basis with a resolution of 500 m. The original algorithm combines daily meteorological inputs and 8-day MODIS data using the Penman-Monteith equation as a basis to calculate ET. Total ET is the sum of evaporation from the surfaces of the wet canopy, dry canopy, and soil (Mu *et al.* 2013).

Three main complications arise when using the MOD16 algorithm to estimate urban ET. Firstly, ET estimates are unavailable for urban areas due to the dependence of the algorithm on Leaf-Area Index (LAI)/Fraction of Absorbed Photosynthetically Active Radiation (FPAR) data which can only be derived from areas classified as non-urban by MODIS. Secondly, the low-resolution group areas that are vegetated under urban areas if they are <500 m, giving many no-data areas over Kumasi. Lastly, the algorithm is affected by cloud cover, which is problematic over Kumasi due to few cloud-free days. This study uses an ET composite derived from MODIS evapotranspiration to carry out the water balance in GEE. The method uses the created land cover classification to estimate the weighted average ET per land cover class on a monthly time step between 2001 and 2020 over the greater region of Kumasi. MODIS ET products are scaled down from an 8-day period to a monthly period to obtain more cloud-free data over the study area. The average ET per land cover class is reapplied to the land cover map to create a composite ET. Moreover, as cloud cover is highest during the rainy season, it is assumed that ET is close to potential ET due to greater water availability. In the dry season, the average ET is derived from the actual ET product from MODIS, whereas in the wet season, this is from potential ET.

Groundwater abstraction

Domestic groundwater consumption

Domestic groundwater consumption requires data on groundwater consumption per capita, total water consumption per capita, and total population. Consumption for 2020 is estimated using Equation (6), where $C_{\text{domestic,monthly}}$ is the total domestic groundwater consumption per month (Mm^3/month), P is the population in the investigated year, $C_{\text{tot, daily}}$ is the total water consumption per capita (Mm^3/cap/d), N_{month} is the days in the corresponding month, and GW use is the percentage of the population dependent on groundwater. The main assumption is that the percentage of households reliant on each source is translatable to the per capita reliance on each source.

$$C_{\text{domestic, monthly}} = P \times C_{\text{tot,daily}} \times N_{\text{month}} \times \text{GW use} \tag{6}$$

From surveys conducted in the city by Kuma *et al.* (2010), the average daily consumption for inhabitants of Kumasi was estimated to be at 0.094 m^3/d. Although this value gives a good starting point for water consumption estimates, it is expected that economic growth of Kumasi has increased consumption, resulting in an underestimate of groundwater consumption. However, the variation of groundwater consumption based on socio-economic factors is not considered in this study. Certain households may rely more on groundwater than others, while their total water consumption is less. The percentage of households dependent on groundwater for drinking is 19.2% and for domestic purposes it is 23.8% (Ghana Statistical Service 2013b). Assuming that domestic water consumption is much greater than drinking water, the value of 23.8% is used as the percentage of groundwater-sourced supply.

Survey for non-domestic groundwater consumption

A survey was carried out by trained Field Assistants at the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED) in Kumasi from June to August 2021 to determine the component of non-domestic groundwater consumption. Companies or institutions that relied on groundwater for their operations were selected through convenience sampling. At each survey point, data were collected on whether the source has dried up before, the usage period in years, the purpose of abstracted groundwater, any water quality issues, and water used per day. The final estimate of total non-domestic groundwater consumption (C) per facility (F) was estimated using Equation (7), requiring estimates on groundwater consumption per facility and how many of each facility exist in Kumasi. Here, C_F is non-domestic water consumption per facility in Mm^3/d, N_F is the estimated number of the facility in Kumasi, C_{survey} is the average daily water use for the facility from survey results in Mm^3/d, and groundwater dependence is the estimated average dependence of the facility on groundwater in percentage. The annual total of non-domestic groundwater consumption for 2021 is then estimated by summing up the consumption per facility and multiplying this by the days in the year. In this study, 2021 consumption is assumed to be the same as 2020 consumption.

$$C_F = N_F \times C_{\text{survey}} \times \text{GW dependence per facility} \tag{7}$$

RESULTS

Land cover classifications

Land cover classifications for 1986, 2013, and 2020 are shown in Figure 3, where the urban growth throughout the years is visible. Figure 3 also shows that Kumasi's urban growth has surpassed the original urban boundary with urban growth not only being seen within the city but also in surrounding municipalities. As shown in Table 2, from 1986 to 2020, there has been a total loss of 63% of vegetated land attributed to the growth of urban areas. In 1986, 81% of the city was covered with vegetation (Table 2). However, currently, only 18% of Kumasi's surface remains vegetated, represented by green patches in Figure 3(c). Much of the destruction has occurred over the past decade – as the period between 2013 and 2020 saw a 53% reduction in semi-pervious surfaces. The increase in impervious areas is due to rapid urbanisation and this means that less

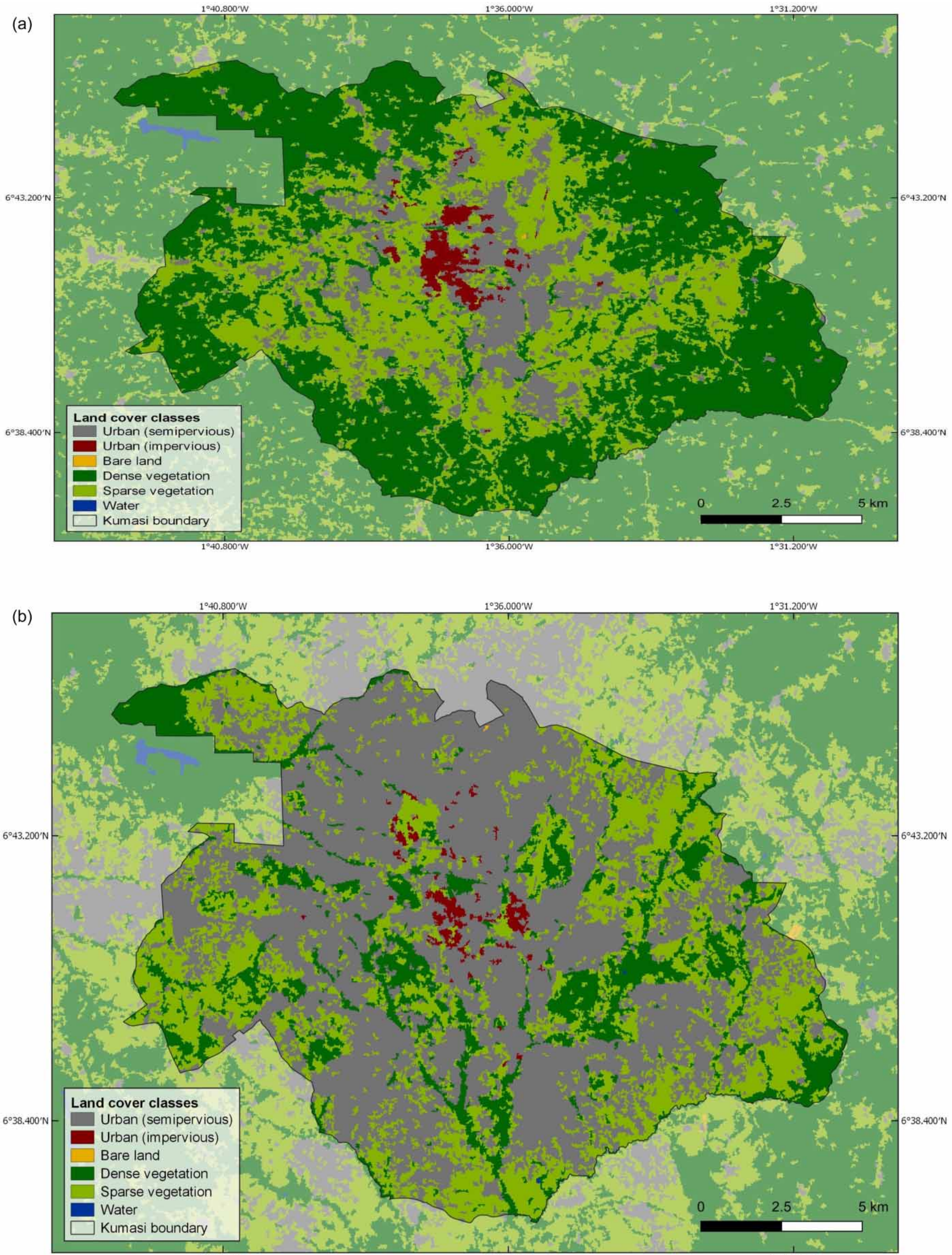


Figure 3 | Land classifications using supervised RF classification algorithm in GEE for (a) 1986 (Landsat 5 composite) (b) 2013 (Landsat 5 composite), and (c) 2020 (Sentinel-2 composite). Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2023.261. (*continued.*).

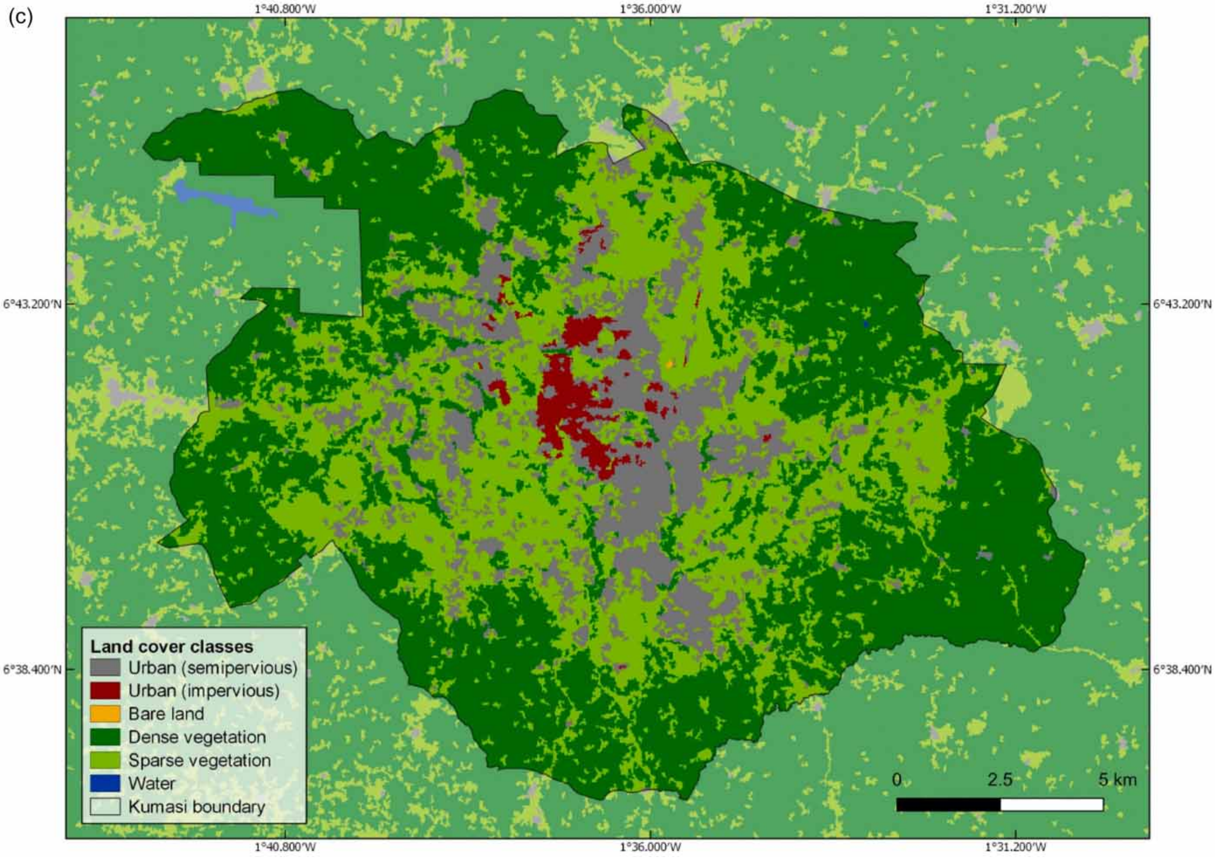


Figure 3 | Continued.

Table 2 | Land cover classification results using supervised RF classification in Google Earth Engine

	1986 Landsat		2013 Landsat		2020 Sentinel-2		Percentage point change		
Land cover	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**1986–2013**	**2013–2020**	**1986–2020**
Urban semi-pervious	38	16	113	47	166	69	*31*	22	53
Urban impervious	4	2	4	2	28	12	*0*	10	10
Bare land	3	1	2	1	3	1	*0*	0	0
Dense vegetation	118	48	40	16	7	3	*– 32*	−14	−46
Sparse vegetation	79	33	83	34	37	15	*2*	−19	−17
Water	0	0	0	0	0	0	*0*	0	0

water can infiltrate the ground surface to recharge groundwater. A lot of the precipitation will therefore rather be transformed into rainfall runoff which would flow into drains eventually leaving the city.

Water balance components

SCS-CN results

The Hydrological Soil Groups (HSGs) for Kumasi are determined with a combination of the soil map by Ewusi *et al.* (2016) and the more detailed soil map from Panagos *et al.* (2011). Characteristics for each soil association, corresponding HSGs, and the distribution of these soils over Kumasi are given in Supplementary Figure A1 and Table A1. Using the CNs defined by

USDA (1986) look-up tables, the CNs for this study are determined. Land use classes in this study correspond to various land types as defined by USDA (1986), therefore the best estimate is determined by averaging the CNs that can be related to one class. The best estimates in Supplementary Table A2 correspond to the CNs used for the recharge computations.

Water balance components

Table 3 shows the results of the water balance over Kumasi. The average annual precipitation over Kumasi for the period of 2001–2020 is 1,333 mm/y. Long-term average runoff and evapotranspiration using the 2020 land use map are 686 and 527 mm, respectively. Average annual runoff and evapotranspiration per land use class between 2001 and 2020 are shown in Table 3 while Figure 4 shows the spatial variation over Kumasi.

The evapotranspiration and runoff results show that areas of high runoff correspond to areas of low evapotranspiration. Urban areas, therefore, have high runoff rates but experience low evapotranspiration, whereas in vegetated areas, the opposite result is seen. In Figure 4(a), the variation in runoff under different land cover is notable (142 mm–1,043 mm) as it is greater than the variation of evapotranspiration (447–627 mm). This indicates that runoff is more sensitive to land use changes than evapotranspiration. Moreover, runoff has increased by 150% since 1986 whereas the change in evapotranspiration is insignificant. Uncertainty ranges are attributed to the variation of CNs per land cover class. The uncertainty in the CNs for dense and sparse vegetation is reflected in the ranges in the runoff for these classes. On the other hand, errors in evapotranspiration are attributed to the original ET values per pixel before creating the averaged composite ET.

Table 3 | Average runoff, evapotranspiration, and groundwater recharge per land use class (excluding water) using 2020 land cover map and long-term forcing (2001–2020)

Land cover	Runoff (mm)	Evapotranspiration (mm)	Groundwater recharge (mm)
Semi-pervious urban	773 ± 85	516 ± 130	45 ± 64
Impervious urban	$1,023 \pm 26$	447 ± 91	-159 ± 4
Bare land	427 ± 114	516 ± 130	382 ± 103
Dense vegetation	142 ± 138	627 ± 90	566 ± 116
Sparse vegetation	222 ± 158	606 ± 101	516 ± 141
2020 sum	**686**	**526**	**120**
2013 sum	**472**	**456**	**399**
1986 sum	**275**	**531**	**515**

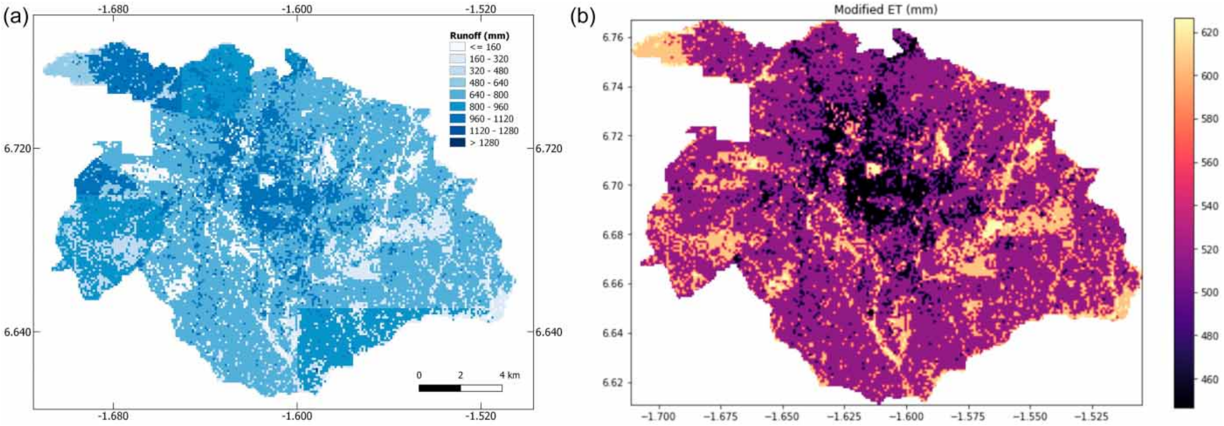


Figure 4 | Long-term average (a) annual runoff and (b) evapotranspiration in Kumasi for the period of 2001–2020 using 2020 land cover classification.

Groundwater recharge

Groundwater recharge per pixel for each month between 2001 and 2020 is calculated using a monthly water balance including the components of precipitation, runoff, and evapotranspiration presented in the previous sections. Intra-annual variations of groundwater recharge have been shown to be significant, ranging between 10 and 200 mm between 2001 and 2020 (see Supplementary Figure A2). Variability between wet and dry years can cause alternations between periods of depletion and recovery (Bierkens & Wada 2019), which is why it is necessary to look at long-term averages when assessing annual recharge. There has been a consistent reduction in groundwater recharge between 1986 and 2020. Monthly variations in groundwater recharge clearly depict a drastic decline – with the highest recharge experienced in the wet season and the lowest during the dry season (see Supplementary Figure A3). The highest monthly groundwater recharge has declined from about 120 mm to about 40 mm representing a 67% reduction between 1986 and 2020. Figure 5 shows the spatial variation of recharge in Kumasi. Due to intensive urbanisation, only a small fraction of vegetated lands remains, mostly located in the southeastern part of the city. At these locations, annual groundwater recharge can be up to 600 mm and serve as major recharge areas for groundwater in the city. These parts of the city have relatively lower concentration of commercial activities compared to the central and northwestern part of the city which are the commercial hubs of the city.

Overall, the long-term average annual groundwater recharge between 2001 and 2020 using the 2020 land use map is 120 mm.

The effect of changing land use on groundwater recharge patterns in Kumasi is shown in Table 4. The most significant change is the 53% growth of the urban semi-pervious area since 1986, which has contributed to a 72% decrease in recharge. The loss of dense vegetation has not translated to a great reduction in recharge, as there has only been a reduction of 4% in recharge since 1986. More concerning is the loss of sparse vegetation and bare land, contributing to a total of 47% reduction in recharge.

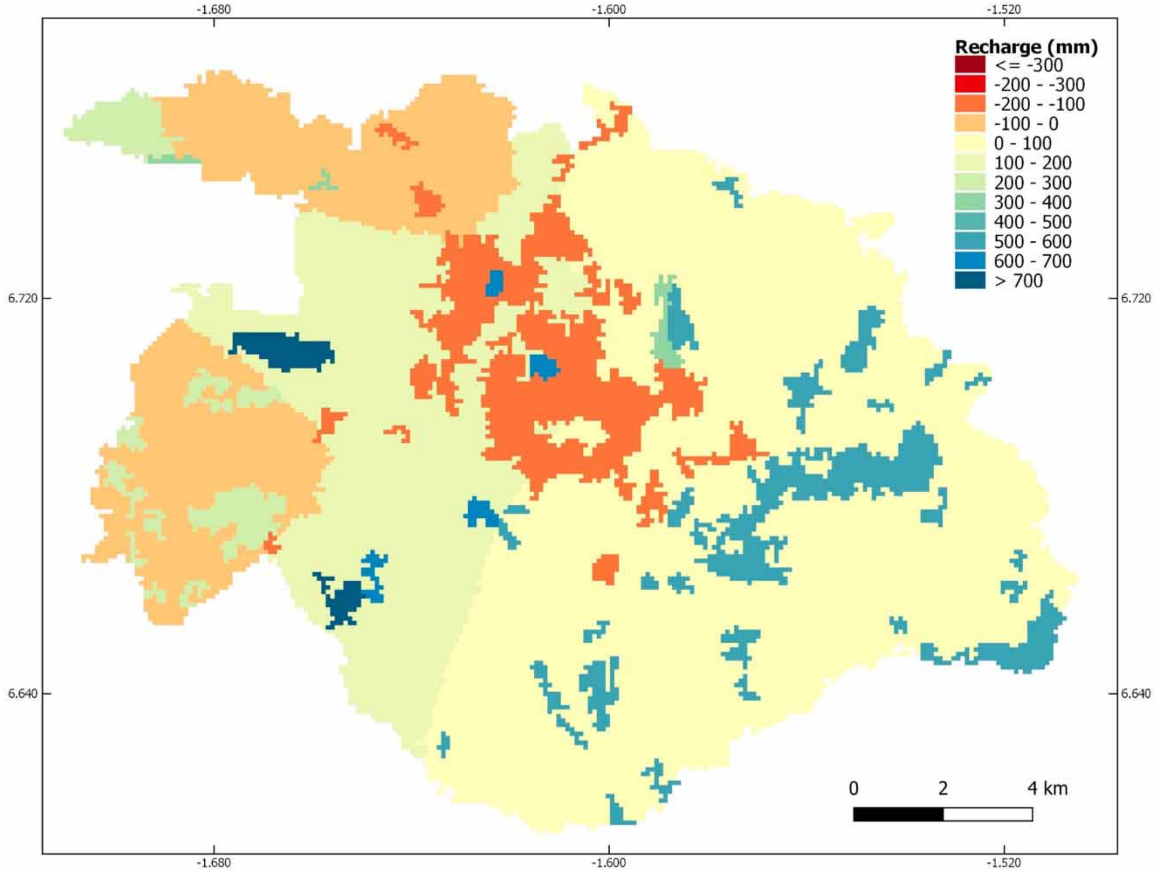


Figure 5 | Average annual groundwater recharge in Kumasi using forcing data from 2001 to 2020 and land cover map of 2020.

Table 4 | Annual average groundwater recharge in mm for 2020, 2013, and 1986 per land cover class using 2001–2020 monthly precipitation and evapotranspiration

Land cover class	1986	2013	2020	Percentage change (1986–2020)
Urban (semi-pervious)	163.2	96.2	45.4	−72
Urban (impervious)	−85.3	−123.9	−159.1	87
Bare land	514.4	499.7	382.1	−26
Dense vegetation	588	581.5	566.1	−4
Sparse vegetation	654	641.5	513.5	−21
Water	−605.7	−640.2	−614.3	1
Sum	**515**	**399**	**120**	

Groundwater consumption

Domestic groundwater consumption

Data used to estimate domestic groundwater consumption are the daily per capita water consumption of 0.094 m^3/d as stated by Kuma *et al.* (2010) and the domestic groundwater consumption reliance of 23.8%. In 2010, the population of Kumasi was 2,035,064 (Ghana Statistical Service 2013a) and was experiencing a growth rate of 5.5% (Ghana Statistical Service 2013b). Assuming the same growth in the last 10 years, the population of Kumasi in 2020 is expected to be 3,476,183. For 2020, total water consumption and total groundwater consumption are estimated to be 119.3 and 28.4 Mm^3, respectively.

Non-domestic groundwater consumption

Data were collected from 52 different locations in Kumasi. Non-domestic groundwater consumption based on survey results is shown in Table 5, where estimates on how many of each type of facility exist in Kumasi (*n*) are retrieved from literature and

Table 5 | Survey results on water use per day alongside estimates on the number of each facility in Kumasi

Facility	Average water use from survey (L/d)	Number of facilities present (*n*)	Proportion using boreholes (%)	Source	Total average per facility (m^3/d)
Hotel	7,000 (1,500–12,500)	242	95	242 search results for the number of hotels in Kumasi	1,609 (345–2,874)
Car wash	9,000 (2,000–16,000)	120	95	Monney *et al.* (2020)	1,026 (228–1,824)
Sachet water	10,000	200	90	Over 190 sachet water brands in Kumasi (Awuah *et al.* 2014)	1,800
Toilet facility	5,750 (1,500–10,000)	400	60	More than 400 public toilet owners and operators (Craig *et al.* 2016)	1,380 (360–2,400)
Laundry	6,000	15	50	Assumption	45
Private Hospital	6,000	30	100	Local knowledge	180
Restaurant	5,350 (2,400–10,000)	150	50	Local knowledge	401 (180–750)
School	5,000	200	50	Ghana MOE (2018)	500
Hostel	2,312.5 (1,000–3,000)	220	90	Local knowledge	458 (198–594)
Public tap	2,000	30	50	Assumption	30
Daily total (m^3)					7,429 (3,866–10,997)
Annual total (Mm^3)					2.7 (1.4–4.0)

'*n*', estimated number of each facility in Kumasi based on the given sources.

assumptions based on local expertise from Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED) in Kumasi. Results on total average water use indicate the most consumptive facilities are sachet water, followed by hotels, toilet facilities, and car wash stations. Survey results indicate only 3 out of 52 facilities experienced drying of the groundwater source and an additional 4 facilities reported low yields during the dry season. However, having sufficient survey points for each facility is important to gain an accurate assessment of how much groundwater is being used. Due to limited sample points, there is an uncertainty in the estimated consumption for each facility. For example, estimated total groundwater use for sachet water, laundry, private hospital, and school facilities is based on one survey point for each facility, meaning that total estimates are based on data collected at that one specific facility. Moreover, data from private manufacturing industries have not been included in this survey due to the difficulty in obtaining water use information from these sectors. Based on the results, the total average annual non-domestic groundwater use from the surveyed facilities is 2.7 $\mathrm{Mm^3}$, ranging between 1.4 and 4.0 $\mathrm{Mm^3}$.

Groundwater sustainability

Figure 6 shows the cumulative monthly recharge compared to monthly groundwater consumption values. For visualisation, recharge is plotted starting from March, as recharge in January and February is negative. Long-term average groundwater recharge calculated using the 2020 land cover map exceeds groundwater consumption from March to October. When the lower boundary of recharge is considered, recharge in April, May, August, and October falls below the monthly consumption. Total groundwater recharge in 2020 is shown to be equivalent to 17.8 $\mathrm{Mm^3}$ (73.8 mm). Compared to the long-term average of 28.9 $\mathrm{Mm^3}$ (120 mm) per year, 2020 experienced slightly lower cumulative groundwater recharge. Total groundwater use (domestic and non-domestic) is estimated to be 31.1 $\mathrm{Mm^3}$ for 2020. Groundwater abstraction, therefore, exceeds long-term average groundwater recharge.

DISCUSSION

Future of groundwater availability in Kumasi

This study has indicated that Kumasi has reached the tipping point of sustainable groundwater use, as estimates of abstraction now exceed those of long-term average recharge. For a better understanding of the future challenges faced by Kumasi's groundwater, the effects of intensification of urbanisation, population growth, and climate change are briefly examined.

Three scenarios are investigated for the intensification of urbanisation and land use changes, namely: business-as-usual, urban intensification, and greening of Kumasi. In the business-as-usual scenario, the general trend of an increase in the impervious area is assumed alongside the loss of sparse vegetation. For the intensification scenario, an increase in impervious is assumed while semi-pervious and vegetated areas decrease. The greening scenario assumes that both vegetated and semi-pervious areas increase, while the impervious areas diminish. Table 6 shows the weighted average groundwater recharge for each

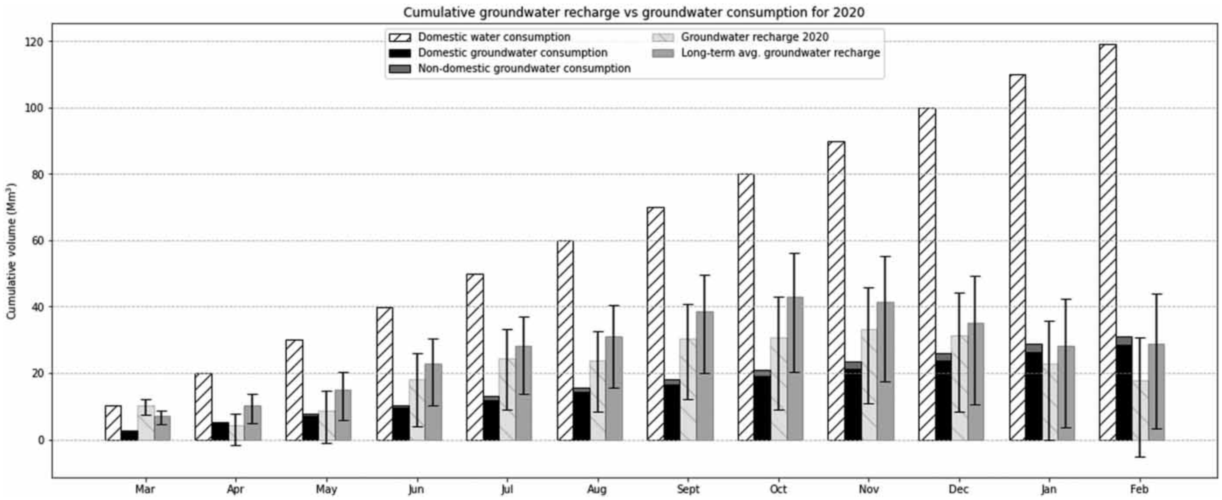


Figure 6 | Cumulative groundwater recharge for 2020 starting from March.

Table 6 | Average groundwater recharge over Kumasi for different land use scenarios in 2050

Land cover		2020 average recharge (mm)	2020 land cover %	Scenarios 2050, land cover % Business-as-usual	Intensification	Greening
Urban (semi-pervious)		45	68	68	34	70
Urban (impervious)		– 160	11	21	60	7
Bare land		382	1	1	1	0
Dense vegetation		566	3	2	1	5
Sparse vegetation		532	17	8	4	18
Water		– 614	0	0	0	0
Weighted average annual GWR	**mm**	**120**		**54**	**– 50**	**141**
	Mm^3	**29**		**13**	**– 12**	**34**

scenario using the average recharge per land use class. The business-as-usual scenario results in a 55% decrease in groundwater recharge by 2050. Intensification may lead to a situation with no groundwater recharge, whereas greening results in the enhancement of groundwater recharge.

Moreover, it is expected that population growth will lead to an increase in per capita water consumption and increased groundwater use. Freshwater supply in Ghana is compromised by the exploitation of freshwater resources resulting from growing populations, pollution, and climate change. Industrial waste, illegal mining, farming, and household waste disposal have been major sources of pollution as around 60% of water bodies in Ghana are polluted (Yeleliere *et al.* 2018). Pollution has been found to be less prevalent in groundwater (Yeleliere *et al.* 2018), thus as populations grow and piped water supply fails to keep up, it can be expected that groundwater use per capita will increase (Jiménez Cisneros *et al.* 2014). Furthermore, in Kumasi, the per capita groundwater use is expected to increase due to the decrease in per capita water availability (World Bank Group 2015). If the current population growth rate of 5.5% persists, the population in 2050 is projected to be 17 million. With a per capita water demand of 0.094 m^3/d and 23.8% groundwater consumption dependency, the 2050 consumption based on population increase is estimated to be 141 Mm^3. This is close to a five-fold increase compared to the 2020 domestic groundwater consumption estimate. If the growth rate slows down to the regional average of 2.5% (Ghana Statistical Service 2013a), domestic groundwater consumption will amount to 60 Mm^3. The growth in water consumption is proportional to population growth, indicating the future will certainly hold a greater demand for fresh water.

Lastly, climate change may also alter the availability of groundwater in Kumasi. Jiménez Cisneros *et al.* (2014) explain that an increased precipitation intensity in humid areas may decrease groundwater recharge due to an exceedance of the infiltration capacity. Changes in groundwater recharge are variable, as Jiménez Cisneros *et al.* (2014) present four different projections using two different climate models, with results ranging from no change in groundwater recharge to a $>$10% decrease in groundwater recharge. For illustration, a groundwater recharge decrease of at least 10% by 2050 (as projected by two climate scenarios of Jiménez Cisneros *et al.* (2014)) results in a recharge of 26 Mm^3 (103 mm). This change is comparatively small considering urbanisation (following the business-as-usual scenario) and is expected to result in a 55% decrease in groundwater recharge. Climate change may indirectly affect groundwater resources as there have been observed river floodings and droughts in West Africa (Douville *et al.* 2021). Surface water resources may become more vulnerable and less reliable, leading to an increased dependence on groundwater through drilling of boreholes. However, with reduced groundwater recharge, an increase in groundwater consumption will translate into a decline in the water table which, as Nyakundi *et al.* (2022) observed, increases cost of borehole construction and the risk of depletion.

Limitations in groundwater recharge methodology

The greatest challenge in this study is estimating groundwater recharge with limited data. Studies revolving around estimating groundwater processes are highly uncertain due to these processes being difficult to measure and not being directly visible (Fitts 2013). The accuracy of this study is limited by data availability and the lack of existing assessments. Remote sensing techniques alone are too indirect to accurately determine groundwater recharge. Comparing the estimated groundwater recharge in this study to existing results from the studies done by MacDonald *et al.* (2021) and Anornu *et al.* (2009), results fall under the given ranges of groundwater recharge around Kumasi. MacDonald *et al.* (2021) reported decadal recharge to be between 340 and 2,800 mm comparable to 1,291 mm in this study and relationships derived in Anornu *et al.* (2009) led to recharge between 93 and 120 mm. Using the simple water balance with remote sensing data is therefore an appropriate method in this specific study as it has allowed for a remote recharge assessment without requiring *in-situ* data.

Understanding the assumptions allows for a better understanding of the shortfalls of this study. Firstly, it is assumed that all infiltrated water reaches the groundwater table neglecting the effect of surface flow, interflow, groundwater flow, and subsurface storage. This assumption is also adopted by Szilagyi *et al.* (2011) and Kortatsi (1994), where over a period of over 10 years, groundwater flow and storage changes are negligible. Secondly, due to the non-perennial nature of Kumasi's streams, it is assumed that interflow (outflow/inflow of water from unsaturated zone to streams) is negligible over a year. Thirdly, surface water inflows and outflows are assumed to be equal over the study area. Recharge from interflow and groundwater flow can be assumed to be small in relation to recharge from direct infiltration, as studies indicate that recharge in the humid regions of Ghana is dominated by direct infiltration from precipitation (Kortatsi 1994; De Vries & Simmers 2002; MacDonald *et al.* 2021). Lastly, the urban component of recharge has not been considered. Pipe leakages, sewage leakages, and irrigation can lead to net recharge. In studies using a water balance approach (Garcia-Fresca 2007; Putra & Baier 2008; Wakode *et al.* 2018), the urban component of groundwater recharge was seen to be greater than or equal to the natural component. Due to frequent leakages in Kumasi's pipeline network, it can be expected that the urban components of groundwater recharge are high. The effect of these urban components should be investigated if a more holistic approach to recharge estimations is to be made in the Kumasi Metropolis.

Moreover, this methodology is dependent on the estimated water balance components of runoff, evapotranspiration, and precipitation. Runoff is estimated using the SCS-CN method, which assumes that urban areas are connected to a drainage system and that precipitation intensity and duration are negligible. The first assumption does not always hold for Kumasi, as Owusu-Ansah (2016) explains an open drain system was established in the 1980s that has not seen many improvements since then. The consequence of this assumption is that with a larger unconnected area, the CN becomes lower and generated runoff is lower leading to higher infiltration and thus recharge. With regard to the second assumption, Kumasi often sees flash floods after heavy rainfall events (Campion & Venzke 2013). In urban suburbs where drainage infrastructure is inadequate, it is expected that less runoff is generated and hence recharge is higher. Long-term surface inundation is also caused in these flood-prone suburbs by effluent stream floods due to a rise in the water table in the peak rainy season (Campion & Venzke 2013). This can lead to higher recharge compared to areas where runoff is guided by drainage infrastructure. The second assumption of neglecting precipitation intensity and duration can have repercussions for recharge. Mishra & Singh (2013) explained that intense precipitation is usually of short duration, therefore these events lead to low infiltration and high runoff as there is less time for retention on the land surface. The SCS-CN method does not account for intensity, which may lead to underestimates of runoff and hence overestimates of recharge. Lastly, the range in recharge estimates in this study account for the ranges in CNs, showing the groundwater methodology is highly sensitive to the chosen CNs.

Overcoming future challenges

Consequences of over-exploitation

It is expected that urbanisation trends in Kumasi will continue, leading to over-exploitation of the natural resource. If current pumping rates continue, this will eventually lead to groundwater depletion. The time scale of this change depends on groundwater residence times and storage volumes. If groundwater residence times in the shallow Basement aquifer are 40–50 years (Lapworth *et al.* 2013), then depletion may occur within that time scale if storage is not considered.

Groundwater depletion can lead to land subsidence, hydrological droughts, degrading water quality, and damage to ecosystems (Bierkens & Wada 2019). This has consequences for infrastructure, health, agriculture, and the hydrological and natural environment to name a few. In numerous cities around the world, such as Bangkok, Manila, Tokyo, and Beijing, excessive groundwater abstraction has led to a lowering of the groundwater table (Foster & Chilton 2003). Consequences thereof have been land subsidence, groundwater contamination, and exhaustion of artesian water supplies resulting in environmental degradation (Sato *et al.* 2006). Similar situations can play out in Kumasi, where the consequent lowering of the water table may lead to contamination of groundwater supply, damage to infrastructure, and degradation of environmental quality for groundwater-dependent systems.

Soils in Kumasi are mostly clay-based well-drained soils (Ewusi *et al.* 2016), which are prone to subsidence. However, land subsidence is a greater problem in cities situated on unconsolidated deposits (Meijerink *et al.* 2007), whereas Kumasi overlies consolidated metasedimentary units (Ewusi *et al.* 2016). The effect that abstraction may have on subsidence therefore depends on where the groundwater is being pumped from and at which rates. Although the consequences are currently unknown, it is important to act cautiously by implementing measures to ensure adverse effects of the over-exploitation of groundwater are avoided.

Sustainable management of groundwater resources

Sustainable groundwater development requires balancing economic, environmental, and human needs through maintenance and protection of groundwater resources (Hiscock *et al.* 2002). This requires focusing on the two components of sustainability: groundwater recharge and abstraction. Strategies to overcome groundwater security can generally be divided into technological and institutional groups (Giordano 2009). Possibilities include enhancing groundwater recharge using rainwater harvesting, artificial aquifer recharge, expanding permeable pavements, and regulating groundwater use (Foster & Chilton 2003; Sato *et al.* 2006).

Firstly, recharge in Kumasi can be enhanced through artificial recharge with water captured from rain, urban runoff, or wastewater (Giordano 2009). From an urban planning point of view, recharge can be enhanced by protecting green spaces in the city, building surfaces with permeable materials, and re-developing impervious areas to contribute to recharge. Kumasi's green spaces are the most important for recharge, and therefore, these areas have to be protected.

Secondly, changing groundwater use patterns can reduce the threat of over-exploitation. It is therefore important to raise awareness of the issues surrounding groundwater and implement strategies to efficiently use and manage the resource. The success of these institutional changes is hindered by the open-access nature of the resource and local politics (Giordano 2009). Limiting groundwater use cannot be done without assessing the root of the issue, which is the current water supply system. Without improving piped water access, the reliance on groundwater cannot be diminished.

Lastly, monitoring groundwater use, quality, and water levels helps effectively manage the resource. Up-to-date surveys are required to understand the different purposes that groundwater is used for to ensure that it is being used efficiently. Changes in groundwater quality and quantity are important to effectively conduct groundwater assessments. Developing the capacity to monitor and manage urban groundwater use is challenging as it requires appropriate technology and financing (Adelana *et al.* 2008). However, such a network can be employed to directly estimate short-term groundwater recharge in shallow aquifers through the water-table fluctuation method. Groundwater quality should also frequently be monitored to assess whether it is safe for consumption. Monitoring is vital for adaptive aquifer management as a hydrogeological understanding is required to make informed decisions around use of land and groundwater (Gleeson *et al.* 2012).

CONCLUSIONS AND OUTLOOK

This study makes significant contributions to understanding groundwater sustainability in Kumasi by incorporating remote sensing data to estimate groundwater recharge in relation to groundwater abstraction. The findings reveal alarming trends, such as an 80% decrease in groundwater recharge due to urbanisation and a 600% increase in groundwater abstraction. The study highlights the urgent need for immediate measures to prevent the dire environmental and socio-economic consequences of groundwater depletion. It also identifies the potential five-fold increase in groundwater abstraction by 2050 if current population growth continues, emphasising the criticality of taking action.

While this study provides valuable insights, it also has limitations. It serves as a preliminary assessment and does not extensively explore the urban component of groundwater recharge or delve into effective groundwater management strategies. Further research is needed to investigate these aspects and develop specific management measures suitable for Kumasi. Additionally, the study acknowledges the complexity of reducing groundwater consumption and suggests a broader perspective on water resource management to address this issue.

The scientific value of this research lies in its use of remote sensing data to assess groundwater sustainability in the context of limited hydrogeological data. The findings raise concerns about the future availability of groundwater in Kumasi, a vital resource for people, agriculture, and industry. By highlighting the decreasing natural recharge volumes and increasing consumption, the study sheds light on the risks faced by both groundwater and surface water resources due to climate change and urbanisation. It underscores the need for preventive measures and serves as a call to action for policymakers and stakeholders.

The findings of this study have direct applicability to Kumasi and provide critical information for decision-makers to implement preventive measures. The study emphasises the importance of increasing groundwater recharge through artificial and natural means, such as protecting vegetated areas and increasing permeable surface coverings. It also stresses the need to investigate and implement effective groundwater management strategies. The identification of excessive groundwater use by industries within the Metropolis suggests the possibility of levies to fund recharge and monitoring efforts. The study's findings can guide sustainable groundwater management in Kumasi and serve as a valuable reference for other regions facing similar groundwater challenges.

Future studies should focus on three main areas. Firstly, investigating the urban component of groundwater recharge, including factors like recharge from pipe leakages and water imports. Secondly, exploring effective groundwater management strategies tailored to Kumasi's context. This requires understanding the dynamics between groundwater supply, recharge, and dependency sources. Thirdly, investigating artificial recharge techniques to supplement natural recharge. Additionally, further investigations into recharge volumes and patterns are necessary to inform preventive measures. Raising awareness of groundwater issues is crucial, given its hidden nature. To ensure the availability of groundwater for future generations, ongoing research should address these areas and incorporate the challenges posed by climate change and urbanisation.

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AUTHOR CONTRIBUTION STATEMENT

I.M. and M.R. devised the study. E.F.P. and I.M. collected the data. E.F.P. and M.R. analysed the data. E.F.P. wrote the manuscript with support from I.M. and M.R. E.F.P., I.M., and M.R. discussed the results and commented on the manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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