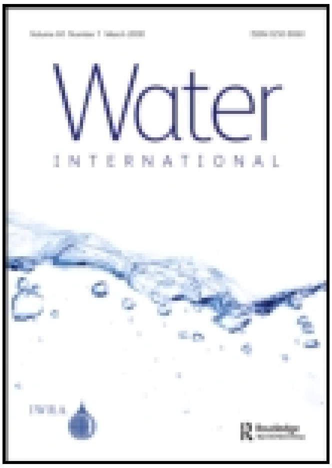

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This study uses a modified Granger and Gray model to estimate evapotranspiration and then groundwater recharge in Ghana. The overall results show that the model is capable of reliably predicting regional evapotranspiration using a small number of monitoring stations with meteorological data only. This information allows the estimation of groundwater recharge via the water balance equation. The results indicate that the aquifer system is sufficiently recharged, especially in northern Ghana, where dry conditions prevail, to allow the development of groundwater resources to satisfy increasing water demands.

Keywords: evapotranspiration; complementary methods; groundwater recharge; Volta Basin; Ghana

Introduction

The focus of this study is on estimating groundwater recharge in the Volta River basin of Ghana through evapotranspiration (ET) calculations. In the water balance equation, recharge is calculated as the residual of rainfall, ET and surface runoff. In arid and semi-arid regions such as the Volta River basin (Carrier, 2008; Obuobie, 2008), runoff accounts for an insignificant portion of the rainfall. Therefore, ET estimation, combined with rainfall measurements, can be used to derive groundwater recharge.

Description of the study area

The Volta River basin in Ghana was selected for this study for several reasons. Ghana was the focus of several important studies conducted more than 50 years ago by pioneering scientists such as Penman (as cited in Rietveld, 1978). Field studies are conducted there by the International Water Management Institute (IWMI), the GLOWA Volta Project funded by the German Technical Cooperation (GTZ), and the Canadian International Development Agency (CIDA).

The Volta River basin covers about 70% of the total area of Ghana (or 238,538 km^2), mainly in the northern and central parts of the country (Figure 1). The basin comprises four principal sub-basins: the Black, White, Oti, and Lower Volta. The agricultural land

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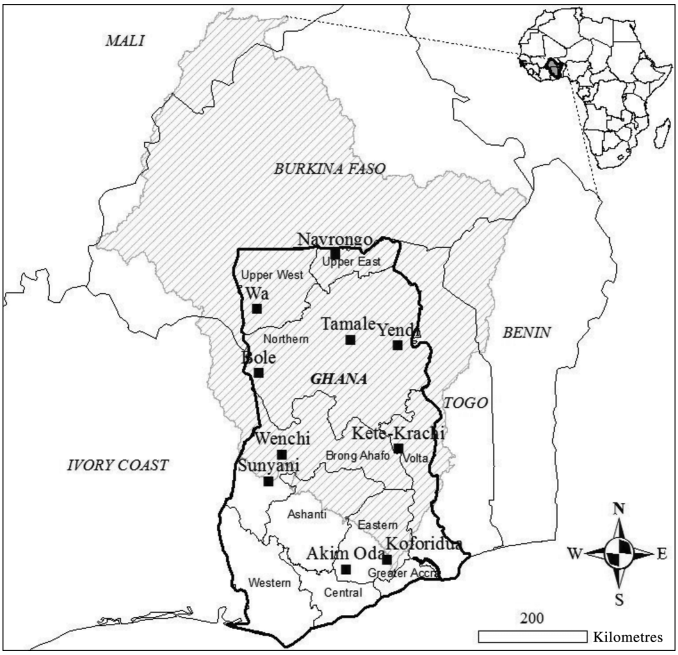

Figure 1. Map of Ghana (within dark solid line) and the Volta River basin (hatched area). The dark squares show the synoptic stations used in the study; the interior divisions are administrative regions of Ghana.

of Ghana is about 57% of the total area (Statistics, Research and Information Directorate [SRID], 2010). Ghana is administratively divided into 10 regions. The population of Ghana in 2009 was 24 million, with a growth rate of 2.1%, and 68% of the population live in rural areas (SRID, 2010). Agriculture is the major source of income and employment for rural communities.

Ghana lies within 4 major agro-ecological zones, and the 10 synoptic stations fall across all 4: the Guinea Savannah Zone (includes Navrongo, Wa, Tamale, Yendi and Bole), the Transitional Zone (Kete-Krachi and Wenchi), the Rain Forest Zone (Sunyani and Akim Oda) and the Coastal Savannah Zone (Koforidua). The climates of Ghana vary from semi-arid in the north, with a monomodal rainfall pattern, to subtropical humid in the south, with a bimodal rainfall pattern. The average annual rainfall varies between 963 mm and 1432 mm from north to south, respectively. At Akim Oda in the south, for instance, the major rainfall season is from March to August, while the minor season is from September to October. In contrast, there is only one rainfall season, from May to September, at Navrongo in northern Ghana (i.e. summer rainfall). Rainfall is high during these months, and ET is low due to increased humidity. In this humid climate, recharge is likely to be high. As in most semi-arid regions, surface-water resources are considerably unreliable due to the high inter- and intra-annual variability in rainfall in the north. The average daily temperature varies from 26.4 °C to 29.3 °C, while the average daily relative humidity fluctuates considerably between 53.8% and 79.2%; the same is true with sunshine hours and average wind speed. Topography is relatively undulating, with gentle slopes, and the average elevation is about 190 m above mean sea level. The topsoil is mostly sandy loam and loam, and the gravel content in the sandy soils increases with depth, indicating lower soil

Table 1. Details of the 10 synoptic stations in Ghana.

Station	Lat. (°)	Long. (°)	Elev. (m)	AI*	Rainfall (mm/y)	T (°C)	RH (%)	S (h)	U (m/s)	Land cover
Navrongo	10.90	−1.10	201	24.5	963	29.3	53.8	8.0	1.5	Savanna woodland
Wa	10.05	−2.50	323	27.0	1040	28.5	58.3	7.8	1.1	Savanna woodland
Tamale	9.50	−0.85	168	26.8	1040	28.8	60.3	7.5	1.8	Savanna woodland
Yendi	9.45	−0.02	195	33.6	1291	28.4	62.7	7.7	0.8	Savanna woodland
Bole	9.03	−2.48	299	31.2	1157	27.1	66.9	6.9	1.3	Savanna woodland
Kete-Krachi	7.82	−0.03	122	35.4	1353	28.3	73.2	7.2	0.8	Savanna woodland
Wenchi	7.75	−2.10	339	34.5	1258	26.5	73.2	6.4	1.0	Herb/bush
Sunyani	7.33	2.33	309	32.9	1197	26.4	75.3	5.4	2.2	Settlement
Koforidua	6.08	−0.25	166	37.1	1384	27.3	77.6	6.1	0.7	Herb/bush
Akim Oda	5.93	−0.98	139	38.4	1432	27.3	79.2	5.3	0.6	Herb/bush

*AI is defined as very humid for higher than 35, humid between 28 and 35, subhumid between 24 and 28, Mediterranean between 20 and 24, semi-arid between 10 and 20, and arid when less than 10 (de Martonne, 1925).

stability, but the drainage characteristics are better during the rainy season (O'Driscoll, Clinton, Jefferson, Manda, & McMillan, 2010).

All the data used in this work were gathered from the Meteorological Services Department of Ghana, the Water Resources Commission of Ghana, CIDA, and the IWMI. Information related to the 10 synoptic stations used here is shown in Table 1 and Figure 1. Daily values of minimum air temperature (T_{min}), maximum air temperature (T_{max}), minimum relative humidity (RH_{min}), maximum relative humidity (RH_{max}), sunshine hours (S), and average wind speed (U) are available from 2000 to 2005.

Methodology

Complementary methods, including the complementary relationship areal ET (CRAE) method of Morton (1983), the advection-aridity (AA) method of Brutsaert and Stricker (1979) and the method of Granger and Gray (1989) (GG), offer viable alternatives to classical methods for calculating ET using meteorological data only under diverse physical and climatic conditions (see the Appendix). According to Morton (1983), complementary methods offer simplicity and practicality, and provide reliable, physically based operational ET estimates at regional scales. The methods also consider the surrounding climatic conditions regardless of the underlying soil-plant system, avoid locally calibrated coefficients, and require no more than the minimal meteorological data typically monitored in most rural areas.

In the complementary methods, wet environment ET (ETW) is the ET that occurs if the soil-plant system is saturated and ET approaches its potential rate, ETP. In spite of the fact that ET is negatively correlated with ETP (Figure 2), there is no defined shape of that relation (see Morton, 1983). The complementary theory posits a complementary relationship between ET and point ETP estimates in a given area. Accordingly, the relationship between ET and ETP under limited water supply is not necessarily linear and does not follow a given law. The earliest complementary method states:

$$\mathrm{ET} + \mathrm{ETP} = 2\mathrm{ETW} \tag{1}$$

where ET, ETW and ETP are in mm/day. Equation (1) indicates that an increase in ET is accompanied by an equivalent decrease in ETP, i.e. $\delta\mathrm{ET} = -\delta\mathrm{ETP}$. In other words, as the

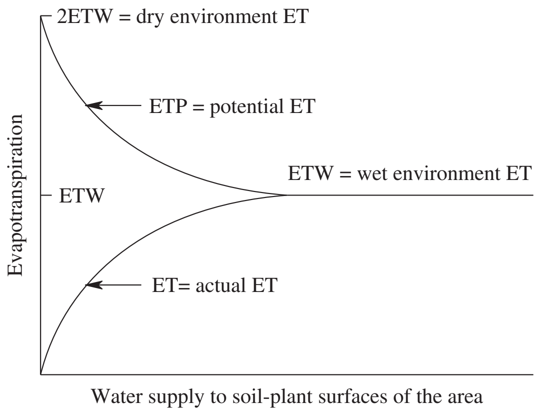

Figure 2. Schematic representation of the complementary relationship between ET and ETP (after Morton, 1983).

surface dries, areal ET decreases, causing a decrease in humidity and an increase in the temperature of the surrounding air, and as a result, ETP increases. This means that ETP is a function of ET, in contrast to the model suggested by Penman (1948), where ETP is independent of ET. This latter claim is true for large moist areas where the effect of ET on temperature and humidity is fully developed and ET and ETP are equal.

The CRAE and AA methods use the same complementary relationship originally developed and shown in Equation (1). However, Granger and Gray (1989) modified the relationship as follows:

$$\mathrm{ET} + \frac{\gamma}{\Delta}\mathrm{ETP} = \left(1 + \frac{\gamma}{\Delta}\right)\mathrm{ETW} \tag{2}$$

where γ is the psychrometric constant (in kPa/°C) and Δ is the rate of change of saturation vapour pressure with temperature (in kPa/°C). Hence, Equation (2) can be reduced to Equation (1) only when $\gamma = \Delta$.

For several decades, the complementary methods have been studied and compared to other methods over different spatial and temporal scales and climates. Oguntunde, van de Giesen, and Andreini (2005) applied the AA method in semi-arid to subhumid tropical regions of West Africa and noted that the complementary relationship is valid across the Volta Basin, but the ET estimates have to be verified. It was found that in cold semi-arid regions of Canada, the CRAE method is not suitable for short periods or field-size areas (Granger & Gray, 1990). However, Doyle (1990) compared the CRAE method and the Thornthwaite soil moisture model on an Irish humid basin to water balance data and found the CRAE method to be valid. The CRAE and AA methods produced ET values at 139 minimally impacted basins in the US (Hobbins, Ramirez, Brown, & Claessens, 2001), and the results showed that as aridity increases, ET is overestimated by the CRAE method and underestimated by the AA method. Still, the CRAE method predicted monthly ET over the climate spectrum. A more detailed discussion of the complementary methods and their applicability and limitations is provided by Anayah (2012).

In a recent study, Anayah (2012) developed a modified complementary model based on the GG model that was validated using measured ET data from 34 global sites with contrasting climatic and physical conditions. The climates of these global sites vary from tropical to subarctic, while the average ET values range from 10.5 mm/month to 134.3 mm/month. The results showed that the average root mean square error, mean absolute bias and R^2 across the 34 global sites were 20.57 mm/month, 10.55 mm/month and 0.64, respectively. It was found that the ET estimates of the proposed model, which requires meteorological data only, outperform those of the most recent ET studies. Given the validity of the proposed modified GG model by Anayah (2012), the purpose of this study is to extend the work to estimate ET and groundwater recharge in Ghana.

Prior studies, for example by Carrier (2008), Friesen, Andreini, Andah, Amisigo, and van de Giesen (2005) and Wagner (2008), showed that there is substantial uncertainty and discrepancy between different studies estimating recharge in Ghana. Given the fact that the aquifer systems of Ghana are not yet fully delineated (Enoch Asare, personal communication, 25 July 2009), regional-scale recharge estimation using the classical methods is difficult.

Carrier (2008) estimated groundwater recharge in northern Ghana using soil moisture and chloride mass balance approaches. Recharge rates from soil moisture balance were found to vary from 1% to 16% of the average annual rainfall. Martin (2006) and Obuobie (2008) used chloride mass balance to estimate recharge in the Upper East Region of Ghana; the estimates of the latter study were considerably higher than those of the former. These findings indicate the uncertainty in the method and suggest that there is no single comprehensive estimation method applicable at regional scales. In general, it is not possible to directly measure fluxes into and out of groundwater over large spatial scales, and therefore indirect methods must be used. The water balance method will offer a good alternative once the ET fluxes are accurately estimated in the highly diverse environments of Ghana.

The modified complementary method

The modified GG model proposed by Anayah (2012) is an enhanced version of the original GG method. Anayah (2012) found that the complementary relationship shown in Figure 2 and Equation (1) can describe the behaviour of ET fluxes more precisely than the more generic expression derived in the original work by Granger and Gray (1989), i.e. Equation (2). More importantly, the predictive power of the GG method is improved when the Priestley and Taylor (1972) (P-T) equation shown in Equation (3) is used to calculate ETW instead of the Penman (1948) equation used in the original GG method.

$$\mathrm{ETW} = \alpha \frac{\Delta}{\gamma + \Delta}(R_\mathrm{n} - G_\mathrm{soil}) \tag{3}$$

Here, α is a coefficient typically equal to 1.26, R_n is the net radiation in mm/d, and G_soil is the soil heat flux density in mm/d. The procedure described by Allen et al. (2005) is used to calculate daily net radiation for both actual and crop ET estimates. The daily data required to calculate R_n are simply T_min, T_max, RH_min, RH_max, and S. It is noticed that soil heat flux density (G_soil) is negligible for daily time steps, especially when compared to R_n.

In the GG method, two new parameters were proposed and empirically correlated together: relative drying power D and relative evaporation G, shown in Equations (4) and (5), respectively. Parameter D indicates the dryness of the surface, i.e. higher D indicates a drier surface. Relative evaopration (parameter G) is assumed to occur under wind and humidity conditions of a saturated surface at its actual temperature (Granger & Gray, 1989).

$$D = \frac{E_\mathrm{a}}{E_\mathrm{a} + R_\mathrm{n}} \tag{4}$$

$$G = \frac{\mathrm{ET}}{\mathrm{ETP}} \tag{5}$$

$$G = \frac{1}{1 + 0.028\mathrm{e}^{8.045D}} \tag{6}$$

In Equation (4), E_a is the drying power of air in mm per day. The average daily values of U are required to calculate E_a. Solving Equation (5) for ETP, substituting this into Equation (1), and solving for ET provides an estimate of ET in the modified GG model, as shown in Equation (7).

$$\mathrm{ET} = \frac{2G}{G+1}\mathrm{ETW} \tag{7}$$

Classical methods

In this work, five additional classical methods of estimating ET are used for comparison purposes; the ASCE method with two reference crops (Allen et al., 2005), the Hargreaves method (Hargreaves, Hargreaves, & Riley, 1985), Turc's method (Turc, 1961), and the Jensen and Haise method (Jensen-Haise, 1963). These classical methods require the calculation of $\mathrm{ET_o}$ first, followed by the use of the crop coefficient K_c to calculate crop ET. The Hargreaves method was developed using the conditions of West Africa, while Turc's method is based on Western Europe under humid conditions (Jensen, Burman, & Allen, 1990). The Jensen-Haise method was developed for well-watered crops in the western United States (Jensen et al., 1990). Hereafter, Jensen-Haise, Hargreaves, Turc, ASCE with grass reference and ASCE with alfalfa reference are referred to as JH, HV, TC, GR and AL, respectively.

Groundwater recharge

Groundwater recharge will be computed using the water balance equation, as shown in Equation (8).

$$\mathrm{Rech} = P - Q - \mathrm{ET} - \Delta S \tag{8}$$

where Rech is the groundwater recharge, P is the rainfall, Q is the surface runoff, and ΔS is the change in soil water storage. All terms of the water balance equation should have the same unit, usually given as a rate (unit depth per unit time) such as mm/month or mm/year. It should be noted that ΔS approaches zero if calculations are made on an annual basis.

Results and discussion

Climate class

The climatic condition of each station was defined using the aridity index (AI) defined by de Martonne (1925). In this method, AI is based on the average annual rainfall and average annual temperature. The reasons for using the AI proposed by de Martonne (1925) compared to other, newer models are its ability to capture the climatic variability across Ghana and the simplicity of data required. In Table 1, AI indicates contrasting climates, varying from subhumid in three stations in the north to very humid conditions towards the south.

Potential evapotranspiration

ETP or ET_o is the first step in calculating crop ET with the classical methods, while the proposed modified GG model estimates ETP and ETW; the results are shown in Figure 3. It is observed that ETP from the modified GG model is high compared to other estimates. The pan evaporation measurements of Acheampong (1986) at Navrongo, Tamale and Wenchi, and the corresponding ETP predictions from the modified GG model, are close and comparable. Similarly, Chiew and Leahy (2003) and Hobbins et al. (2001) found that ETP from the CRAE method is high enough to be a good estimator of pan evaporation that considers ideal conditions where neither energy nor water is limited. ETP is calculated using ET from Equation (7) and the parameter G in Equation (5). G indicates the dryness of the surface and is empirically correlated to D in Equation (6), which represents the convective properties of the environment. High values of ETP indicate convective environments (high D values) under dry surface conditions (low G values). Apparently, ETP values in the north are considerably higher than those in the south.

In contrast, ETW predicted by the modified GG model is comparable to other ET_o estimates. For example, the mean values of ETP predicted by the modified GG model range from 157 to 222 mm/month, whereas mean ETW values from the same model vary between 116 and 138 mm/month. The corresponding mean values of ET_o for grass and alfalfa range from 100 to 155 mm/month and from 109 to 199 mm/month, respectively. These results suggest the possibility of comparing the ETW of the modified GG model with the ET_o of the GR method. Compared to the ETW estimates, the GR method slightly overestimates ET_o under arid climates and underestimates it under humid climates (see Figure 3 and Table 2). The variability of ET_o from the GR method is slightly higher than ETW with the modified GG model. It is noticed that the AL method overestimates ET_o compared to the GR method; however, the difference gradually diminishes as humidity increases.

Table 2 shows the annual estimates of ETP, ETW and ET_o predicted by the different methods. The ETW estimates are consistent, and the variation among the stations is not substantial. The relative absolute difference (RAD) is simply defined as the absolute value of the difference between ETW from the modified GG model and ET_o from the classical method, divided by ETW. It is noticed however that RAD_{GR} ranges from zero at Bole to 16% at Akim Oda, with an average of 9% and no obvious trend. Basically, this is a comparison between the Penman-Monteith (P-M) and P-T equations. The P-M equation is a combination of the radiative and convective energy demands of the climate, while the P-T equation consists of the radiative demand multiplied by the coefficient α which accounts for the convective demand. Although advection energy is lumped into the radiation energy of the P-T equation in the modified GG model, the P-T equation is still a good substitute for the P-M equation. The results of the JH method are close to those of the AL method. The performance of the HV method improves with aridity, whereas the TC method moves

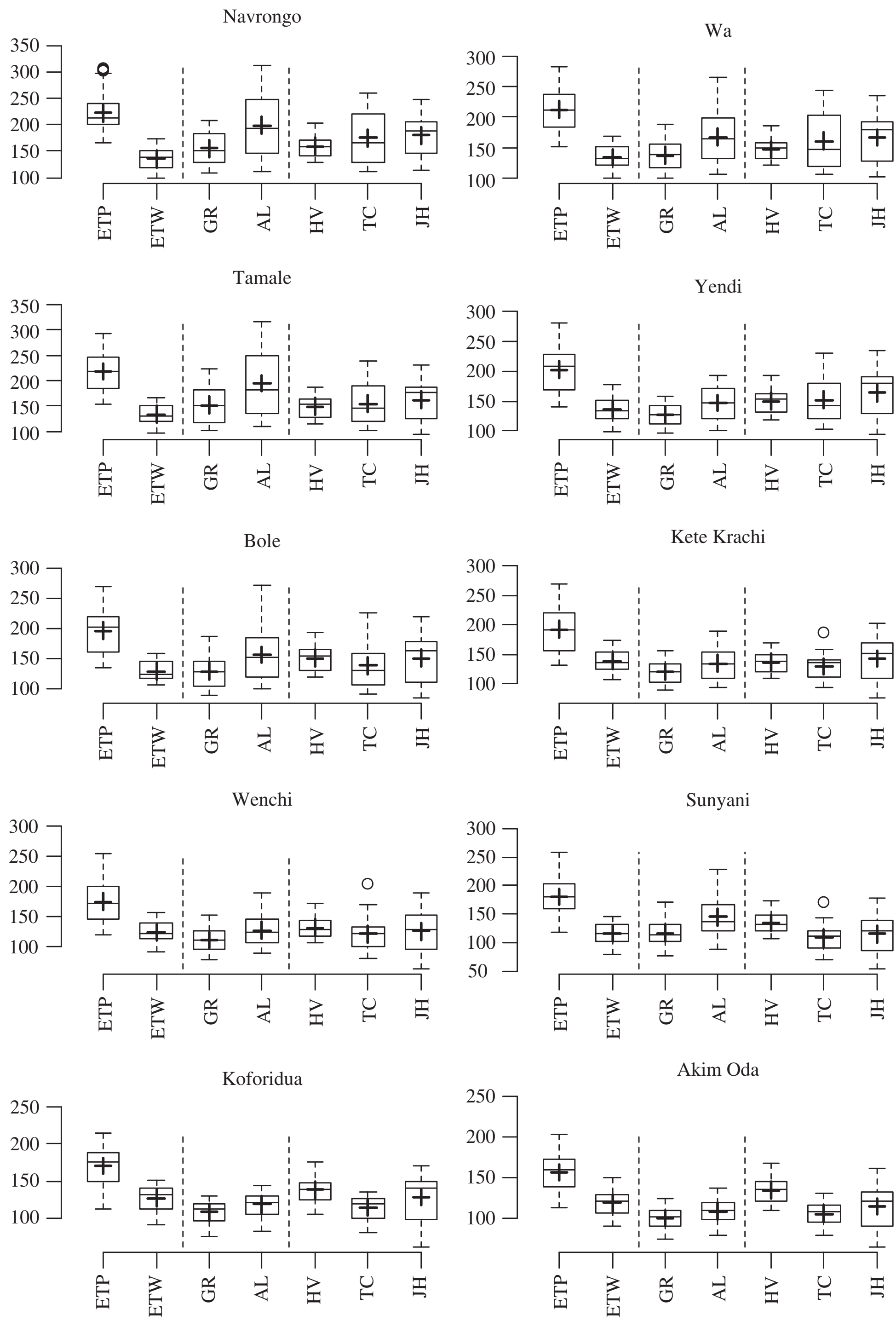

Figure 3. Boxplots for monthly potential evapotranspiration, in mm. (+: average value. ETP: GG model. ETW: GG model. GR: grass ET_o. AL: alfalfa ET_o. HV: Hargreaves ET_o. TC: Turc ET_o. JH: Jensen-Haise ET_o.)

Table 2. Average annual ETP estimates (mm) computed by different methods and their relative absolute difference (RAD) as a percentage.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
Method	Complementary		Classical						RAD_{GR}	RAD_{AVG}
	Modified GG		ASCE					Avg.	$\frac{\lvert[2]-[3]\rvert}{[2]}$	$\frac{\lvert[2]-[8]\rvert}{[2]}$
Station	ETP	ETW	GR	AL	HV	TC	JH	[3] to [7]		
Navrongo	2662	1623	1862	2386	1905	2102	2161	2083	15	28
Wa	2547	1616	1651	2008	1767	1928	2001	1871	2	16
Tamale	2614	1609	1824	2343	1793	1856	1943	1952	13	21
Yendi	2432	1635	1527	1766	1801	1826	1964	1777	7	9
Bole	2341	1540	1540	1864	1794	1648	1801	1729	0	12
Kete-Krachi	2308	1657	1446	1609	1642	1549	1713	1592	13	4
Wenchi	2105	1497	1341	1530	1576	1460	1514	1484	10	1
Sunyani	2165	1389	1398	1736	1608	1302	1385	1486	1	7
Koforidua	2044	1523	1296	1420	1654	1364	1533	1453	15	5
Akim Oda	1882	1426	1202	1305	1614	1269	1374	1353	16	5
Min	1882	1389	1202	1305	1576	1269	1374	1353	0	1
Avg.	2310	1551	1509	1797	1716	1630	1739	1678	9	11
Max	2662	1657	1862	2386	1905	2102	2161	2083	16	28

in the opposite direction. One criticism of these two methods is the opposite behaviour of the results. A possible reason for this behaviour may be that the parameters used are locally developed under specific conditions and may not be applicable elsewhere. The HV method was constructed to calculate the water requirements for crops under dry conditions in Senegal, Mauritania and Mali. The TC method was exclusively developed for Western Europe under more humid conditions. Nevertheless, an interesting trend is observed when ETW and the average of the five ET_o estimates from the classical methods are compared by RAD_{AVG} values, as shown in Column 10 of Table 2. The closure between these two estimates significantly increases with humidity.

Acheampong (1986) estimated pan evaporation at Navrongo, Tamale and Wenchi to be 2550, 3085 and 1985 mm/y, respectively. These estimates are close to the ETP values from the modified GG model, except at Tamale, where the difference is about 18%. The estimates from the other three methods are in agreement with the estimates from the modified GG method. At Navrongo, for instance, Compaore et al. (2008) stated that average annual ETP from 1961 to 2003 was 2423 mm. Carrier (2008) studied ET in northern Ghana, including eight stations discussed in this work. It is no surprise that ET_o from the GR method agreed at around 90% to 95% with the estimates of Carrier (2008), who used the P-M equation. In a total of seven previous studies (e.g. Acheampong, 1986; Carrier, 2008; Compaore et al., 2008), ET_o was estimated using both Penman and Thornthwaite methods at Navrongo, and the average annual ET_o ranged from 1647 mm to 2423 mm. In Table 2, the values of ETW and ETP at Navrongo are 1623 mm/y and 2662 mm/y, corresponding to the lower and upper bounds, respectively, of the ET_o range of the seven previous studies.

Actual ET

Actual ET is the total water loss from the land surface, which may or may not include vegetation, and includes evaporation from water bodies and soil moisture. Since most synoptic stations used in this study are located within agricultural areas, crop ET is comparable to actual ET.

It is worthwhile to add that the data used by Anayah (2012) are at monthly time steps from global sites, while the data used from Ghana are daily. The question is whether this difference in temporal resolution may affect the results of the modified GG model. For this purpose, the time series of monthly meteorological data was made available by the Meteorological Services Department of Ghana from 1961 to 2005 for five northern stations, namely Navrongo, Tamale, Wa, Bole and Yendi. Monthly data from these five stations from 2000 to 2005 were used for comparison with the daily estimates of the modified GG model. The root mean square errors (RMSEs) of the two estimates ranged from 2.8 mm/month at Wa to 5.9 mm/month at Tamale. The bias of the mean values varied between –1.6 mm/month at Bole and 2.6 mm/month at Tamale, and the lowest coefficient of determination (R^2) was 0.96, at Bole. These results suggest that the modified GG model can accommodate both daily and monthly time series to produce consistent results.

Crop ET

The ASCE method is used to calculate crop ET, and the crop coefficients used are adjusted to suit the existing climatic conditions of each station. Since the growing stages of each crop vary by region and climate, the data provided by Allen, Pereira, Raes, and Smith (1998) cannot be used. Therefore, the detailed data for Ghana published by the FAO (n.d.) were used. For example, the growing seasons for 29 crops are locally adapted to suit the four major agro-ecological zones of Ghana. The other key information needed was the cropping patterns across Ghana. The distribution of each crop in all 138 districts in 2008 was available from the Ghanaian Ministry of Food and Agriculture.[1] For this calculation, the representative area of each station was determined using the Thiessen polygon method. These calculations were conducted on the basis that "agriculture is predominantly on a smallholder basis in Ghana" and "about 90% of farm holdings are less than two hectares in size" (SRID, 2010). Although the details of crop coefficients are not given here, the data are readily available from the authors.

Comparison of actual and crop ET

Figure 4 shows the average monthly actual ET computed from the modified GG model and crop ET computed by the GR method. The actual ET estimates in most stations are close to those of crop ET, in particular during the growing seasons. There is one major exception at Sunyani and a minor discrepancy at Tamale. Kete-Krachi shows a unique behaviour that does not exist in other stations. Sunyani is the only station where crop ET is always higher than actual ET. This station exists in a residential area (see Table 1), and typically residential areas have less ET than agricultural areas. This is similar to the urbanization (or "deforestation") effect explained by Morton (1983), which causes increased runoff and decreased ET. This argument is proven here too, where the modified GG model captures the land cover/land use effect using climatic variables only. In essence, the complementary method represented here using the modified GG model recognizes the effect of land use/cover on the adjacent atmospheric layer without the details of soil–plant interactions.

A similar effect is noticed at Tamale, where the crop ET is higher than the actual ET in the last half of the year during the growing cycle. This could be simply referred to as an urbanization effect, similar to in Sunyani, because Tamale is the capital city and the economic hub of northern Ghana. Urban areas with a high proportion of impervious

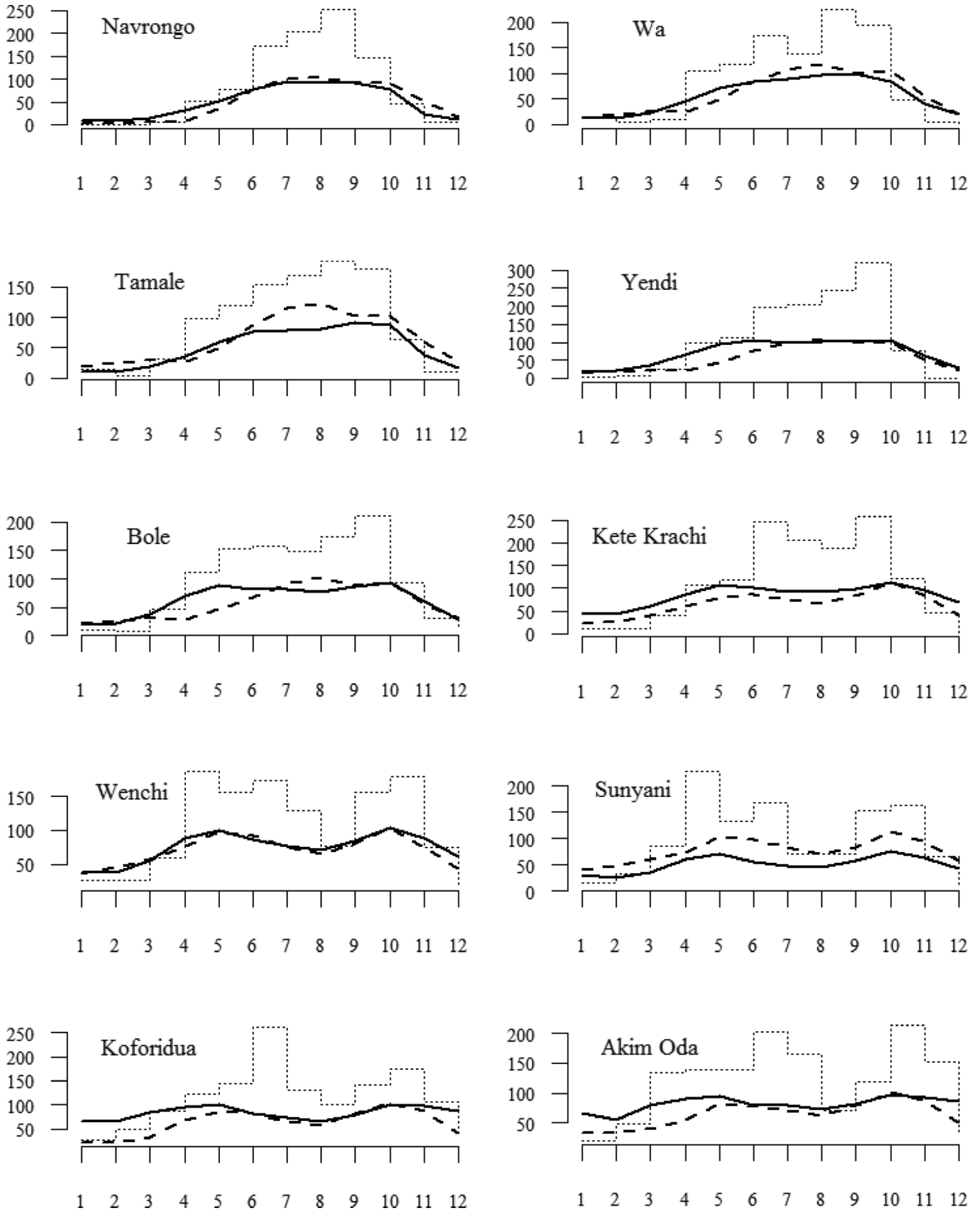

Figure 4. Average monthly actual ET, crop ET and rainfall, in mm. (Solid line: actual ET from GG model. Dashed line: crop ET from GR method. Dotted line: rainfall.)

surfaces "are drier and release more heat than surrounding rural areas", which is the "urban heat island effect" explained by O'Driscoll et al. (2010). Compared to vegetated surfaces, impervious surfaces have lower ET rates, and therefore rainfall is more likely to produce runoff or infiltration (O'Driscoll et al., 2010).

Crop ET is marginally higher than actual ET during the growing season in other semi-arid stations, Navrongo and Wa, indicating that a smaller number of crops may actually exist. Kete-Krachi is uniquely different from all other stations. Kete-Krachi is situated at

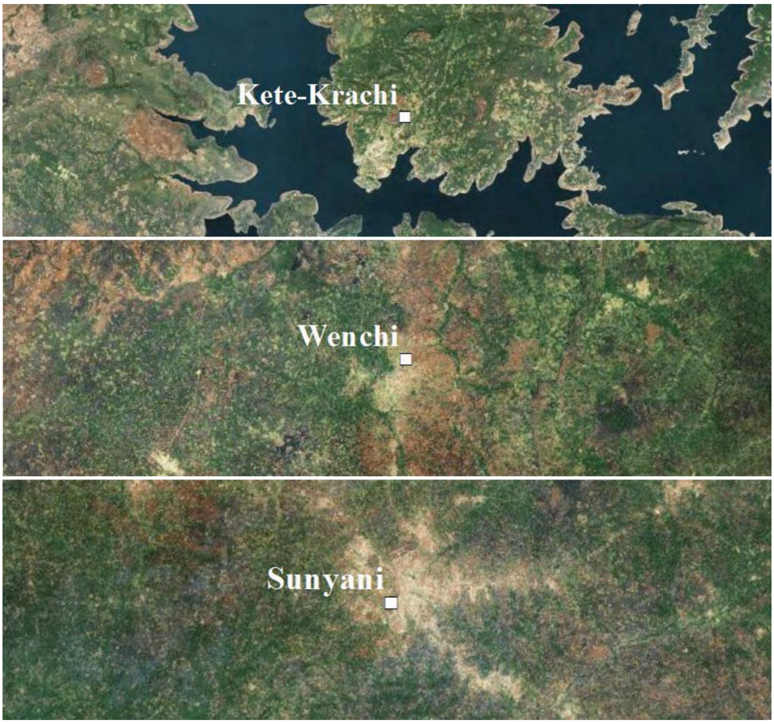

Figure 5. Land use in areas surrounding the Kete-Krachi, Wenchi and Sunyani stations, using the areal basemap feature of ArcMap 10 at 1:250000 scale.

the confluence of the river discharging from the Oti sub-basin and the river discharging from the Black and White sub-basins. It therefore acts as an "oasis", because the open water body surrounding the station causes ET to elevate beyond typical values of crop ET. The excess water vapour in the low atmospheric layer indicates higher relative humidity and lower temperatures in the surrounding air, which could be related to cooling caused by higher evaporation. The single exception occurs when the peak of the growing season is reached in September/October and water is abundant on the land surface. Hence, the difference between actual ET and crop ET at this station could be justified by the additional evaporation from the water bodies in the surrounding area.

Figure 5 shows the areal basemap generated by ArcMap 10 showing the land use pattern of each station. The maps clearly show that Kete-Krachi is surrounded by large water bodies whereas Wenchi and Sunyani are not. The signals from the meteorological variables (i.e. temperature, relative humidity, etc.) are induced by the interactions developed between the atmosphere and the underlying soil-plant system. These signals are processed and translated by the modified GG model to produce the regional estimated ET. Based on the previous discussion and the images shown in Figure 5, it can be concluded that the modified GG model is capable of predicting ET or total water loss from the land surface using meteorological data only and independent of land cover/land use information.

It is noticed that actual ET is higher than crop ET in late spring and early summer. This is the onset of the rainfall season, when the crops are in the initial stages of growing with a high water demand (high R_n and therefore high ETP). Therefore, ET is high during this period due to the high rates of evaporation. However, this is not the case during the minor rainfall season since soil moisture is still high enough to accommodate the water demand; therefore actual ET and crop ET are almost same during this period. In the fall season, actual ET in many stations is again higher than crop ET due to the end of the growing cycle when the soil is moderately moist.

Annual ET estimates

To better understand ET distribution in Ghana, annual ET estimates and ratios of ET to rainfall are shown in Table 3. Generally, there is a trend of ET decreasing with latitude. At Navrongo, the actual ET estimates are in good agreement with all crop ET estimates, but not at Sunyani. In general, the agreement between the actual ET and the crop ET estimates increases with latitude. The crop ET estimates from the GR and AL methods are almost identical, as expected.

Comparing actual ET from the modified GG model and crop ET from the GR method, the absolute difference between the two estimates (as a percentage of rainfall) ranges from zero at Navrongo to 27% at Sunyani (Table 3, Column 13). The average value of that absolute difference is 12%. This value is still close to the typical measurement uncertainty of about 10%. This finding also indicates that the modified GG model can reliably estimate ET using minimal data and unequivocally represent areal ET. The actual ET estimates from the modified GG model vary between 51% and 74% of the average annual rainfall, and the average ET/P value is 65%. This value is in excellent agreement with the globally observed average percentage of ET/P of 60% to 65% (Brutsaert, 1982) and is exactly equal to the mean value of the average percentages from the five classical methods as well. The crop ET estimates from the GR method range from 52% to 78% of the average annual rainfall, with an average of 62%. The metrics used here to compare the monthly ET estimates from the modified GG model and the GR method are root mean square error (RMSE), the bias of the mean values, and the coefficient of determination (R^2). The RMSE ranges from 11 mm/month at Wenchi to 32 mm/month at the neighbouring station, Sunyani. The

Table 3. Computed average annual actual or crop ET (mm) and corresponding ET/P ratios as a percentage. Diff. is the absolute difference between the percentages in Columns 2 and 4.

		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Method		Complementary		Classical										Diff.
		Modified GG		ASCE										
Station	Rainfall	ET	%	GR	%	AL	%	HV	%	TC	%	JH	%	|[2] - [4]|
Navrongo	963	584	61	585	61	586	61	647	67	618	64	592	61	0
Wa	1040	686	66	723	69	713	69	808	78	787	76	735	71	3
Tamale	1040	603	58	765	74	784	75	809	78	770	74	702	67	16
Yendi	1291	838	65	670	52	647	50	797	62	746	58	708	55	13
Bole	1157	739	64	683	59	684	59	831	72	714	62	668	58	5
Kete-Krachi	1353	1006	74	776	57	747	55	875	65	830	61	783	58	17
Wenchi	1258	889	71	848	67	836	66	998	79	906	72	810	64	3
Sunyani	1197	612	51	930	78	974	81	1085	91	874	73	773	65	27
Koforidua	1384	1001	72	749	54	724	52	950	69	791	57	763	55	18
Akim Oda	1432	970	68	765	53	737	51	1021	71	814	57	766	53	14
Min	963	584	51	585	52	586	50	647	62	618	57	592	53	0
Avg.	1212	793	65	749	62	743	62	882	73	785	65	730	61	12
Max	1432	1006	74	930	78	974	81	1085	91	906	76	810	71	27

average RMSE is 22 mm/month, which is acceptable, given the uncertainty of the methods and the diversity of the environments. Knowing that the average bias is 3.7 mm/month, Sunyani has the minimum bias of –26 mm/month while Koforidua has the maximum of 21 mm/month. R^2 values vary between 0.34 at Koforidua and 0.83 at Wa, with an average of 0.65. As a result, it can be concluded that the modified GG model produces good regional estimates of ET.

The HV method tends to overestimate crop ET compared to the GR method, specifically under humid climates. As mentioned earlier, the reason could be the arid conditions under which the HV method was developed. The TC method simulates the ET estimates from the GR and AL methods perfectly among all different climates. With the exception of Sunyani, the JH method shares the same behaviour with the TC method. This information indicates that ET in the region is driven by radiation fluxes more than temperature. Hence, the radiation methods, developed under humid conditions, outperform the temperature method, which was implicitly developed for the study region. Therefore, the use of simple methods that require minimal data can be a good alternative to the more complex methods, such as the P-M equation, that are data intensive. Yet, estimates are sometimes incorrect and misleading, as the simple methods are unable to explain the dynamic interactions between the soil-plant system and the surrounding climate from the temperature signal only. The HV method, developed exclusively for West Africa, cannot be readily used in the same area under different hydro-climatic conditions. Each method constructed for a specific region under specific hydro-climatic conditions is subject to verification and perhaps calibration when applied elsewhere.

Comparison with prior studies

Acheampong (1986) computed ETP by three methods at six synoptic stations across Ghana, whereas Asare, Banini, Ayeh, and Amenorpe (2011) recently estimated ETP at the Atomic-Kwabenya site, 20 km north of Accra, using six models. Such comparative studies do not exist for actual ET estimates in Ghana. Given the fact that actual ET varies significantly, regional studies are important in managing the transboundary water resources of the Volta Basin. Oguntunde et al. (2005) verified the complementary relationship between ETP and ET for the Volta Basin, but they also found that actual ET estimates were unacceptably high (even higher than rainfall), and the values have still to be validated by further studies.

Remote sensing provides a good alternative for regional studies that can demonstrate the spatial distribution of ET. Remote sensing was applied to estimate actual ET using Makkink's equation and compared to scintillometer observations from August to December 2002 at three stations, namely Ejura (in the humid tropical region), Navrongo and Tamale (Schuttemeyer, Schillings, Moene, & de Bruin, 2007). In Upper East Ghana, Compaore et al. (2008) used remote sensing during the dry season of 2002/2003 at two spatial scales: MODIS (1000 m) and Landsat (30 m). In effect, prior remote-sensing studies conducted in Ghana are spatially and temporally confined and, more importantly, required large amounts of data and information.

The average annual actual and crop ET estimates are compared to the estimates from prior studies in the region, and the results are shown in Table 4. The comparison to prior studies conducted in different time periods should be made carefully, as hydro-climatic conditions may vary significantly. Rainfall, as an example, could play a pivotal role in explaining the uncertainties in the ET estimates from the different studies shown in Table 4. This is particularly true for Ghana, where rainfall varies significantly from north to south.

Table 4. Comparison of annual ET estimates (mm) and percentage of annual ET to annual rainfall (%) from this study with results from prior studies conducted in the region.

		Present study				[1][a]		[2][a]		[3][a]		[4][a]		[5][a]		[6][a]		[7][a]	
Method		Modified GG		Classical methods		Rushton		K-J/Mike SHE		Rushton and WASIM		WASIM		Ritchie/SWAT		Water balance		Thornthwaite–Mather	
Study area		Ghana		Ghana		Ghana		Densu River basin		Upper East		White Volta		White Volta		Volta Basin		Volta Basin	
Period		2000–05		2000–05		2000–05		2007–08		2003–04		1961–00		1986–99		1936–98		1931–95	
ET and ET/P		mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
Station	Navrongo	584	61	606	63	758	79			762	76								
	Tamale	603	58	766	74	862	83					739	75	603	74				
	Wa	686	66	753	72	891	86												
	Bole	739	64	716	62	970	84												
	Yendi	838	65	714	55	919	71												
	Kete-Krachi	1006	74	802	59	915	68												
	Wenchi	889	71	880	70	1071	85									910	91	892	89
	Sunyani	612	51	927	77	1006	84												
	Koforidua	1001	72	795	57				71										
	Akim Oda	970	68	821	57														
Average		793	65	778	65	886	80												

[a][1] Carrier (2008), [2] Alfa et al. (2011), [3] Martin (2006), [4] Wagner (2008), [5] Obuobie (2008), [6] Andreini et al. (2000), and [7] Friesen et al. (2005).

Thus, ET/P ratios are better indicators than the absolute ET rates. It should be mentioned here that average annual crop ET represents the average value of the five crop ET estimates from the classical methods. First, comparing the estimates of the modified GG method with those of the classical methods, both sets of results have similar average values (793 and 778 mm/year) and percentage of rainfall (65%). Second, areal averages (not shown here) were calculated for both estimates using Thiessen polygons, and these areal average values are similar to the simple average values shown in Table 4. However, the areal average values cannot be used for comparison with estimates from the prior studies that only used simple average values.

The results of the classical methods show that the estimates from the proposed modified GG model are closer to those of both Obuobie (2008) and Wagner (2008), who worked in the White Volta River basin. However, Carrier (2008) and Martin (2006) overestimated actual ET, and both studies used the same method. Alfa, Hasholt, Jørgensen, and Banoeng-Yakubo (2011) used the MIKE SHE hydrologic model, which uses the Kristensen-Jensen (K-J) method, to predict ET over the Densu River basin, and their ET/P percentage (no mention of actual values) is close to that of the modified GG model at Koforidua, which lies within the same basin. The remaining two studies, by Andreini, van de Giesen, van Edig, Fosu, and Andah (2000) and Friesen et al. (2005), are generic studies in the upper basin, where climate is semi-arid to hyper-arid. The high value of ET/P may be due to the areas of high aridity, where most rainfall is lost as ET. Each of these studies produced an overall average ET that is close to that of Carrier (2008), whose area of study is much wetter (due to relatively high rainfall) compared to the upper basin. This observation is also shown by the difference in ET/P ratios, since the upper basin has much less water available for ET. A study in the upper basin, specifically south-eastern Burkina Faso, produced an ET/P ratio range of only 28% to 32% (Bagayoko, 2006). In contrast, the ratios from Andreini et al. (2000) and Friesen et al. (2005) are much higher than those found in similar regions of Africa (Brutsaert, 1982). Therefore, the ratios cannot be compared to the typical values of Ghana, in which the climate varies from semi-arid in the north to subtropical humid in the south. In addition, the tropical evergreen forests of south-western Ghana have higher rates of rainfall and very humid climatic conditions. In summary, the estimates of the modified GG model are comparable and similar to the average from most prior studies conducted in the same region. More noteworthy is that the ET/P ratio of the modified GG model agrees well with the globally known ET/P ratio.

Spatial distribution of ET

Figure 6 shows the spatial distribution of ET across Ghana using the simple kernel smooth method in ArcMap 10. ET decreases from south-east to north-west, but the trend changes to north-east in northern Ghana. This trend is similar to the distribution of rainfall, which is apparently the main driver of ET. Volta Lake contributes significantly to the water loss in the area which was evident at Koforidua and Kete-Krachi. Carrier (2008) conducted a study in northern Ghana and found that the trend is from south-south-west to north-north-east, consistent with the findings of this study.

The polygons in Figure 6 are the representative areas of synoptic stations used in this study; the numbers inside each polygon provide the total water loss as ET using actual ET from the modified GG model. The total volume of annual rainfall is approximately 297 km^3, while the actual ET represents 66% of the rainfall volume, or about 195 km^3. The difference between these two values is the water excess which is available as surface runoff and groundwater recharge.

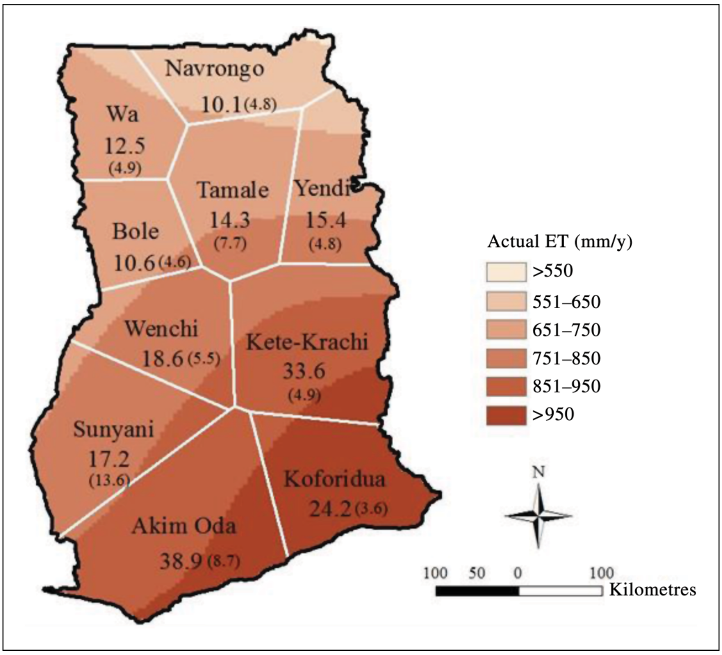

Figure 6. Spatial distribution of actual ET, where the polygons show the representative areas falling within each synoptic station. The number inside each Thiessen polygon is the volume of annual water loss from each area in km^3, while the number in parentheses is the volume of annual groundwater recharge in km^3.

Andreini et al. (2000) performed a water budget analysis for the Volta Basin and found the average total rainfall to be 400 km^3, of which 195 km^3 (or 48.8%) falls in Ghana. An additional 100 km^3 falls in southern Ghana, outside the Volta River basin (see Figure 1). Given the high humidity and prevailing tropical climate, rainfall in this southern part is high. Friesen et al. (2005) performed a similar water balance in the Volta Basin and found that the average annual rainfall is 401 km^3, while the average ET accounts to 357 km^3, or 89% of the rainfall, which is much higher than predicted by this study. The model used by the other study was a modified Thornthwaite-Mather, and no details of the model were provided. There is no obvious reason for this extremely high value, but compared to all other studies, the ET/P ratio of 89% is too high.

Groundwater recharge

Normally, surface runoff data are critical to determining groundwater recharge, but this information is not readily available in the Volta River basin (Carrier, 2008; Obuobie, 2008). Yet runoff can be estimated, since it accounts for a relatively small portion of the rainfall in this region. Most studies, including Andreini et al. (2000), Barry, Obuobie, Andreini, Andah, and Pluquet (2005), Carrier (2008), Friesen et al. (2005) and others, used simple methods such as a constant runoff coefficient to estimate runoff. In this method, runoff is computed as a fixed percentage (constant coefficient) of the rainfall for a given catchment; these coefficients are derived from historic observations and previous knowledge of hydrology of the region. Runoff derived by this method may include contributions from baseflow or interflow. Therefore, runoff estimates may be overestimated, especially in humid regions. Runoff estimation adds more uncertainty to the recharge predictions.

The Nawuni station, which has the longest streamflow time series, is considered the outflow to the White Volta River (see Obuobie, 2008; Wagner, 2008). Daily streamflow data (in m^3/s) are sporadically available from 1954 to 2005. Although not shown here, plotted streamflow showed interesting and different patterns from 1954 to 1994 and from 1995 to 2005. Before 1995, the average streamflow volumes were almost negligible in the dry season of January to April. However, these volumes increased significantly (4–9 times higher) during the dry season in 1995, after the construction of the Bagre Dam in Burkina Faso in the same year. Given these uncertainties and variability, runoff is simply computed using the constant coefficient method, assuming that the contribution of baseflow is insignificant, especially in dry areas.

In this study, the runoff coefficients developed by Barry et al. (2005) are used for two reasons. First, coefficients are given for the four sub-basins of the Volta River basin; and second, the coefficients are adjusted to suit the Volta River basin of Ghana, which is wetter than the conditions of neighbouring Burkina Faso. Barry et al. (2005) found runoff coefficients (as a portion of the annual average rainfall) of 8.3% for Black Volta, 10.8% for White Volta, 14.8% for Oti River and 17% for Lower Volta. One may note that Akim Oda lies outside the boundaries of the Volta River basin. Therefore, the runoff coefficient of the closest station (Koforidua) is used, and this value conforms with the data of Alfa et al. (2011). Eventually, the average annual recharge rates are determined from Equation (8) and shown in Table 5.

According to Table 5, groundwater recharge ranges from 11% to 41% of the average annual rainfall. An obvious trend is that groundwater recharge rates (absolute values) generally increase with latitude in Ghana. Gumma and Pavelic (2012) delineated zones of high groundwater potential using many techniques and found the same trend with latitude (with minor exceptions, mostly in south-western Ghana). Forkuor, Pavelic, Asare, and Obuobie (2013) developed a groundwater development potential map for the northern regions, namely the Upper East, the Upper West, and the Northern.

The upper limit may be questionable; Sunyani, which has a unique behaviour as per this study, should have generated higher rates of runoff rather than recharge. Sunyani also

Table 5. Average annual values of water budget components (mm) and the corresponding percentages of the average annual rainfall rate.

		Rainfall	Evapotranspiration		Runoff		Recharge	
Station	Sub-basin	*P*	ET	%	*Q*	%	Rech.	%
Navrongo	White	963	584	61	104	11	275	29
Wa	Black	1040	686	66	86	8	267	26
Tamale	White	1040	604	58	112	11	324	31
Yendi	Oti	1291	838	65	191	15	262	20
Bole	Black	1157	739	64	96	8	322	28
Kete-Krachi	Oti	1353	1006	74	200	15	147	11
Wenchi	Black	1258	889	71	104	8	265	21
Sunyani	Black	1197	612	51	99	8	485	41
Koforidua	Lower	1384	1001	72	235	17	147	11
Akim Oda	Lower	1432	970	68	243	17	218	15
Average		1211	793	65	147	12	271	23

produced a lower percentage of ET/*P*. Sunyani is the capital of the Brong-Ahafo Region, which is a part of the forest zone of Ghana. Typically, forest ecosystems have the probability of decreasing runoff and increasing ET. Such trends, however, are more prominent at the neighbouring station, Wenchi (see Table 5). Gumma and Pavelic (2012) found that the groundwater potential is higher at Wenchi than at Sunyani. The authors believe that further data and information are required from this region to investigate this discrepancy.

The second-highest percentage of recharge is 31%, at Tamale, in which a semi-arid climate prevails and groundwater is the main source of water (John Aduakye, personal communication, 1 August 2009). The results of this study are promising and show that the aquifer system is sufficiently recharged in semi-arid northern Ghana (see Figure 6) compared to the estimated groundwater abstraction rates documented by Carrier (2008) and John Aduakye (personal communication, 1 August 2009) and the groundwater development maps of Gumma and Pavelic (2012) and Forkuor et al. (2013).

Despite the high rates of rainfall, Forkuor et al. (2013) found that lower rates of recharge are expected from the Oti sub-basin (Yendi station), which has a "steep topography" and hence generates 30–40% of the Volta River basin's annual, perennial flow (Barry et al., 2005). At Kete-Krachi station, the low recharge rate contradicts the findings of Gumma and Pavelic (2012). It is worth mention that the low recharge rates in the south, namely at Koforidua and Akim Oda, perfectly match with those predicted (15–22% of rainfall) by Alfa et al. (2011) and agree with the findings of Gumma and Pavelic (2012). The annual recharge rates for different soil types range from 120 mm to 153 mm in the Densu River basin (Alfa et al., 2011), and these data are very close to the average recharge rate at Koforidua.

According to Figure 6, high rates of recharge are expected in the south-west of Ghana, where a humid climate prevails, the rainfall is bimodal, and the land cover consists of intensive tropical forests. The potential for developing groundwater resources in the northern region is promising, as supported by Gumma and Pavelic (2012) and Forkuor et al. (2013). It is important to note that the total volume of recharge is approximately 63 km^3, or 21% of the rainfall volume, and produces a runoff volume of about 13%, or 38 km^3. Hence, the water excess comprises 34% of the rainfall volume across Ghana. The percentages of the water budget components from Figure 6 are a little different from those depicted in Table 5. This is because the figures from the former are corrected by the area of the corresponding polygon for each station.

Given the minimum recharge for the four principal sub-basins of the Volta River basin (see Barry et al., 2005), the groundwater resources of Ghana are adequately replenished and recharged. Across the country, the average annual recharge rate is 23% of the rainfall, suggesting a high potential for groundwater availability to satisfy the growing future demands.

Comparison to prior recharge estimates

Recharge rates computed by the water balance method cannot be directly compared to those estimated by water table fluctuation methods in which the water flows to the water table and directly contributes to the aquifer system. In other words, recharge rates determined by the water table fluctuation method and chloride mass balance represent "actual or net recharge", i.e. recharge minus ET from groundwater (see Martin, 2006). However, recharge rates computed by water balance represent "potential recharge" that may not fully reach the water table, given the presence of the soil moisture zone and loss due to ET.

Table 6. Comparison of estimated annual recharge between this study and previous studies in absolute and percentage terms.

Reference	Method	Rainfall range (mm/y)	Recharge (% of rainfall) Min.	Avg.	Max.	Study area
This study	Water balance	963–1432	11	23	41	Ghana
Houston (1982)	Penman-Grindley	640–1470	0.0	30.8	84.6	Kabwe in Zambia
Friesen et al. (2005)	Thornthwaite-Mather		0.0		10.0	Volta River basin
Martin (2006)	Chloride mass balance	910–1138	3.0	5.9	6.2	Upper East Region
	Water table fluctuation		1.4		12.5	
	Water balance		4.0		13.0	
	WaSiM-ETH model		7.2		14.3	
Nyagwambo (2006)	Chloride mass balance	507–962	4.0	12.0	25.0	Central Zimbabwe
	Water balance		6.0	8.0	9.0	
	Water table fluctuation		9.0	13.0	14.0	
Sandwidi (2007)	Water table fluctuation	573–1197	5.3	17.0	29.4	Southern Burkina Faso
Carrier (2008)	Chloride mass balance	800–1250	1.5	4.4	10.6	North of Ghana
	Water balance		1.8	6.8	15.9	
Obuobie (2008)	Chloride mass balance	870–1294	3.4	8.3	18.5	Upper East Region
	Water table fluctuation		2.5		16.0	White Volta of Ghana
	SWAT model			7.0		White Volta Basin
Alfa et al. (2011)	MIKE SHE	850–1650	15.0		22.0	Densu River basin

A modified Thornthwaite-Mather model developed by Friesen et al. (2005) showed that groundwater recharge could approach 10% of average annual rainfall in a wet year, while recharge is negligible in a dry year (see Table 6). In northern Ghana, recharge from water balance (as depicted in Table 6) was found to be lower than the estimates of chloride mass balance conducted by Carrier (2008).

Martin (2006) and Obuobie (2008) estimated groundwater recharge rates using chloride mass balance, water table fluctuation, and modeling approaches. In the Upper East Region of Ghana, chloride mass balance produced recharge rates from 3.4% to 18.5% and from 3% to 6.2% of the rainfall, according to Obuobie (2008) and Martin (2006), respectively. Applying the same method in the same Upper East Region resulted in recharge estimates that are three times the others (Table 6); this gives an indication of the high uncertainty of the methods despite the variation in rainfall rates. Using the water table fluctuation method, however, the results of the two studies matched, as both used the same specific yield range while the study areas varied. It should be noted that the Upper East Region is much wetter than the remaining parts of the White Volta River basin.

In the White Volta River, Martin (2006) and Wagner (2008) used the Water Balance Simulation Model, or WaSiM. Such models provide good simulations but require large amounts of data that are typically not available and may have to be assumed or obtained from calibration. It is important to mention that most prior studies were conducted by the GLOWA Project (http://www.glowa-volta.de/), and therefore these studies (e.g. Andreini et al., 2000; Friesen et al., 2005) used common approaches. Although the previous estimates are mostly lower than the estimates from this study, there are many unanswered questions about the methods and corresponding assumptions, given the significantly different trends and findings from these studies. In addition, Alfa et al. (2011) applied MIKE SHE to the Densu River basin in southern Ghana and found that annual recharge may approach 22% of rainfall.

Houston (1982) estimated recharge in a semiarid climate at Kabwe in Zambia using a modified version of the Penman-Grindley recharge model. The mean annual precipitation was 911 mm from 1965 to 1980, while the annual recharge varied from 26 mm to 771 mm and 0 to 534 mm under bare soil and open forest, respectively. The mean annual recharge values were 281 mm and 80 mm for bare soil and open forest, respectively. The water table fluctuation method was applied to the Kompienga Dam basin in Burkuna Faso, in which the annual rainfall is 830 mm (Sandwidi, 2007). The recharge rate was estimated to be 5.3% to 29.4% of the annual rainfall. In another study in Zimbabwe, Nyagwambo (2006) applied the chloride mass balance method in a semi-arid region and estimated the recharge rate to be between 4% and 25% of rainfall. Groundwater studies across many tropical countries of Africa have shown that actual recharge may exceed 20% of the annual rainfall (as estimated by the water table fluctuation method; see Nyagwambo, 2006), indicating high rates of recharge. All abovementioned independent studies suggest that recharge rates are likely to be higher than a few per cent of rainfall in similar and neighbouring environments of Ghana.

Conclusions

This study provides water balance information for all of Ghana using ET estimates from a modified complementary method that relies on meteorological data only. Ghana has a complex hydrology, varying from humid regions in the south to semi-arid and arid regions in the north. Given the fact that ET is an influential driver of water balance, estimating ET with available data is a prerequisite to any accurate estimation of groundwater recharge. Given the limited data on land cover and land use available in Ghana, the use of simple but reliable methods to estimate ET from readily available data is an important step. In this work, the proposed modified GG model of Anayah (2012) is used to estimate country-wide ET for Ghana, followed by estimating groundwater recharge.

In general, the estimates from the modified GG model that represents the complementary methods are in good agreement with crop ET calculated using the classical methods. In selected stations such as Kete-Krachi and Sunyani, where other types of land uses such as water bodies and urban areas are present, the modified GG model captured total water loss from all sources, confirming the argument that the complementary methods are capable of predicting ET independent of land use/cover information. More importantly, the modified GG model that uses the complementary relationships requires meteorological data only, making the analysis simple and straightforward.

The results indicate that the actual ET ranges from 51% to 74% of the total annual rainfall, with an average of 65%. The spatial distribution shows that actual ET decreases from south-east to north-west; the trend switches to north-east in northern Ghana, following the rainfall distribution. The P-T equation used to compute ETW from the modified GG model is close to the P-M equation used in the ASCE grass reference (GR) method, and the relative absolute difference of annual values is around 9%. Comparing the ET estimates from the GG model and the GR method, the average RMSE and R^2 over the 10 stations are 22 mm/month and 0.65, respectively. Most importantly, this comparison shows that the modified GG model provides regional-scale estimates of ET from point observations of meteorological data only.

Although many recharge studies have been conducted in this region, none have been rigorously tested and evaluated using direct recharge measurements. There are a few exceptions, as cited in this study, that are of limited spatial and temporal scales and cannot be used at a national level. Therefore, prior studies cannot be directly followed. The water balance equation was used on a country-wide scale from 2000 to 2005. The results show that Ghana has on average 1211 mm of annual rainfall, of which 65% accounts for ET, 12% for surface runoff, and the remaining 23% for groundwater recharge. The natural groundwater recharge rates range from 11% to 41% of the average annual rainfall rates.

An obvious trend is found, that groundwater recharge generally increases with latitude in Ghana. These results are encouraging in northern Ghana, where a semi-arid climate prevails and groundwater is a major source of water. These findings are supported by recent studies conducted in Ghana (e.g. Forkuor et al., 2013; Gumma & Pavelic, 2012). When compared to the minimum recharge rates for the four principal sub-basins of the Volta River basin provided by Barry et al. (2005), this study indicates that the aquifer systems of Ghana are adequately recharged. This suggests a high potential for developing these groundwater resources to accommodate the increasing demands for water. Still, water quality is a concern recently, because of pollution produced by the disposal of residential and agricultural wastes (see Carrier, 2008). The other concern is the drying climate trend experienced in Ghana over the past 50 years (Lacombe, McCartney, & Forkuor, 2012), which suggests the necessity of better management of the available water resources to minimize the impacts of climate change and climate variability in the next century.

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Note

1. These data from the Ghanaian Ministry of Food and Agriculture website (http://mofa.gov.gh/site/) are no longer available, but a copy can be obtained on request from the first author.

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Appendix 1. Classical methods of calculating evapotranspiration

Potential ET (ETP) is widely used by hydrologists, meteorologists and agronomists. Three concepts are common in the scientific community and sometimes used interchangeably: ETP, reference ET (ET_o) and open water evaporation (E_p). In water resources studies, ETP is widely used to indicate the climate-driven water demand that is governed only by atmospheric conditions and not restricted by availability of water on the surface. However, ETP and ET_o are different, because ETP does not depend on a reference crop while ET_o is specified for a given reference crop. Moreover, ET_o is extensively used in irrigation practices. In contrast, open water evaporation, introduced by Penman (1948), differs from ETP since ETP is influenced by the soil-plant system. In effect, the ambiguity in using ETP is still present, and it largely depends on the application. Brutsaert (1982) mentioned that ETP is often estimated by meteorological data that are not necessarily measured under potential conditions. In comparison, water resources studies focus on seasonal or annual estimates at regional scales, as opposed to local estimates.

Worldwide, the common classical methods for estimating ETP are the temperature methods (Hargreaves et al., 1985), radiation methods (Priestley & Taylor, 1972), and combination methods (Penman, 1948). Among all the methods of estimating ETP, the Food and Agriculture Organization (FAO) version of the Penman-Monteith equation (Allen et al., 1998), similar to the American Society of Civil Engineers (ASCE) version (i.e. Allen et al., 2005), is currently considered to be the best method.

As described by Allen et al. (1998) and Allen et al. (2005), ETP is computed for a reference crop such as grass or alfalfa and then multiplied by a crop coefficient for a given crop to determine crop ET. These crop coefficients are computed using prevailing climatic conditions for water-unstressed plant communities, mostly under humid environments. Extrapolation of these coefficients to arid and semi-arid climates is therefore questionable (Shuttleworth & Wallace, 2009). Another limitation is the lack of information on crop coefficients and growing cycles for different regions or countries. Examples include crops such as yam, cocoyam and plantain that are common in Ghana. For instance, maize is grown in Ghana but not addressed by Allen et al. (1998). Maize grown in Nigeria has published information, but climatic differences are significant between that country and Ghana, affecting the growing cycle.