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Water productivity (WP) in reservoir irrigated schemes in the upper east region (UER) of Ghana

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ABSTRACT

Improving water productivity is one important strategy for addressing future water scarcity, which is driven particularly by increasing human population and potential climate and land use changes. Although an understanding of water productivity is required to develop improved water management strategies, little is known about it in irrigated systems of the sub-Saharan Africa. This study assesses the physical crop water productivity at farm and scheme scales for two distinct systems: a medium and small reservoir in semi-arid environment of the Upper East Region in Ghana. The study concludes that water productivity for the study reservoirs is low, and that potential for improvement exists through improved irrigation water management and agronomic practices.

1. Introduction

Improving water productivity (WP), i.e. the physical quantity derived from the use of a given quantity of water, is one important strategy for addressing future water scarcity which is driven particularly by population growth and potential changes in climate and land use. Improving WP in agriculture will reduce competition for scarce water resources, mitigate environmental degradation and enhance food security simply because by producing more food with less water rewards the saved water to other natural and human uses (Rijsberman, 2001). Molden et al. (2001) contend that an increase of WP in agriculture by 40% may reduce the amount of additional freshwater withdrawals needed to feed the world's growing population to zero. How, when, and where such breakthrough could be realized is currently uncertain. However, it is clear that WP improvement is a critical condition for sustained human development (UNDP, 2006).

The effective identification of the unit of analysis is the basic requirement in WP assessments. According to Cook et al. (2006), estimates of WP have two basic uses: firstly, as diagnostic tool to identify the level of water-use efficiency of a system under study and secondly, to provide insight into the opportunities for better water management towards increased WP for the scale under consideration. Although an understanding of WP is a prerequisite for improvement strategies, little is known concerning empirical WP for reservoir-irrigated systems of the UER. This study therefore determines the water productivity of dry season irrigated crops in small and medium reservoirs in the UER using the water balance analysis approach.

2. Description of the study area

2.1. Location

This study was conducted in the UER which is located on the north east corner of Ghana between latitudes 10°30′ to 11° north and longitudes 0° to 1°30′ west within the White Volta River Basin. The region covers a land surface area of 8860 km^2. Two sites, i.e. Tono and Dorongo, were identified during the 2005/2006 dry season for physical crop water productivity analysis at farm and scheme scales. The two schemes are very distinct in terms of size (i.e. 2500 ha of irrigation for Tono versus 10 ha for Dorongo, respectively) and management but have similarities in terms of types of crops grown during the cropping season Fig. 1.

2.2. Climate

The climate of the region is influenced by the movement of harmattan and monsoon winds, which controls the climate of the West African sub-region. The UER is characterized by mono-modal rainy season starting between April and May and lasting until the end of September or beginning of October. Rainfall is erratic and

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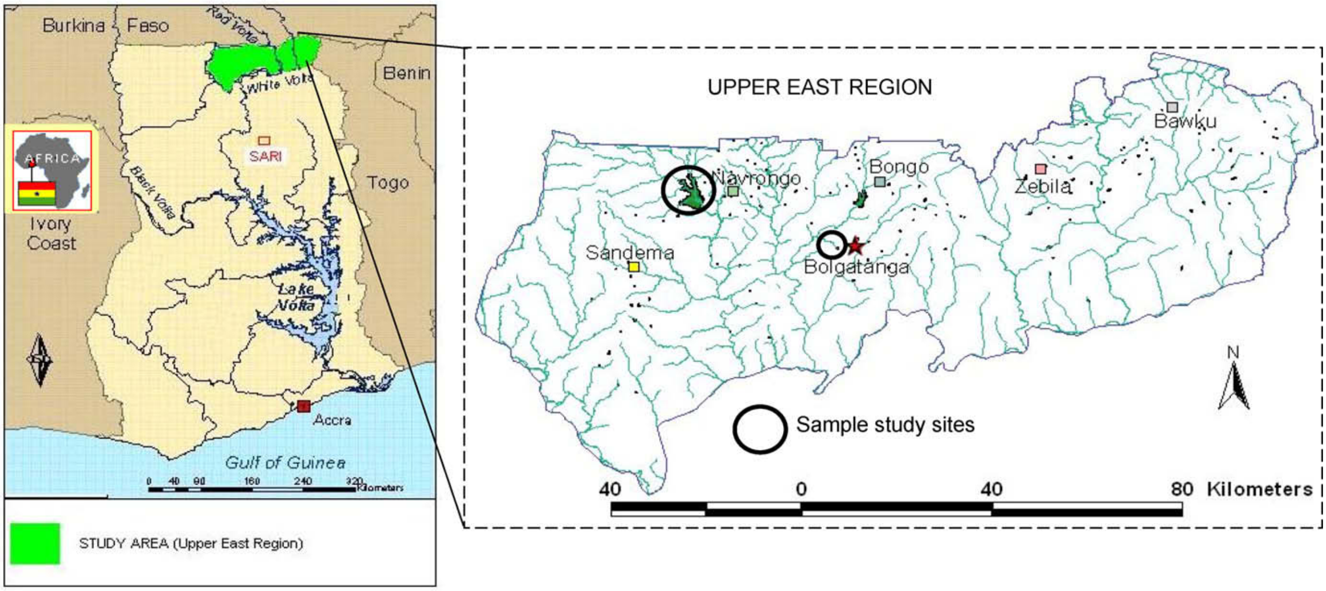

Fig. 1. Study area and sites.

spatially variable. Average annual rainfall ranges between 700 mm and 1010 mm per year with peak rainfall occurring in late August or early September. Annual evapotranspiration is generally twice the annual precipitation and therefore, water storage reservoirs provide an important source of water supply during the dry season. Temperatures in the region are consistently high. March and April are the hottest months while August is the coolest month per year. Relative humidity is high during rainy season and low during the dry season. Wind speed is low, varying between 0.4 m/s and 3 m/s. The region is characterized by high sunshine from October to November and from February to May and the sunshine is low throughout the rest of the months.

2.3. Soils, relief and drainage

The main soil types found in the study area are sandy clays, clay loam and sandy loam. The relief is generally gently undulating with broad, poorly drained valleys and extensive flood plains adjacent to the Volta River. The region is drained by the White Volta River with nearly all tributaries from various sub-catchments in the northern segment of the region draining southward into the White Volta River. Most of the drainage sub-catchments in the UER have developed into inland valleys of different sizes and shapes. Water reservoirs have been constructed (Liebe, 2005) in these inland valleys to supply water for different uses such as crop irrigation, livestock watering, domestic, and fishery uses during the dry season.

3. Materials and methods

3.1. Soil water balance analysis

Both at farm and scheme scales the water balance was defined (Eq. (1))

$$\Delta S_t = (P + I) - (\mathrm{ET_c} + \mathrm{SD} + Q_{\mathrm{bot}} + E_{\mathrm{nb}}) \tag{1}$$

where, ΔS_t is the change in water storage over the period t, P is rainfall (mm), I is irrigation (mm), $\mathrm{ET_c}$ is crop evapotranspiration (mm), SD is surface drains (mm), Q_{bot} and E_{nb} are ground water percolation and non beneficial evaporation (mm). Non beneficial evaporation was assumed to occur on uncultivated fallow plots and in undeveloped areas at Tono due to water leakages from the canals and seepages from irrigated plots.

An automatic HOBO weather station was installed at Tono site to record rainfall, temperature, relative humidity, solar radiation and wind speed. At Dorongo site the above climatic variables for Bolgatanga weather station were collected from Ghana meteorological services. Irrigation diversions at farm scale in Tono and at scheme scale in Dorongo were measured with the long-throated flumes that were installed in the canals during the study period. At scheme scale in Tono, an existing rating curve for the parshall flume in the primary canal was used to estimate the volume of water diverted for irrigation during the study period. The parshall flume's flow rate equation was calibrated by current-meter measurements.

Crop evapotranspiration was estimated as a product of crop factors (K_c) and reference evapotranspiration ($\mathrm{ET_o}$). Crop factors for cultivated crops were obtained from FAO guidelines for crop water requirements (Allen et al., 1998) and adjusted based on local crop growth condition and water supply. The FAO–Penman Monteith equation (Eq. (2)) was used to estimate the reference evapotranspiration using climatic data recorded and collected from the weather stations.

$$\mathrm{ET_o} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

where $\mathrm{ET_o}$ is the reference evapotranspiration ($\mathrm{mmd^{-1}}$), $\mathrm{R_n}$ is the net radiation ($\mathrm{MJm^{-2}\,d^{-1}}$), G is the soil heat flux density ($\mathrm{MJm^{-2}\,d^{-1}}$), assumed equal to 0 for daily interval calculation of $\mathrm{ET_o}$, T is the average daily temperature (°C), $\mathrm{U_2}$ is the wind speed at 2 m height ($\mathrm{ms^{-1}}$), $\mathrm{e_s}$ is the saturation vapour pressure (kPa), $\mathrm{e_a}$ is the actual vapour pressure (kPa), $\mathrm{e_s}-e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve (kPa $°\mathrm{C}^{-1}$), and γ is the psychrometric constant (kPa $°\mathrm{C}^{-1}$).

Two V-notch weirs and a gauging station were installed on drainage exit points to measure surface drains at farm and scheme scales respectively in Tono. At Dorongo scheme, low flow surface drains was impounded by blockade and a 7.6 cm PVC pipe was installed at the drain outlet. The drainage flows was measured using a bucket–stopwatch approach.

Deep groundwater percolation and non beneficial evaporation losses ($Q_{\mathrm{bot}} + E_{\mathrm{nb}}$) were estimated as residuals in the water balance equation (Eq. (1)) and the seasonal soil moisture storage change (S) was assumed negligible because of minimal differences in soil moisture between the beginning and end of the crop season. Cropped areas during the growing season were estimated with ARC view GIS 3.2 using GPS survey and physical measurements.

3.2. Water productivity estimation

Average long-term and seasonal crop yields were utilized to estimate WP at farm and scheme scales for the study sites and WP was estimated as a ratio of crop yield to ET_c. For a meaningful discussion of WP between grain crops and vegetables (tomatoes and onions), which are harvested while fresh, the physical WP values for the respective crops were converted into equivalent nutritional WP, i.e., the product of physical WP and the nutritional content per kg of the product (Renault and Wallender, 2000). The nutritional crop content of energy (Kcal), protein and fat per kg as defined by Renault and Wallender (2000) are adopted to estimate the nutritional WP.

4. Results and discussion

4.1. Soil water balance

The water balance results at farm scale shows that ET_c accounted for only 38% of the irrigation supply. More than 60% of the water supply (irrigation and precipitation) appeared as losses at farm scale as surface drainage (SD), percolation to groundwater (Q_{bot}) and non-beneficial evaporation (E_{nb}) from non-crop fields (Table 1).

The water balance for Tono scheme present an un-proportionate relationship between inflows and outflows in the water balance equation. Crop evapotranspiration accounted for only 17% of water supplies and as result irrigation water use efficiency at scheme scale was less than 20%. Non-crop vegetations evapotranspiration, deep percolation losses and open surface water evaporation accounted for 69% of water supply while 14% of water supply appeared as surface drains. Contrary to Tono scheme, there was a deficit in crop water requirement at Dorongo scheme. The deficit in crop water requirement was offset by the contribution of soil moisture capillary rise to crop root zone. Such rise of capillary soil moisture to crop root zone might have been resulted from leakages and seepage of the reservoir water and not directly from soil moisture stored from the previous rainy season. The deficit in crop water requirement resulted to unusually high irrigation water use efficiency for Dorongo scheme.

Table 1
Soil water balance at farm and scheme scales

Component	Soil water balance (mm)		
	Farm scale at Tono	Tono scheme	Dorongo scheme
P	100	100	13
I	1537	3313	430
ET_c	577	564	468
SD	626	484	30
$Q_{bot} + E_{nb}$	−434	−2365	56

Q_{bot} is negative (−) downwards and positive (+) upwards.

4.2. Crop water productivity

Water productivity result shows that at farm scale in Tono, grain crops had higher calorie, protein and fat nutritional WP than tomatoes (Table 2). Calorie nutritional WP was highest for rice, while soybean showed the highest protein and fat nutritional WP. With the exception of onions, which had higher calorie nutritional WP than cowpea and maize at scheme scale, the nutritional WP of other crops was similar to values obtained at farm scale. The differences in nutritional WP between scales for similar crops were mainly due to differences in physical WP values, while differences between crops were due to both differences in nutritional contents per unit output and the physical WP values. The physical WP and per unit nutritional contents of crops are the main decisive factors of crop nutritional WP.

Crop water productivity (WP_{ETc}) for tomatoes for Dorongo scheme (2.58 kgm^{-3}) was higher than that of Tono scheme (1.35 kgm^{-3}). The difference in WP_{ETc} between the schemes was due to differences in length of the crop season, crop yield and water management which is influenced by water availability. For example, average crop season for tomatoes at Tono lasted for about 212 days while at Dorongo the crop season was only about 120 days. A longer crop growth period resulted in a comparably higher ET_c (503 mm) at Tono than at Dorongo (468.4 mm). Furthermore, average seasonal crop yield at Tono was 6.8 t/ha while at Dorongo it was 12 t/ha. Low WP at the medium reservoir as compared to the small reservoir also reflects loose water management due to secure water availability in the former than the later reservoir. Although the current study compares two distinct water reservoirs, similar WP results for onions are reported by Faulkner et al. (2008) between two small reservoirs within the UER. Using the concept of relative water supply, Faulkner et al. (2008) provide some evidence for a relaxed water management in reservoirs with relatively more water supplies compared to those with scarce water supply in the UER.

Table 2
Crop water productivity at farm and scheme scales at Tono

Crop	WP_{ETc} (kg/m^3)	Crop nutritional output per kg			Nutritional water productivity		
		Calories (k cal/kg)	Protein (g/kg)	Fat (g/kg)	Calories ($kcal/m^3$)	Protein (g/m^3)	Fat (g/m^3)
Farm scale							
Rice	0.56	2800	69	7	1568.00	38.64	3.92
Soybean	0.23	4160	365	200	956.80	83.95	46.00
Maize	0.20	2738	55	12	547.60	11.00	2.40
Tomatoes	1.35	184	8	1	248.40	10.80	1.35
Scheme scale							
Rice	0.55	2800	69	7	1540.00	37.95	3.85
Soybean	0.25	4160	365	200	1040.00	91.25	50.00
Maize	0.24	2738	55	12	657.12	13.20	2.88
Cowpea	0.14	4160	365	200	582.40	51.10	28.00
Tomatoes	1.35	184	8	1	248.40	10.80	1.35
Onions	2.66	331	12	0	880.46	31.92	0

Table 3
Water productivity of different crops under varying climatic conditions reported in literature

WP_{ETc} (kg/m^3)	Source	Location
Rice		
0.4–1.6	Tuong and Bouman (2003)	Various literature under Asian field conditions
0.51	Ahmad et al. (2004)	Pakistan
0.94	Singh (2005)	India
1.08	Zwart and Bastiaanssen (2003)	Review of 82 experimental literature in the last 25 years
0.15–0.6	Cai and Rosegrant (2003)	Global averages based on 1995 production scenarios
Maize		
0.59–0.71	Giorgis et al. (2006)	Ethiopia
0.4–0.7	Igbadun et al. (2006)	Tanzania
0.11–0.34	Some et al. (2006)	Burkina Faso
0.24	Diop (2006)	Senegal
0.14	Durand (2006)	South Africa
0.12	Molua and Lambi (2006)	Cameroon
Cowpea		
0.08–0.11	Some et al. (2006)	Burkina Faso
0.01–0.04	Moussa and Amadou (2006)	Niger
Soybean		
0.13	Molua and Lambi (2006)	Cameroon
Onions		
3.83–5.96	Durand (2006)	South Africa
Pepper		
1.5–8	Möller and Assouline (2007)	Israel

Generally, WP_{ETc} exhibit high spatial variability (Table 3), mainly due to climatic and crop yield variations (Tuong and Bouman, 2003). Although WP_{ETc} values for rice from this study are low, falls within general ranges of reported WP values. Lower values of WP_{ETc} for maize, cowpea and soybean as compared to values obtained in this study have been reported in Burkina Faso, Niger, Cameroon and Senegal under semi-arid and semi-humid climates (Some et al., 2006; Moussa and Amadou, 2006; Molua and Lambi, 2006; Diop, 2006; Durand, 2006).

Low values of WP for maize, cowpea and soybean in the current study could be attributed to low crop yield due to poor crop timing, excessive water application, and poor field crop management. Crop water productivity could be improved by improving field crop management practices such as correct crop timing that will lead to shorter crop season, proper supply of irrigation water, improved seeds and correct application of chemical inputs. A great deal of irrigation water productivity improvement could be achieved by reducing irrigation supplies at farm and scheme scales at Tono which contributed to above 50% losses. The potential for irrigation water productivity improvement for Dorongo scheme, which appeared more water use efficient, is minimal because of limited unbeneficial depletion to which increases in WP could be capitalized. Water productivity improvement strategies in this scheme should be directed to the factors that enhance crop yield, such as control of pests and diseases, use of better crop varieties, good crop timing and correct use of chemical inputs.

4.3. Conclusions

The WP values of similar crops at farm and scheme scales at Tono were similar. The difference in WP_{ETc} between the schemes for tomato was mainly due to differences in planting dates and harvested crop yield. Average crop yield at Dorongo was about three times higher than that at Tono. The WP of the studied crops is generally low, although smaller WP values especially for maize and soybean have been reported under semi-arid and semi-humid climates. WP can potentially be enhanced in the study sites by improving the agronomic practices and irrigation water management.

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