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EFFECT OF EVAPOTRANSPIRATION MODELS ON OPTIMISED VALUES OF APRON AREA AND TANK CAPACITY IN TANK IRRIGATION SIMULATION

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Abstract

The purpose of tank irrigation system is to provide a mechanism for making better and sustainable use of the scarce and infrequent rainfall resource occurring in arid and semi-arid regions for agricultural production. Three models which attempt to explain the mode of evapotranspiration under drip irrigated agriculture in these regions are applied in the simulation to determine their impact on tank irrigation performance. Three agro-ecological regions in Ghana are used in these simulations, and results from a 5000 m^2-citrus, tomato and maize fields with 16.2, 44.0 and 65.0 per cent rainfall-runoff coefficient during a 12–22 year period are compared. The assumption is that evapotranspiration under semi-arid conditions are significantly different from that from humid regions because of the relatively lower soil moisture regime and the smaller fraction of land exposed to moisture under drip irrigation. The results obtained from the simulations agree with this assumption and present a case for further study and validation in the evapotranspiration pattern under drip irrigation in arid and semiarid regions.

Introduction

The semi-arid and dry sub-humid regions of Ghana make up more than two-thirds of the country's landmass of 238,305 km^2. Most of these areas area lie below an elevation of 200 m and is relatively flat. Rainfall, which is very variable, falls in two rainy seasons in southern Ghana and one in northern Ghana. Though annual rainfall is adequate, occurrence and distribution are not uniform and large rainwater runoff results. Most of the runoff water is not only inaccessible for agriculture because of the substantial runoff that results but also a major factor in soil loss from agricultural lands. This phenomenon is due mainly to increased removal of vegetative cover, forest depletion and the practice of shifting cultivation Prinz (1997). To ensure all year-round agricultural production in these areas, it was proposed to establish tank irrigation schemes, which will concentrate rainwater runoff from adjacent fields into a tank for use as irrigation water (Amu-Mensah *et al.*, 1998, 1999, 2000). An immediate benefit of this process is the reduction in shifting cultivation as a result of easy access to water for irrigation.

A computer programme was developed to simulate the processes involved in the tank irrigation scheme. Results of the simulation is influenced by tank size, crop type, climate, runoff conditions and size of apron area, were analysed. It was determined that for a specific climate, runoff coefficient and crop type, a minimum apron area (suitable apron area) can be found that would sustain agricultural production without the tank running dry. The tank size (optimum tank capacity) that supported the suitable apron area was also determined.

In the development of the theory underlying the operation of tank irrigation, the effective irrigation area under drip and sprinkler and the evapotranspiration patterns (Stern, 1980) under the two irrigation systems were investigated. The extraction of moisture from the root-zone of crops under drip irrigation is considered from two perspectives. The model presented by JIID (1990) assumes that for drip irrigation, moisture is extracted from the entire crop field through evapotranspiration but from a depth much smaller than for sprinkler irrigation. The model presented by Ben-Asher *et al.* (1978) suggest that relative evapotranspiration on a drip field is smaller than from a sprinkler field for the same crop. This suggests that only the wetted portions under drip irrigation contribute to evapotranspiration as opposed to sprinkler irrigation where the entire field is irrigated (Bouwer, 1990). This concept is denoted by the wetted fraction (p).

Based on the above, comparison was made from tank irrigation simulations from a 5000 m² crop field with similar soil types. Three crop types, under different agro-ecological climates, were used. The simulations were conducted under three evapotranspiration regimes and equal evapotranspiration conditions for drip and sprinkler irrigation with the same effective crop area (EETa Model). Different evapotranspiration for drip and sprinkler, with the same effective crop area (DETa Model) and wetted fraction (WFETa Model), assumes an effective crop area according to the wetted fraction of the crop under drip irrigation. Evapotranspiration is assumed to occur only over this area and evaporation over the dry sections of the field is assumed to be insignificant compared to that from the wet sections.

Experimental

Evapotranspiration is made up of transpiration from the above-ground bio-mass of the crop and evaporation from the bare surface of the soil (Doorenbos & Prutt,1977). Under the same condition of weather, crop health and soil, the varying factor to evapotranspiration is the amount of bare soil that is exposed to evaporation. Information obtained from two literature sources and a theory proposed by the authors were used to investigate the effect of evapotranspiration on the outcome of the tank irrigation simulation on apron area and tank capacity. Three crops – citrus, tomato and maize, each on a 5000 m² field and receiving 16.2 44.0 and 65.0 per cent, respectively, of the rainfall through rainwater runoff stored in a

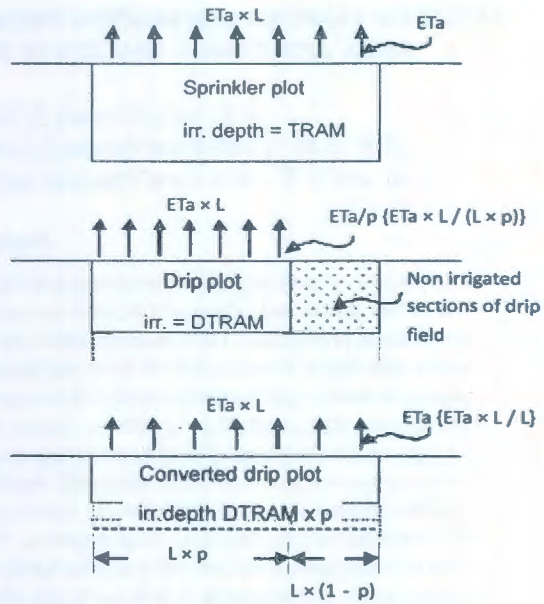

Fig. 1. Evapotranspiration under equal-evapotranspiration model

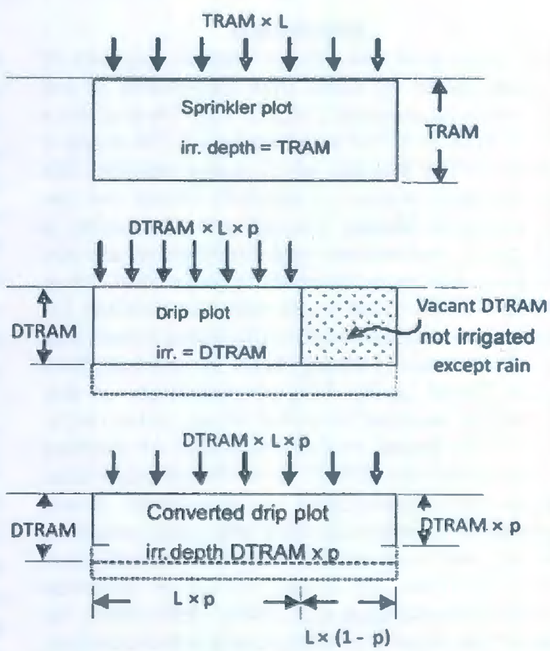

Fig. 2. Irrigation depths under equal-evapotranspiration model

tank were used for the simulation. Water application efficiency was 95 per cent for drip irrigation and 85 per cent for sprinkler irrigation (Feddes & Bastiaanssen, 1990). Rainfall on the crop field was 80 per cent effective in contributing to soil moisture storage. The simulations were conducted for three climatic regions in Ghana; Accra, Kumasi and Tamale.

Equal evapotranspiration model

The equal-evapotranspiration model proposes that the mechanism of evapotranspiration in both drip and sprinkler irrigation conditions are the same (JIID, 1990). Evapotranspiration rate in the wet portions of the drip field is higher than the rate in the sprinkler field. The drip rate is given as ETa/p where p is the wetted fraction of the field and (ETa) is actual crop evapotranspiration rate over the entire field under sprinkler irrigation. Under this condition, there was no difference between the total crop evapotranspiration under the two irrigation systems (Fig. 1).

The entire rooting depth or total readily available moisture (TRAM) was irrigated under sprinkler. This covered the whole crop area so that all the soil was wet. Under drip irrigation, however, the drip total readily available moisture (DTRAM) was confined to uniformly distributed cones surrounding the root mass of the crop. In row crops, these become strips of wet zones bounded by strips of dry soil. In order to relate this to the entire crop area, DTRAM was transformed to the converted DTRAM or CDTRAM (Amu-Mensah *et al.*, 2000). By this analysis, irrigation amount and interval is easily determined. Irrigation is assumed to apply to the entire crop area under both irrigation types and evapotranspiration will be identical in both fields. Irrigation depths will, however, be CDTRAM and TRAM for drip and sprinkler, respectively (Fig. 2).

Different evapotranspiration models

The findings in Ben-Asher *et al.* (1978) lead to the concept that evapotranspiration, under drip and sprinkler irrigation are dissimilar. The presence of dry portions of the soil in the drip field is the main reason for this difference and is peculiar to arid and semi-arid regions or places that experience long periods of no rainfall as exists in several areas of Ghana. The implication of this result is that, especially in semi-arid regions where rainfall is neither frequent nor uniformly distributed, dry portions are prevalent for a considerable length of time. Accra and Tamale, which experience drought represent such areas. Lack of data on evapotranspiration under maize and citrus data on tomato (Ben-Asher *et al.*, 1978), summarised in equation 1, is used to model evapotranspiration in drip fields.

$$\frac{ETa}{E}(\text{drip}) = 0.5 \times \frac{ETa}{E}(\text{Sprinkler}) \qquad (1)$$

where (ETa) is actual crop evapotranspiration and (E) is evaporation from US Class "A" Pan on the same crop field. Irrigation is treated as in Fig. 2, and the effective area of irrigation is determined by the value of the wetted fraction (p).

Wetted fraction model

Under drip irrigation, wet cones of soil surround the root zone of the crop created by the slow but constant dripping of water near the plant stem and the equally constant suction exerted by the root mass. The infiltration capacity of the soil and the flow rate of the drip nozzles, determine the size of the cone of wet soil. For low flow rates, narrow and shallow cones develop and for highly permeable soils, narrow and deep cones develop. The theory of the WFETa model is that evapotranspiration from the drip field is related to the magnitude of the wet fraction. High evapotranspiration is, thus, expected from closely spaced (high-density row) crops. This is expressed in equation 2.

$$ETa\ (\text{drip}) = p \times ETa\ (\text{Sprinkler}) \qquad (2)$$

Results and discussion

Table 1 shows the results of the simulations which illustrate the effects of these models on the suitable (minimum) apron area and optimum tank capacity for citrus under the three environmental and three rainwater runoff conditions. Irrigation intervals for sprinkler and drip were calculated from equation 3. Sandy loam soils with similar properties, found in the locations, were used.

$$Int = CU/ETa\,(max) \qquad (3)$$

where CU (consumptive use) is equal to TRAM for sprinkler and DTRAM × p for drip irrigation. ETa(max) is maximum crop evapotranspiration within the period of simulation. Since sprinkler irrigation uniformly distributes water over the crop field, the evapotranspiration models do not affect the parameters. This is shown in Table 1 for citrus. Similar results occur for the tomato and maize simulations.

Minimum apron area

The EETa model gives larger suitable apron areas and optimum tank sizes for drip as compared to the WFETa and DETa models. Resulting apron areas from the WFETa model are 86 per cent smaller than those derived from the EETa model in Accra and Kumasi. In Tamale, the WFETa model achieved a reduction of 53.1per cent in the apron area as compared to the EETa model. Reduction in apron area and tank capacity is generally obtained for the DETa model in relation to the EETa model. In Kumasi and Tamale, the DETa model dispensed with the apron area all together. Because rainfall is more frequent and plentiful in Kumasi as compared to Tamale, a small tank is required for sustainable operation of the tank irrigation system. In Tamale, a larger tank was required to store sufficient water from rain falling directly into the tank. Table 1 shows the effect of the models on the optimised tank irrigation parameters for drip and sprinkler irrigation. The optimised parameters were derived from simulation results. No differences were found between the results obtained from the models, for the apron area and tank capacity in each location.

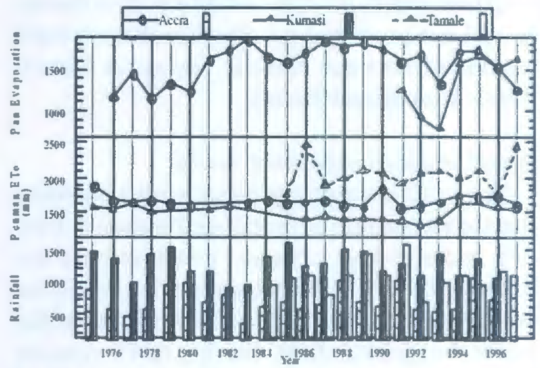

Fig. 3. Annual rainfall (bar), Penman evapotranspiration and pan evaporation (line) of three locations in Ghana

The DETa model, which assumes half values for drip evapotranspiration, suggests that it is possible to dispense with the apron under drip irrigation for Kumasi and Tamale. Compared to the WFETa model, tank sizes under drip for Kumasi and Tamale are larger, thus, compensating for the lack of a water-harvesting medium. The cropped field is, thus, watered with direct rainfall over its surface area. Amu-Mensah *et al.* (2000) reported the relation between the spatial and time variability of rainfall and evapotranspiration on the size of tank and apron. This variability for the period 1975-1996 is shown in Fig. 3.

The operational similarity between the performances of the WFETa and EETa models are shown in Fig. 5, 6 and 7. The trend is very similar although the scale of tank size is very different. If evapotranspiration under drip is dissimilar to that under sprinkler irrigation, the WFETa model offers more economy in tank capacity. DETa, on the other hand shows performance characteristics that are different from the other two models. The scale of tank size for Accra and Kumasi is in line with the results from EETa. The performance of DETa for Tamale shows that the tank size may not sustain

TABLE 1

Effect of evapotranspiration models on optimised tank irrigation system parameter for citrus in Ghana under drip and sprinkler irrigation

Model	*Equal evapotranspiration (EETa)*						*Different evapotranspiration (DETa)*						*Wet fraction (WEETa)*					
Location	*Accra*		*Kumasi*		*Tamale*		*Accra*		*Kumasi*		*Tamale*		*Accra*		*Kumasi*		*Tamale*	
Irrigation type	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler
Irr. interval (day)	1	10	2	20	1	10	1	10	2	20	1	10	1	10	2	20	1	10
Runoff coefficient = 16.2 %																		
Apron area (m^2)	22110	209485	36128	26903	142562	128726	43061	209485	0	26902	0	128730	30958	209485	5086	26902	19960	128726
Tank capacity (m^3)	9973	9633	18915	18377	12653	12109	5924	9633	5770	18376	36045	12108	1397	9633	2648	18378	1772	12109
Runoff coefficient = 44.0 %																		
Apron area (m^2)	81409	77129	13376	9905	52489	47395	15855	77129	0	26902	0	47396	11406	77129	1873	9905	7349	47395
Tank capacity (m^3)	9973	9633	18910	18373	12653	12109	5924	9633	5770	18378	36045	12108	1395	9633	2645	18373	1772	12109
Runoff coefficient = 65.0 %																		
Apron area (m^2)	55108	52211	9055	6705	35531	32083	10733	52211	0	6705	0	32084	30958	52211	1268	6705	4975	32083
Tank capacity (m^3)	9973	9633	18904	18370	12653	12109	5924	9633	5770	18370	36045	12108	1396	9633	2644	18370	1772	12109

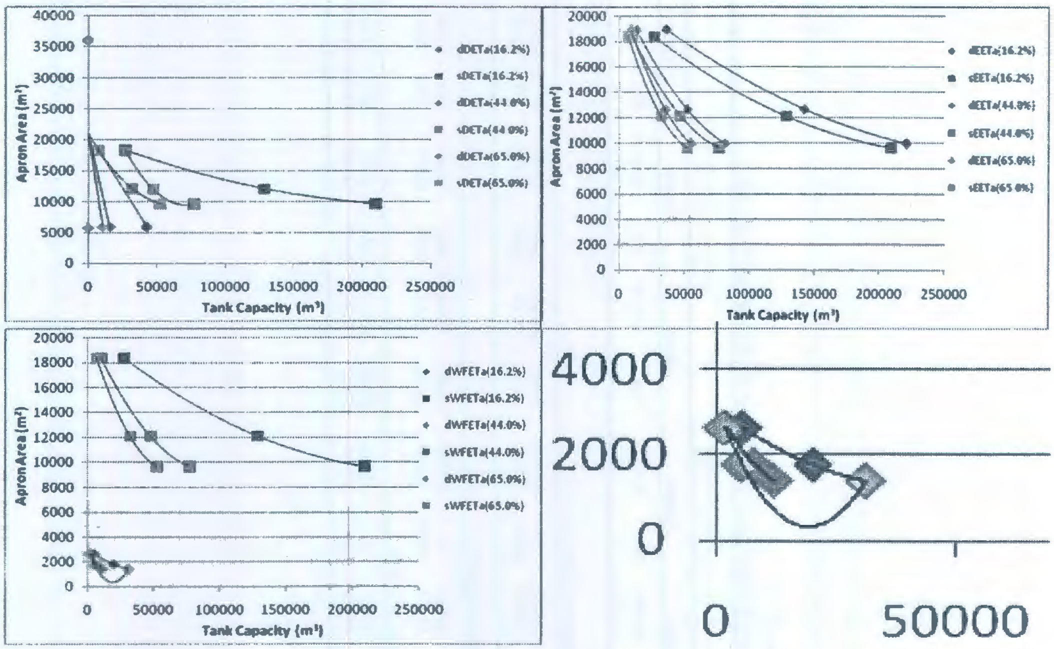

Fig. 4. Graphical representation of simulation results from evapotranspiration models under drip and

agricultural production for the 22 years that simulation was carried out in Accra and Kumasi. This was due to the lack of an apron and is in contrast to Kumasi, which had no apron but was sustainable over for the 22-year period and featured a relatively smaller tank capacity. The higher rainfall and frequency, as well as the lower evapotranspiration in Kumasi (Fig. 3), may account for this. Thus, although Tamale has frequent rainfall, the high evapotranspiration leads to large tank sizes. Direct rainfall into the tank is enough for irrigation.

Optimum tank capacity

Tank capacity in all the locations are reduced by 86 per cent using the WFETa model as compared to the EETa model. This has significant implications for cost savings in tank construction and in the efficient use of water for production. Crop production under drip irrigation in arid and semi-arid environments can be significantly beneficial in reducing the amount of water required for production, reduce the size and cost of tank construction and still maintain high yields. This is excellent for these regions where the main limiting factor to crop production is availability of water. The use of available land (which is plentiful in these regions) for water harvesting and storage should be encouraged to promote agricultural production.

Conclusion

The concept of wetted fraction in the determination of evapotranspiration rates in arid and semi-arid environments, as described above, has significant impact on the development of drip irrigated agricultural production in these regions andon the management of the scarce water resources. A reduction of close to 86 per cent in the size of optimal tank sizes, required to store water for agricultural production, is possible under drip irrigation in these regions as compared to

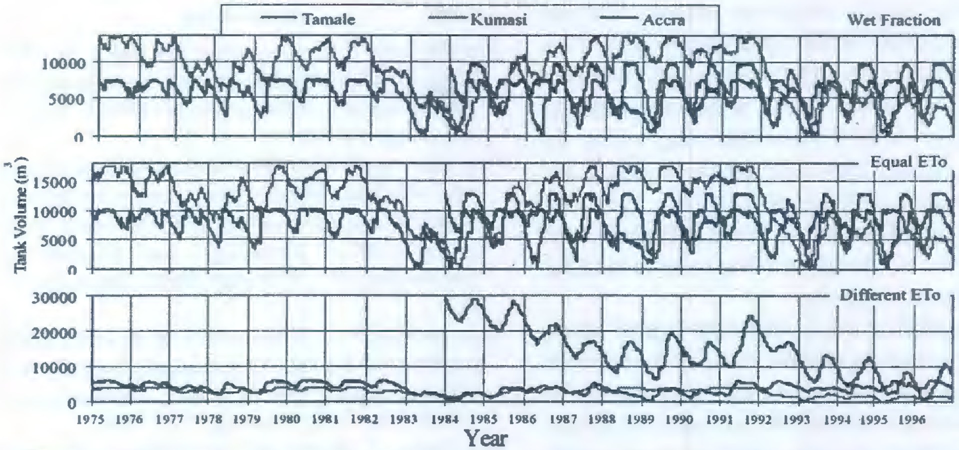

Fig. 5. Effect of evapotranspiration models on drip performance in tank irrigation for 16.2 per cent runoff coefficient and tomato crop

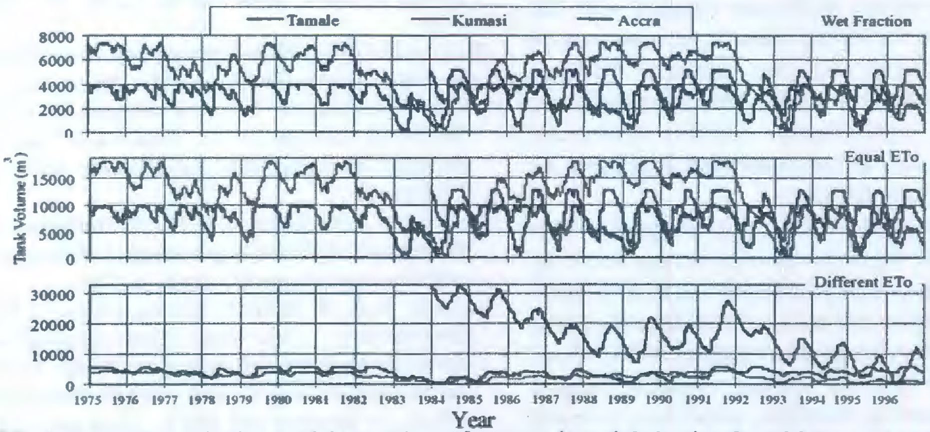

Fig. 6. Effect of evapotranspiration models on drip performance in tank irrigation for 16.2 per cent runoff coefficient and maize crop

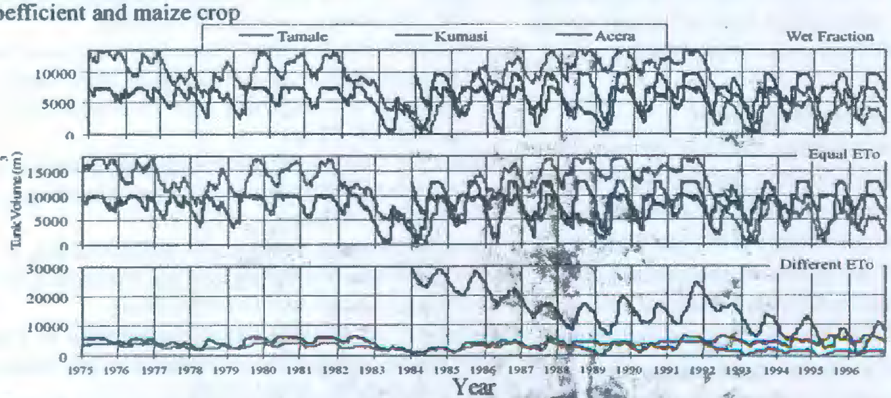

Fig.7. Effect of evapotranspiration models on drip performance in tank irrigation for 16.2 per cent runoff coefficient and citrus crop

sprinkler or surface irrigation methods that wet the entire surface of the agricultural land. This meant less water stored leading to lower exposed surface areas of the stored water and reduced evaporative losses from the reservoirs. In addition, lower tank construction costs are possible because of the smaller tank sizes and smaller area devoted to the construction of storage tanks on the land leading to more land for agricultural production.

The possibility of a rainwater runoff tank, sustainably servicing an irrigation plot for between 12 and 25 years, is an interesting prospect for agricultural production in arid and semi-arid regions where food security is constantly threatened by water stress from irregular rainfall. Water harvesting technique coupled with the efficient use of stored water by a management system, based on the wetted fraction evapotranspiration model, promises good and sustained agricultural yields, improved livelihoods and better health and education for the farming population.

Since not all areas of a drip irrigated plot is irrigated, the dry areas become storage areas for rainfall events that enable the crops to receive additional water and reduce runoff from the plots. This is contrary to sprinkler irrigated fields, whose entire land area has varying moisture content conditions and is, therefore, more likely to reach field capacity in the event of rainfall, thus, leading to runoff and subsequent loss of water to the crop for growth (Yamamoto *et al.*, 1998).

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