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Estimation of crop coefficient of irrigated transplanted puddled rice by field scale water balance in the semi-arid Indo-Gangetic Plains, India

B.U. Choudhury[a,b,*], Anil Kumar Singh[a,c]

[a] Water Technology Center, Indian Agricultural Research Institute, New Delhi 110 002, India
[b] Division of Soil Science, ICAR (RC) for NEH Region, Umiam, Meghalaya-793 103, India
[c] Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya, Gwalior, 474 002, India

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ABSTRACT

Estimation of specific crop coefficient (k_c) based on local climate, genotype and management conditions for irrigated rice will help in improving irrigation scheduling and water productivity. We estimated k_c values of continuous flooded transplanted puddled rice (CFTPR) (cultivar *Pusa-44*) from field scale water balance measured actual crop evapotranspiration (AET_c), Penman-Monteith reference evapotranspiration (k_{c1}) and pan evaporation (k_{c2}) losses in the Indo Gangetic Plains (IGP), New Delhi, India. Measured k_{c1} values ranged from 1.15–1.58, 1.44–1.75, 1.90–1.96, 1.59–1.82 and 1.0–1.41 at tillering (14–18 DAT), panicle initiation (27–34 DAT), flowering (62–65 DAT), physiological maturity (97–101 DAT) and harvesting (112–113 DAT), respectively. Based on FAO-56 defined stages, the measured k_{c1} values were 1.06–1.120 for initial (k_c-*ini*), 1.73–1.88 at mid- (k_c-*mid*) and 1.36–1.45 at end-season (k_c-*end*) growth. Due to higher pan evaporation (8–11%) losses over estimated reference evapotranspiration of grass surface, the measured kc_2 values at initial and end- seasons were 2–5% less while at mid-season, it was 7–8% less than k_{c1}. The FAO-56 climate adjusted model improved k_c-*ini* by 9.5% but improved k_c-*mid* and k_c-*end* values only marginally (<2.5%) over FAO-56 climate unadjusted model. As a result, FAO-56 climate adjusted model considerably under-estimated k_c-*mid* by 42–53% and k_c-*end* by 50–58% over measured k_c values (k_{c1} & k_{c2}) while k_c-*ini* value (1.15) was comparable to measured k_c values during both the seasons. Measured k_c values suggest adjustment of available FAO-56 model derived k_c values by 1.30–1.53 times at mid-and 1.40–1.60 times at -end seasons of CFTPR ecosystems for improving irrigation scheduling and water productivity in semi-arid and other similar agro-ecological regions.

1. Introduction

The continuous flooded transplanted puddled rice (CFTPR) based cropping system, which is characteristically highly water intensive with low water productivity, occupies nearly 13.5 M ha areas in the Indo-Gangetic plains (IGP) of India and contributes significantly to the total food grain production of the country (Dhillon et al., 2010; Sudhir-Yadav et al., 2011; Choudhury et al., 2013). Due to wet tillage (puddling) and the common practice of maintaining continuous standing water (5 ± 3 cm) in rice fields from transplanting till crop maturity (Bouman and Tuong, 2001), huge amount of water input (>2000 mm) is required to harvest one single rice crop. Majority of the applied water is lost (50–80%) in the form of unproductive deep percolation, underbund seepage and evaporation loss from the ponded surfaces (Bouman and Toung, 2001; Choudhury et al., 2007a; Sudhir-Yadav et al., 2011). As a result, despite higher grain productivity in irrigated CFTPR, crop water productivity in this system is one of the lowest among the cereals.

With the continuous decrease in availability of water for irrigation, sustainability of this system (CFTPR) particularly, in the irrigated rice bowls of semi-arid IGP of India is at peril (Chahal et al., 2007; Choudhury et al., 2007b; Sudhir-Yadav et al., 2011). The knowledge of crop water requirement to compensate the actual evapotranspiration loss from the cropped field (AET_c) and its extrapolation through crop coefficient (k_c), which is the ratio of AET_c to reference evapotranspiration (ET_0), is an important practical consideration to improve crop water productivity in irrigated agriculture (Doorenbos and Kassam, 1979; Tyagi et al.,

* Corresponding author at: Division of Natural Resource Management, ICAR Research Complex for NEH Region, Umiam, Meghalaya 793 103, India.
E-mail addresses: burhan3i@yahoo.com, burhan.icar@gmail.com (B.U. Choudhury).

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2000). The choice of reference ET_0 estimation methods are most critical since a little shift in estimated ET_0 loss may bring considerable changes in k_c values and finally, weekly or monthly irrigation scheduling will be affected since irrigation demand is highly sensitive to k_c values (Cai et al., 2003; Satti et al., 2004). The FAO Penman-Monteith method is generally considered to be the best approach for estimating reference evapotranspiration (ETo), particularly under semi-arid to arid climate with least error of over-estimation (~1%) (Allen et al., 1998, 2006; Beeson, 2011). Knowing weekly/stage wise crop AET_c and k_c values help in proper irrigation scheduling based on sensitive growth stages, thus, optimization of irrigation water use in the paddy fields (Choudhury et al., 2013).

Since k_c values vary with local climate and multiple field scale management practices (Doorenbos and Kassam, 1979; Allen et al., 1998, 2006; Cai et al., 2003; Satti et al., 2004), few studies across different agro-climatic regions of India have been conducted to derive k_c values of rice. But these studies were mostly based on measured AET_c loss from traditional non-weighing (Tripathi, 2004) and weighing (Mohan and Arumugam, 1994; Tyagi et al., 2000; Kingra et al., 2004) type of lysimeters. While using traditional lysimeters including manual lysimeter with top loading balances or other with smaller size weighing lysimeters as used in India, there are chances of either over-or under-estimation of crop AET_c losses (Lopez-Urrea et al., 2006; Beeson, 2011; Schradera et al., 2013), as simulating real field condition of puddled (sub-surface compacted) continuous flooded lowland rice ecosystem is difficult. Artificial boundary in lysimeter restricts root growth (root bound effect), disturbs soil structure and compaction level causing changes in hydro-thermal regimes (water movement and heat transfer) including rise in tank temperature over natural field conditions (Kingston et al., 1996; Krennet al., 2003). Processing real time data from lysimeter is also error-prone because of the data gaps, noise caused by mechanical vibration, outliers caused by wind or other factors, temperature dependence of the scale and offset in mass after sampling of leachates (Schradera et al., 2013). It also exerts edge/oasis and bouquet effects whereby the canopy of the plants grown in the lysimeter is above and extends over the surrounding crop and thus, results in modification crop AET_c loss over natural field condition (Kingston et al., 1996; Krennet al., 2003). Extrapolation of k_c derived from lysimetric studies, thus may not always be precise for irrigation scheduling, particularly for paddy field water management in lowland puddled ecosystem.

Measurement of crop AET_c loss using water balance of rice root zone under natural field condition in lowland ecosystem is time consuming, difficult and complex (Droogers and Bastiaanssen, 2002; Chusnul et al., 2012), as it involves difficulties in accurate measurement of periodic water balance components. Because of this, very few attempts (Sudhir-Yadav et al., 2011) were made in estimation of AET_c loss of CFTPR under natural field conditions in most parts of the world including the irrigated rice bowl of IGP-India. As a result, information on k_c values for irrigated CFTPR derived from AET_c loss under natural field conditions is almost negligible. With precise water control (irrigation) and an accurate measurement of water balance components, field water balance approach offers measurement of crop AET_c loss of CFTPR closer to natural field conditions. In the present study, an attempt has been made to derive the weekly and crop growth stage wise crop coefficient (k_{c1}) values of irrigated CFTPR from field scale measured crop AET_c losses by water balance approach and Penman-Monteith based reference evapotranspiration (ET_0) estimation. Since in most of the semi-arid regions, adequacy of weather data for estimation of ET_0 by parameter intensive Penman-Monteith method is a major problem, therefore, we also estimated k_c based on pan evaporation data (Epan, k_{c2}) and compared with k_{c1} for its suitability as an alternative to k_{c1} in irrigation scheduling. The measured k_c values (k_{c1} and k_{c2}) were compared with the widely used FAO-56 climate adjusted model derived single k_c values since this information (deviation of FAO-56 vs. field measured values) is critical for water management through irrigation scheduling in other similar rice growing semi-arid agro-ecological regions.

2. Materials and methods

2.1. Experimental site, soil and climate

The experiment was conducted for two consecutive years (2001 and 2002) at the research farm of Indian Agricultural Research Institute, New Delhi at an elevation of 228 m from mean sea level (28°36′N, 77°12′E). The climate of the area is semi-arid with an average annual temperature of 25 °C and average annual rainfall of 650 mm. Soils were classified as Typic Haplustept, with loamy texture, medium in organic carbon (0.45–0.51%), low nitrogen (215 kg N ha^{-1}), medium phosphorus (15–23 kg P_2O_5 ha^{-1}) and potassium (340 kg K_2O ha^{-1}) contents in the surface layer. The groundwater table was more than 4 m below the soil surface throughout the year. Details of the study area have been given in Choudhury et al. (2007b).

2.2. Experiment design

The experiment on transplanted puddled rice (cultivar *Pusa-44*) was laid out with four replicates and a plot size of 10 m × 7 m *Pusa-44* is a medium duration (120–140 days) cultivar and medium in plant height (<100 cm). For transplanting of seedlings, puddling was done with four passes of a tractor drawn cultivator in standing water followed by one planking with a wooden plank. Seedlings of 3 weeks old were transplanted during summer season (19–21st July) in hills spaced at 15 × 20 cm apart and conventional practices (followed by the farmers of IGP) of standing water of 3 ± 5 cm depth was maintained from establishment to one week before harvesting on 7–10th November. Irrigation water was applied using flexible hoses. Nitrogen in the form of urea was applied at the rate of 120 kg ha^{-1}, of which 50% at basal, 25% at maximum tillering and the remaining 25% at flowering. Other basal fertilizer applications were 30 kg P in the form of single super phosphate (SSP), 60 kg K in the form of murate of potash (MOP), 25 kg $ZnSO_4$, and 50 kg $FeSO_4$ ha^{-1}.

2.3. Measurement of actual crop evapotranspiration (AETc)

Water balance components including actual crop evapotranspiration (AETc) were measured with water balance of root zone of rice fields by the following equation

$$AET_c = (I + R) - (R_{off} + P + S + DW) \quad (1)$$

where I is the irrigation, R the rainfall, P the percolation below the root zone, S the seepage, R_{off} the runoff and dW is the change in soil water storage in the root zone. I and R were directly measured. A total of 1313–1360 mm irrigation water was applied in 31–33 irrigations (approximately twice a week) at 3–7 cm depth each time during the entire crop growth period. In addition, crop also received 249–265 mm of water in the form of rainfall. R_{off} was 0 because the plots were bunded (30 cm height) and no bund overflow occurred. S was assumed to be 0 because of the installed plastic sheets and the light-textured soil favored vertical rather than horizontal water movement. Percolation rates were measured daily by recording the depth of water in plastic cylinders of 45 cm length (15 cm kept above the soil surface). The cylinders were kept closed at the top to prevent evaporation losses. The water level in the cylinders was kept at the same level as the surrounding water depth in