

Water balances and evapotranspiration in water- and dry-seeded rice systems

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Abstract Rice is a crop that is usually grown under flooded conditions and can require large amounts of water. The objective of this 3-year study was to quantify water use in water- (WS) and dry-seeded (DS) systems. In WS systems, the field is continuously flooded, while in DS systems the field is flush irrigated for the first month and then flooded. Research was conducted on commercial rice fields where the residual of the energy balance method using a sonic anemometer and the eddy covariance method were used to determine crop evapotranspiration (ET_c) and crop coefficient (K_c) values. In addition, inlet irrigation water and tailwater drainage were determined. Across years, there was no difference in ET_c (averaged 862 mm), seasonal K_c (averaged 1.07), irrigation water delivery (averaged 1839 mm) and calculated percolation and seepage losses (averaged 269 mm) between systems. An analysis of

the first month of the season, when the water management between these two practices was different, indicated that K_c and water use were lower in DS systems relative to WS systems when there was only one irrigation flush during this period, while two or three irrigation flushes resulted in similar values between the two systems.

Introduction

Drought and high water use are depleting water reserves in many parts of the world (Schewe et al. 2014), with irrigation being by far the largest component of anthropogenic demand for fresh water (Haddeland et al. 2014) leading to increased calls to reduce agricultural water use (Elliot et al. 2014). Rice is the staple crop for the largest number of people on earth and about half of rice under production

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Table 1 Monthly mean solar radiation (R_s), maximum (T_{\max}) and minimum (T_{\min}) temperature, wind speed (Wind), dew point temperature (T_{dew}), precipitation (Pcp), and reference evapotranspiration (ET_o) from the Colusa CIMIS station #32 within the rice-growing region

Mon	R_s (MJ m ⁻² day ⁻¹)	T_{\max} (°C)	T_{\min} (°C)	Wind (m s ⁻¹)	T_{dew} (°C)	Pcp (mm)	ET_o (mm)
Jan	7.1	13.6	3.0	2.2	4.8	128.6	1.2
Feb	10.6	16.1	4.1	2.4	5.6	113.7	1.8
Mar	15.8	19.4	5.8	2.5	7.0	87.2	2.7
Apr	20.9	22.8	7.1	2.4	7.2	34.1	4.3
May	25.1	27.1	10.8	2.4	9.7	29.8	5.4
June	28.1	31.2	13.9	2.4	12.4	10.6	6.4
July	28.3	34.1	15.4	2.2	14.4	0.3	6.8
Aug	25.3	33.8	14.3	2.1	13.0	1.6	6.1
Sept	20.2	31.6	11.8	1.9	11.3	9.2	4.8
Oct	14.3	26.3	8.3	1.9	8.1	25.2	3.2
Nov	8.9	18.4	4.7	1.9	6.0	63.2	1.7
Dec	6.4	13.0	2.3	2.2	3.9	104.8	1.1

Means and totals were calculated over the period January 1, 1986 through December 31, 2014

Mean daily values for the ratio of total global irradiance to estimated clear sky solar irradiance (Allen et al. 2005) were 0.81, 0.85, 0.89, 0.93, 0.94 and 0.89 for the months April through September, respectively, during 2007–2010 at the Colusa CIMIS station

is irrigated, which produces over 75 % of the total rice (Maclean et al. 2002).

California is the second largest rice-producing state in the USA and produces some of the highest yields in the world. Over the past 10 years, California rice yields have averaged 9.2 Mg ha⁻¹ (USDA 2014). High yields are in part due to a Mediterranean climate which provides high solar radiation and little-to-no rainfall during the growing season (Table 1). All rice is irrigated and farmers rely on water deliveries from large regionally managed water systems which are fed by winter snow melt. Over the past few decades, and most recently during the 2013/2014 winter, drought has severely limited California's agricultural water supply.

In California, all rice is direct-seeded with the predominant form of seeding being water seeding (WS). In this system, the fields are completely flooded before planting and seed is dropped from an airplane onto the field. The field usually remains flooded for the duration of the season until it is drained in preparation for harvest. Another form of direct seeding, which is practiced to a limited degree in California but more commonly in the southern USA, is dry seeding (DS). In this system, the seed is either drill planted or broadcast (with seed being lightly harrowed in) and managed like other cereal crops for the first month after which the field is permanently flooded for the remainder of the season. In California, due to the lack of rainfall in April and May (when fields are tilled and planted), DS fields usually need to be flush irrigated to establish the crop prior to the permanent flood. In these initial flush irrigation events, the fields are completely flooded and then the water

is immediately drained from the field. Since WS systems typically remain flooded for the duration of the season, they are flooded about 1 month longer than DS systems. In both systems, after 30–45 days, when water hold periods for herbicides have been lifted and the crop is well established, most growers manage water so that it is continually flowing into and out of the field (referred to as maintenance flow). This maintenance flow of water helps flush out salts that may accumulate due to evapo-concentration (Scardaci et al. 2002), and maintain a uniform and desired water level. Flood water height during this maintenance flow period is typically between 10 and 15 cm although it may be increased between panicle initiation and flowering to help prevent floret sterility (blanking) caused by cool night time temperatures (Board et al. 1980).

Differences in early-season water management may result in differences in water partitioning and use between these systems; however, to our knowledge, this has not been tested. Therefore, the objective of this study was to quantify the partitioning of water in WS and DS systems to better understand the fate of water in these systems. We tested the hypothesis that DS systems require less water due to lower evapotranspiration (ET) and irrigation water requirements than WS systems—especially during the first month of the season. Our objectives were accomplished by measuring ET (using measured net radiation, water and ground heat storage and fluxes, and sensible heat flux from both the eddy covariance and surface renewal techniques) and water inputs and tailwater drainage from paired (side by side) WS and DS grower's fields over a 3-year period.

Table 2 Summary field management data for 2007 through 2009 comparing the water balance between water-seeded (WS) and dry-seeded (DS) rice systems

Field code	Planting method	Field size (ha)	Variety	Planting date	Harvest date	Grain yield (Mg ha ⁻¹)	First water	DS flushes; PM date ^a
2007								
C-122	WS	45.7	M205	May 6	17 Oct	8.41	2 May	
C-126	DS	41.7	M206	Apr 27	10 Oct	6.03	20 May ^b	1; Jun 8
2008								
W4	WS	14.8	M202	May 8	Sept 28	10.08	May 5	
W3	DS	14.6	M202	May 4	Sept 25	8.98	May 6	3; Jun 8
2009								
W3	WS	14.6	M202	May 18	Oct 7	11.27	May 16	
W4	DS	14.8	M202	May 15	Oct 7	9.80	May 16	2; Jun 16

^a DS flushes refer to the number of irrigation flushes applied to DS system before the onset of the permanent flood (PM). The date the PM was established is provided

^b In 2007, the dry-seeded field was planted when there was still subsurface water available to germinate the seed. Therefore, first-irrigation water was applied more than 3 weeks after planting

Materials and methods

Sites

Experiments were established from 2007 through 2009 to quantify the water balance in WS and DS rice systems. In each year, two adjacent fields were selected with one field being WS and the other DS. All fields were located in Colusa County in the Sacramento Valley of California. Climatic conditions for Colusa County are described in Table 1. Field sizes ranged from 14.6 to 45.7 ha in size (Table 2). Soils were all vertisols and classified as Wil-lows silty clays. In 2008 and 2009, the same pair of fields was used; however, the planting method was switched in 2009 (Table 2). In each year, the paired fields had similar planting dates and were completely managed by the grower. The varieties used in all studies were popular medium grain varieties. In 2007, the WS field was planted with M205 and the DS with M206. These two varieties are very similar in terms of crop phenology and yield potential (Jodari et al. 2012). In 2008 and 2009, all fields were planted with M202. In the 2007, in the DS field the grower planted the seed using a drill seeder on April 27 to a depth of 2–4 cm where there was adequate soil moisture to establish the crop. On May 20, the field was flushed with irrigation water and permanent flooding started on June 8. In 2008 and 2009, the DS fields were dry-seeded by flying on seed and lightly incorporating into the soil with a harrow. Fields were then flushed with water to germinate the rice seed. In 2008 and 2009, three and two irrigation flushes, respectively, were required to establish the rice crop (Fig. 1—2009 only). In the WS fields, all rice was planted by airplane with soaked rice seed dropped onto a flooded

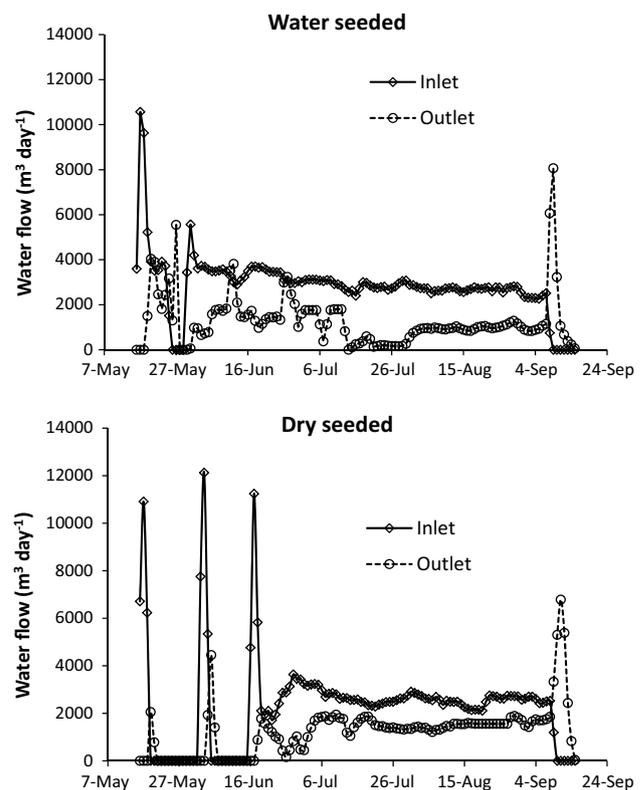


Fig. 1 Water volume flowing into and out of water- and dry-seeded rice fields in 2009

field. In general, the WS fields stayed flooded throughout the growing season; however, during the first month of the season, water may have been added or drained to facilitate herbicide applications and promote stand establishment. After the first 30–40 days, all fields were kept permanently

flooded until about 3 weeks before harvest when fields were drained.

Field inflow/outflow

The volume of water was measured going into the field as irrigation water and draining from the field as tailwater. In 2007, the fields were initially irrigated with both well and surface water but converted to surface water after about a month. The incoming surface water was quantified using a McCrometer flow meter for water flowing through a full pipe. The water from the well was determined by taking regular measurements of the water flowing over a rectangular contracted weir at the end of the canal that received the well water. In 2008 and 2009, at the inlet of each field a small holding pond was built with an outlet from the pond flowing over a rectangular contracted weir. The height of water flowing over the weir was measured at hourly intervals using a water pressure sensor (Global Water—WL16). In all years, at the outlet of each field a rectangular weir was placed and the tailwater flowing over the weir was determined hourly using the same types of pressure sensors as used at the field inlets. The volume of water flowing over both the inlet and outlet weirs was calculated using Cone's formula (Scott and Houston 1959). Usually, little-to-no rainfall occurs during the growing season; however, in 2007, there was 47 mm of precipitation in May and June that was added to the input water for that year.

Evapotranspiration and crop coefficients

We measured crop evapotranspiration (ET_c) using the residual of the energy balance (REB) method by measuring net radiation (R_n), ground heat flux (G), and sensible heat flux density (H) using both eddy covariance (EC) and surface renewal (SR) methods. The REB method has been widely used to determine ET_c of a wide range of crops using either EC or SR to determine the sensible heat flux with the assumption that the R_n , G and H are accurately measured. It is also well known that full eddy covariance stations typically do not close the energy balance, and closure is worse over wetlands and crops than over drier surfaces (Stoy et al. 2013). Thus, in general, EC energy balance closure is better over drier surfaces, when sensible heat flux dominates over latent heat flux. This implies that the lack of EC closure is likely to be more associated with the LE than the H measurement. Castellví et al. (2008) reported good closure when SR was used to measure H and LE over rangeland grass, and the EC closure was not as good. Since the H from SR was quite similar to H from EC, it also implies that the lack of closure is likely due to the EC measurement of LE. Castellví et al. (2006) also reported good closure for SR measurements over rice and poor closure for EC measurements

over rice. Thus, using the REB method to determine ET_c and K_c values seems much more reasonable than direct usage of LE from EC measurements.

The flux density variables were measured half-hourly in $W m^{-2}$ and were converted to $MJ m^{-2} h^{-1}$. Then, the daily latent heat flux density (LE) was determined by summing the 48 half-hourly values to obtain the daily LE in $MJ m^{-2} day^{-1}$. Rearranging the energy balance equation and ignoring energy used for photosynthesis and respiration, the latent heat flux density (LE) is estimated as:

$$LE = R_n - G - H \quad (1)$$

After determining daily LE, the ET_c in $mm day^{-1}$ was calculated by dividing the LE in $MJ m^{-2} day^{-1}$ by the latent heat of vaporization (L , $MJ kg^{-1}$) and by the water density (ρ , $kg m^{-3}$) to obtain ET_c in $m day^{-1}$ [multiplying the depth (m) by 1000 converts to ET_c in $mm day^{-1}$].

Measuring sensible heat flux with a sonic anemometer was described in Shaw and Snyder (2003). Net radiation was measured using a radiation and energy balance systems (REBS), Inc., Q7.2 Fritschen net radiometer set at a height of 2.0 m above the ground. Soil and water heat storage and fluxes were measured with one REBS HFT3 heat flux plate inserted at 0.05 cm depth below the soil surface and soil and water temperature measured at three depths above the heat flux plates using 107 thermistor (temperature) probes from Campbell Scientific, Inc. The first thermistor was inserted horizontally at about 2.5 cm below the soil surface. The other two thermistors were mounted on a length of PVC pipe with a hinge on the bottom. There was a floating device attached to the top of the PVC pipe, and the combination of the hinge and float allowed the pipe and sensors to move up and down with the water level so that the soil and water temperatures were always recorded just below the soil surface, just under the level of the water surface and midway between the upper and lower sensors. Global Water Instrumentation, Inc. WL400 water level recorders were used to measure the depth of water to determine the volume of water above the ground and the volumetric heat capacity of the saturated soil and water above the heat flux plates.

Estimates of H were determined using RM Young Inc., Model 81000RE tridimensional sonic anemometers. The center of the sonic anemometers was set at about 2.0 m height above the ground for all treatments and years, and the towers were located with between 100 and 150 m fetch distance in the prevailing upwind direction in all years and between 50 and 60 m fetch in the non-prevailing wind direction. The maximum height of the rice canopy was about 0.9–1.0 m above the soil. Sonic anemometer data were collected at 10 Hz and analyzed following Lee et al. (2004) using half-hourly calculation intervals. The high-frequency wind velocities from the sonic anemometer were

rotated into the natural wind coordinate system using the first and second rotation algorithms. Sensible heat flux density was calculated from the product of the air density, the specific heat of air, and the covariance of the vertical wind and the virtual sonic temperature. The WPL corrections were applied to the sensible heat flux densities data (Webb et al. 1980).

High-frequency (10 Hz) temperature data were collected with 76.2 μm chromel-constantan thermocouples during the experiments, and sensible heat flux density was computed from the data using the surface renewal (SR) method (Paw et al. 2005; Shapland et al. 2013). The thermocouples were mounted at 1.2 m above the ground in 2007 and about 1.5 m above the ground in 2008 and 2009. The SR values for H were calibrated against H from EC as described in Shapland et al. (2013). Although not shown, the LE from SR (LE_{sr}) and EC (LE_{ec}) matched well most of the time. For 2007, 2008 and 2009, the slopes of linear regressions through the origin of LE_{ec} versus LE_{sr} were 0.98, 0.99 and 0.99 with the corresponding R^2 values being 0.94, 0.98 and 0.98, respectively. Using Eq. (1), LE was calculated using H from the EC method. If the EC values for H were missing for some reason, H from the SR method was used. In this way, the SR method provided an excellent backup for bad or missing EC data.

In some cases, we had missing data for a period of time due to instrumentation problems. For short periods, i.e., <3 h, we estimated critical missing data using a linear trend between observed points. This mainly happened during nighttime, due to weak battery problems, but the ET_c rates were low, and a linear interpolation gave reasonable values. In a few cases, data were missing much of the night and data from the previous night were substituted if there was no reason to expect changes. At the beginning of some of the field measurements, there were missing data for several days due to faulty sensors or late delivery of instrumentation. In some instances, there were missing data at the end of some experiments due to the grower requesting that we remove the stations. Adjacent fields were used to compare wet-seeded with dry-seeded rice ET_c , so data from the adjacent field were infrequently substituted for missing data if the two fields had similar conditions.

Crop evapotranspiration (ET_c) is often approximated as the product of reference evapotranspiration (ET_o) and a crop coefficient (K_c) factor, where ET_o is a measure of evaporative demand of the atmosphere. Reference evapotranspiration is calculated using the standardized Penman–Monteith equation for short canopies (Allen et al. 2006) by assuming a canopy resistance of 50 s m^{-1} during daytime and 200 s m^{-1} during the night. The ET_o equation calculates the aerodynamic resistance (r_a) as:

$$r_a = 1/u_2 \text{ s m}^{-1} \quad (2)$$

where u_2 is the wind speed (m s^{-1}) measured at 2 m height over an irrigated grass surface. While the equation is for virtual evapotranspiration, it approximates the evapotranspiration of a 0.12-m-tall, well-watered, cool season pasture grass. The weather or climate data for estimating ET_o are collected over a broad expanse of well-watered grass. The ET_o values used in these studies came from the California Irrigation Management Information System (CIMIS), which is an online automated weather station network operated by the California Department of Water Resources (CIMIS 2015).

Crop coefficients are computed as the ratio of ET_c to ET_o , with the idea that the same K_c will occur under similar crop and environmental conditions in the future. If that is the case, then one can use the K_c that is appropriate to the crop and environmental conditions to estimate the crop evapotranspiration as $\text{ET}_c = \text{ET}_o \times K_c$. Estimates for reference evapotranspiration (ET_o) were obtained from Spatial CIMIS which spatially interpolates weather data from existing CIMIS weather stations (Hart et al. 2009). The ET_o values were selected using the latitude and longitude of the rice field from the Spatial CIMIS website <http://www.cimis.water.ca.gov/>. The crop coefficient (K_c) was determined as:

$$K_c = \frac{\text{ET}_c}{\text{ET}_o} \quad (3)$$

Percolation and seepage

Percolation and seepage were not measured directly. However, estimates of percolation plus seepage loss were made by subtracting ET_c and tailwater drainage from the amount of water applied to the field.

Results

Field and growth conditions

Fields were planted between late April and mid-May (Table 2) which is typical for California. The WS rice yields ranged from 8.4 to 11.3 Mg ha^{-1} and in all years were higher than for the DS fields by an average of 1.65 Mg ha^{-1} (Table 2). The primary difference between the WS and DS system was at the onset of the growing season during crop establishment when water management differed. The duration of this establishment period varied depending on crop growth and weed management but generally lasted about a month after which there was a shift to maintenance flow in which water continually flowed into and out of the field (Fig. 1—only 2009 shown; Table 3). Flood water height varied but was generally 10–20 cm deep (Fig. 2).

Table 3 Total irrigation water applied and water released from the field over a 3-year period in water-seeded and dry-seeded rice systems

Event	Water-seeded				Dry-seeded			
	Date ^a	Water input (m ³ ha ⁻¹)	Water output (m ³ ha ⁻¹)	ET _c + I (m ³ ha ⁻¹)	Date	Water input (m ³ ha ⁻¹)	Water output (m ³ ha ⁻¹)	ET _c + I (m ³ ha ⁻¹)
2007								
Establishment	5/2–5/24	1981 ^b	152	1829	4/26–6/7	1372 ^b	183	1189
MF	5/25–9/1	11,643 ^b	3871	7772	6/8–9/7	11,765 ^b	518	11,247
Total		13,625	4023	9601		13,137	701	12,436
2008								
Establishment	5/5–5/24	4054	1829	2225	5/6–6/7	4572	732	3840
MF	5/25–8/26	16,673	8352	8321	6/8–8/26	19,477	10,333	9144
Total		20,726	10,180	10,546		24,049	11,064	12,984
2009								
Establishment	5/16–25	3383	1798	1585	5/16–6/15	3322	701	2621
MF	5/30–9/8	20,757	9022	11,735	6/16–9/9	15,972	9662	6309
Total		24,140	10,820	13,320		19,294	10,363	8931
Mean (Total across years)		19,497	8341	11,156		18,826	7376	11,450

The ET_c plus losses due to infiltration (ET_c + I) is calculated as the difference between irrigation and rainfall water inputs and water output (tailwater drainage)

^a Date: month/day

^b Includes 25 mm rainfall during May and 11 mm in June

Crop evapotranspiration and crop coefficient

Seasonal ET_c was similar between the WS and DS fields, averaging 853 and 871 mm, respectively (Fig. 2; Table 4). The ET_c rate averaged 6.09 mm day⁻¹ for the WS and 6.12 mm day⁻¹ in the DS field (Fig. 3). In the WS systems, the ET_c rate was highest during the first 30 days (6.6 mm day⁻¹) and declined to 6.1 mm day⁻¹ between heading and draining the field and further declined to 4.5 mm day⁻¹ after the field was drained. The DS system generally followed a similar trend except that ET_c was lower during the first 30 days (6.2 mm day⁻¹) than during the mid-season (6.7 mm day⁻¹). The crop coefficient, K_c, averaged 1.07 across years for both WS and DS systems (Fig. 3). In general, K_c was high during the first month of the season averaging 1.13 across years and treatments; and then from 1 month after planting until the end of the season ranged from 1.08 to 1.01 with the K_c generally being lower after the final drain.

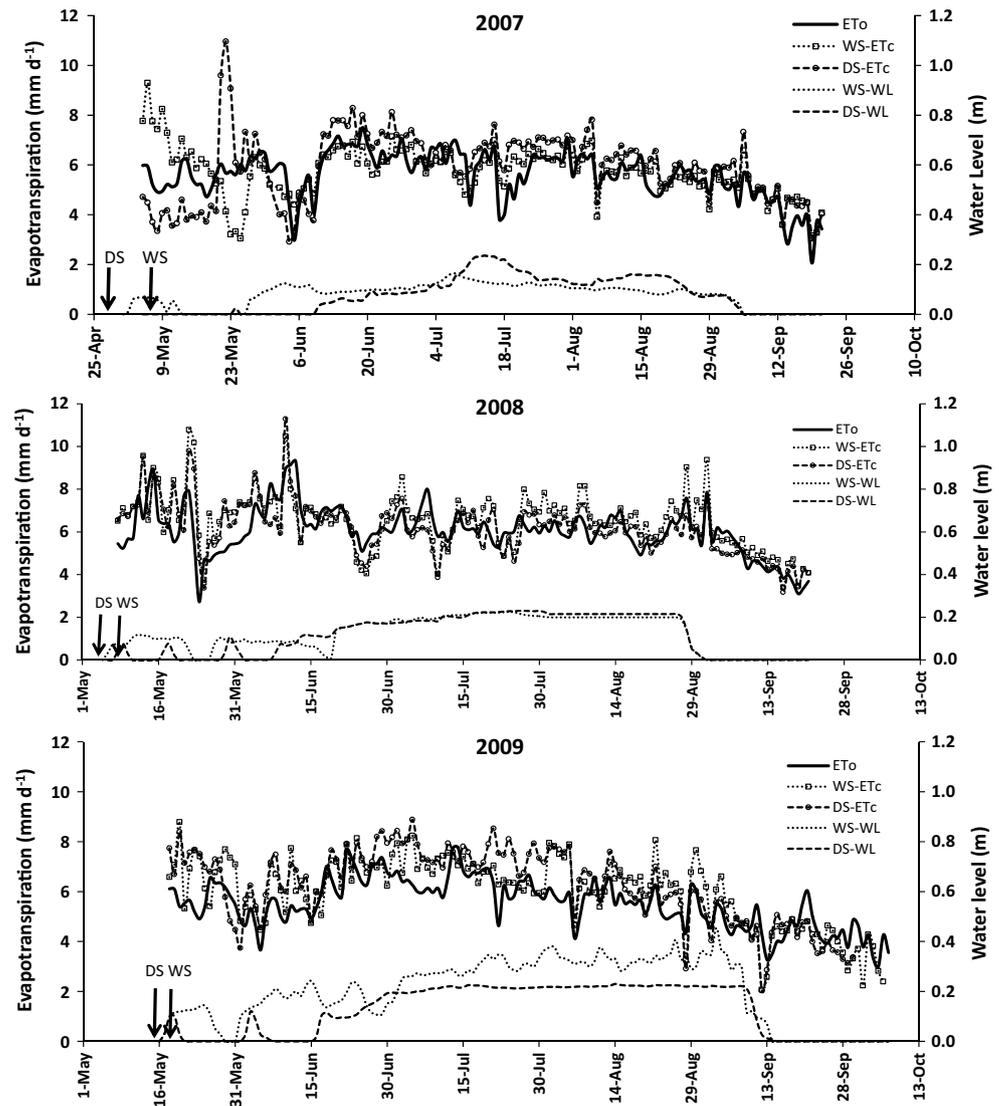
The WS and DS systems differ mostly from each other during the first month of the season. The WS field was flooded almost entirely during the first month with some exceptions where water was lowered in the field to facilitate herbicide applications. In contrast, the DS systems were flush irrigated during the first month in order to germinate the rice seed and establish the crop before a permanent flood is put in place. In 2007, the DS field was flushed only once (23 days after planting) before a permanent flood as the seed was planted to moisture; however, in 2008 and 2009, the DS fields required three and two irrigation flushes,

respectively, prior to the permanent flood (Table 3). During the first 30 days of the season, ET_c ranged from 5.03 to 7.30 mm day⁻¹ (Table 5). The difference in ET_c between WS and DS was small in 2008 and 2009 when the DS fields were flushed two to three times before permanent flood to establish the crop; however, in 2007 when the DS field was flushed only once, ET_c was 18 % lower in the DS field (5.03 mm day⁻¹) than in the WS field (6.10 mm day⁻¹). Similarly, in 2008 and 2009, the K_c values during the first 30 days were similar to the WS system (1.24 vs. 1.19 in 2008 and 1.17 vs. 1.20 in 2009 for the WS and DS systems, respectively) (Table 5). However, in 2007 the K_c in the DS system was 0.91 which was 14 % lower than in the WS system (1.06). The ET_c plus losses due to infiltration (deep percolation and seepage) were also about 35 % lower in the 2007 DS field than in the WS during the establishment period (Table 3).

Water balance

The amount of water delivered to fields across years and establishment systems ranged from 1314 to 2405 mm (Fig. 1; Table 3). There were no consistent differences in the amount of water delivered to the WS and DS fields which averaged 1795 and 1883 mm, respectively, across all 3 years. The amount of tailwater drainage was highly variable across fields, ranging from 70 to 1107 mm—also with no consistent differences between establishment systems

Fig. 2 Daily evapotranspiration for reference ET (ET_o), and observed crop ET (ET_c) for water-seeded and dry-seeded rice fields. At the bottom of each figure the water level (WL) is shown for each field. The arrows indicate the planting date for each field



(Table 4). The 2008 and 2009 fields were characterized by a high amount of tailwater drainage from fields with over half the applied water running off as tailwater in some cases.

On average, ET_c plus infiltration losses were similar between systems averaging 1116 mm in the WS and 1145 mm in the DS fields (Table 4). Subtracting out measured ET_c indicates that 19–476 mm (268 mm average) was lost to infiltration (percolation and seepage) across years and establishment practices.

Discussion

Most of the rice grown in California is established using WS practices. From 2007 through 2009, California average statewide wide yield ranged from 9.2 to 9.6 Mg ha⁻¹ (USDA 2014) which is in line with yields from the WS

study fields (Table 2). In all study years, the yields for the WS fields were higher than for the DS fields by an average of 1.65 Mg ha⁻¹. It is not clear why yields were lower in the DS systems as Pittelkow et al. (2012) reported that the yield potential between these two systems are similar in this environment. Early in the season when the DS rice fields were being flush irrigated there was no indication of crop water stress. One possibility is that in all cases, the farmers were relatively new to DS practices and thus the DS field may not have been managed optimally.

First 30 days of growing season

The WS and DS systems differ from each other primarily during the first month of the season. During this period, crop vegetation in both systems is minimal, although by the end of this period rice will typically be at the 3- to 4-leaf

Table 4 Water balance (mm) for water- and dry-seeded rice systems

	2007	2008	2009	Mean
Water-seeded (mm)				
Total water delivered ^a	1362	2073	1938	1795
Tailwater drainage	402	1018	606	679
ET _c + infiltration loss ^b	960	1055	1332	1116
Seasonal ET _c	813	889	856	853
Infiltration ^c	147	166	476	263
Dry-seeded (mm)				
Total water delivered	1314	2405	1929	1883
Tailwater drainage	70	1107	1036	738
ET _c + infiltration loss	1244	1298	893	1145
Seasonal ET _c	873	865	875	871
Infiltration	370	432	19	274

^a Includes rainfall

^b ET_c + infiltration loss was calculated by subtracting tailwater drainage from total water delivered

^c Infiltration loss (percolation and seepage) were estimated by subtracting ET_c from ET_c + infiltration loss

Table 5 Average crop evapotranspiration (ET_c) per day and the crop coefficient during the first 30 days of the growing season for water-seeded (WS) and dry-seeded (DS) rice systems

Year	Irrigation flushes in DS system	ET _c (mm day ⁻¹)		Crop coefficient (K _c)	
		WS	DS	WS	DS
2007	1	6.10	5.03	1.06	0.91
2008	3	7.30	7.02	1.24	1.19
2009	2	6.32	6.45	1.17	1.20

The number if irrigation flushes in the DS system were all done before the establishment of a permanent flood and were all done during the first 30 days of the season

stage and there may be weeds. In the WS system, the field is flooded almost entirely during the first month with some possible exceptions where water may be lowered briefly to facilitate herbicide applications. In contrast, the DS system is typically flush irrigated during the first month in order to germinate the rice seed and establish the crop before a permanent flood is put in place. We found that ET_c and K_c during this period were only lower in the DS system relative to the WS in 2007 when the field was flush irrigated only once before the permanent flood. When the DS fields were flushed two or three times, the ET_c and K_c were similar to the WS system. Although the DS fields had less time with standing water than the WS fields during the early part of the season, the soil surface in the DS fields was not often dry. Since a soil with a wet surface is likely to exhibit stage-1 evaporation, which means the ET_c rate is limited only by energy availability, the evaporation from the wet soil surface is likely to have an ET_c rate similar to a flooded surface. For example, Ventura et al. (2006) reported good estimates of stage-1 maximum K_c values for evaporation from bare soil (K_x) using the equation:

$$K_x = 1.22 - 0.04 ET_0 \tag{4}$$

where ET₀ is in mm day⁻¹. Using this equation, we would expect a K_x = 1.02 for ET₀ = 5 mm day⁻¹, which is not much lower than the K_c for a flooded field during stage-1 evaporation. The length of time when a soil is in stage-1 evaporation can be 5–7 days. Thus, the reduction in ET_c due to flushing really depends on the length of time that water is off the field and whether the soil surface is allowed to dry out sufficiently to restrict evaporation more than it is restricted by the energy to vaporize water. In these experiments, the soil surfaces did not dry thoroughly between flushes, so the impact of draining and flushing on ET_c was small.

Crop evapotranspiration plus water infiltration losses during this period are difficult to compare between systems as the flushes occurred at different times and periods each year. What is clear though is that ET_c plus infiltration losses

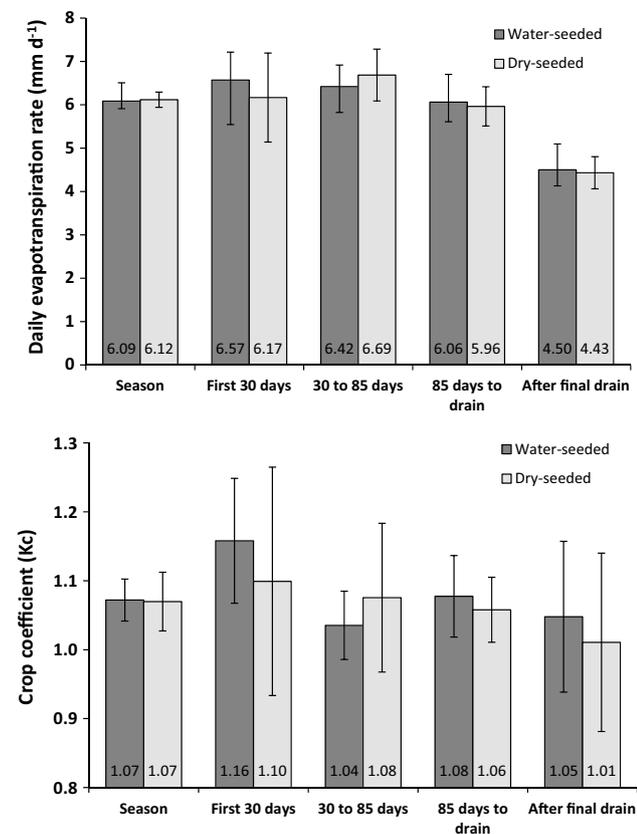


Fig. 3 Evapotranspiration (ET_c) and crop coefficients (K_c) for water- and dry-seeded rice systems averaged over three years. Seasonal average is shown as well as values for different periods within the season. The bars represent the SD across the 3 years. The breakdown by year of the first 30 days is provided in Table 5

were not lower in the DS systems with multiple early-season irrigation flushes (2008 and 2009) than in the WS (Table 3). However, it was lower in the DS system in 2007 when there was only one irrigation flush. One possible reason for the high water use with the irrigation flushes is that when these fields are flush irrigated the soils started to dry. These soils are vertisols which by definition are prone to shrink and swell, and develop cracks upon drying, and there can be rapid preferential flow of water to the underlying subsoil resulting in increased water losses (Sanchez 1973). In the DS fields, these soil cracks may develop between flush irrigation events as soil dries and allows for preferential flow of water downward. As is evident from Fig. 1, a lot of water is applied in each irrigation flush in the DS system; however, relatively little is drained off the field following the flush.

These results suggest the potential for reduced water use in DS systems where it is possible to reduce the number of flush irrigation by planting seeds into existing soil moisture. This is the case in the southern USA, where most growers rely only on subsurface soil moisture and rainfall during the first month to establish the crop before applying a permanent flood (Street and Bollich 2003) thus allowing for irrigation water savings.

ET_c and K_c

The average ET_c across the whole season was 6.1 mm day⁻¹ and did not vary between systems (Fig. 3). The ET_c rates reported here are higher than that reported in tropical countries using eddy covariance methods (Alberto et al. 2011; Hossen et al. 2012). The main reason for higher ET_c in California than in tropical climates is that the climate is characterized by more solar radiation, higher temperature and lower humidity, which leads to higher ET_o and ET_c. Importantly, when comparing results from this study with those from Asia, the different establishment practices between studies need to be considered. In Asia, most rice is transplanted. In transplanted rice systems, 20- to 30-day-old seedlings are transplanted into flood water. In transplanted rice systems, ET_c measurements begin when the field is transplanted and thus the field has both flood water and plants present. In direct-seeded systems, measurements begin at planting when fields are flooded (WS) or bare (DS) and the seed requires time to emerge and grow. In transplanted rice systems, ET_c rates averaged 4.29 mm day⁻¹ in the Philippines (Alberto et al. 2011) and in Bangladesh 3.3 and 2.9 mm day⁻¹ in the dry and wet seasons, respectively, (Hossen et al. 2012).

The K_c, which averaged 1.07 across years for both WS and DS systems were higher (≥ 1.10) during the first month of the season than the rest of the season (Fig. 3). This occurs because the albedo from 0.12-m-tall grass

(approximately the reference surface) and a rice canopy are similar, but the albedo from a flooded field is lower. Thus, as the seeded rice emerges and grows to a full canopy, the albedo increases and the available energy for ET_c decreases. Therefore, the K_c (=ET_c/ET_o) should decrease during rapid canopy growth. Since transplanted rice already has vegetation shading the flooded field at the beginning of the first month, it has a higher albedo initially and during the early growth than a seeded field.

In general, the K_c values reported here are similar to those reported by Alberto et al. (2011) for flooded transplanted rice systems in the Philippines. They reported K_c values of 1.04, 1.11 and 1.04 for the vegetative, reproductive and ripening stages, respectively. They did not report higher K_c values at the beginning of the season as we did most likely because they evaluated transplanted rice systems (see “Discussion” above). More comparable values from this study are those 30 days after planting (Fig. 3). A number of studies evaluating ET in rice systems show increasing K_c values as the crop progresses through flowering and then decreasing (Tomar and O’Toole 1980; Lourence and Pruitt 1971; Alberto et al. 2011; Shah and Edling 2000)—a trend that is not immediately apparent in this study.

The seasonal ET_c was not different between establishment practices and averaged 862 mm across years and establishment practices (Table 4). One reason why the cumulative ET_c in DS systems does not differ from WS is that DS tends to prolong crop duration by up to 10 days relative to WS and thus requires a longer period to irrigate. In this study, the period from planting to final drain averaged 4 days longer in the DS fields than in the WS fields. In 2007, where the ET_c and K_c were lower in the DS system during the first 30 days (Table 5), seasonal ET_c was 60 mm (7 %) higher in the DS system (Table 4). This was at least in part due to the longer crop duration (10 days longer between planting and drainage than in the WS system) in the DS system.

Seasonal water balance

The amount of water delivered to fields across years and establishment systems ranged from 1314 to 2405 mm with no significant differences between establishment practices (Table 3). The variability and values are in line with that reported by Hill et al. (2006). In the southern USA, Smith et al. (2007) reported that on straight-levee fields such as the ones in this study, irrigation plus precipitation inputs averaged 1045 mm in Arkansas to 1326 mm in Mississippi where DS is the predominate form of rice establishment. These values are roughly in line with the 2007 fields but much lower than the 2008 and 2009 fields (Table 3). In our study, the variability in water delivery between fields

was largely due to the high variability in tailwater drainage which ranged from 70 to 1107 mm—also with no consistent differences between establishment systems (Table 4). The amount of water flowing through a field is often a matter of grower choice and water availability. For example, in saline soils or where the irrigation water may have higher salinity levels, growers often apply more water to the field to flush out salts and reduce salinity build up due to evapo-concentration (Scardaci et al. 2002).

Infiltration losses (seepage and percolation) were estimated by difference with an average loss of 268 mm across sites and establishment practices. We were not able to separate out losses due to either percolation or seepage; however, we could estimate the relative importance of each. Liang et al. (2014) measured hydraulic conductivity in eight California rice fields. On the clay soils, similar to those in this study, the hydraulic conductivity averaged 0.32 mm day^{-1} . On average the WS fields were flooded for 118 days. Using this estimate of hydraulic conductivity, the amount of percolation during the growing season would be 38 mm—only 14 % of the estimated infiltration losses. The DS fields are flooded for a shorter period of time, and thus, infiltration losses may be expected to be less. However, these soils are vertisols which develop cracks upon drying. It is likely that for the DS fields between irrigation events at the onset of the season that soil cracks develop which allow for preferential flow of water downward (discussed earlier). Therefore, despite being flooded for a shorter period of time during the growing season, it is possible that more water was lost below the rooting zone in the DS than in the WS system.

Given the relatively low percolation losses, it suggests that most of infiltration losses are due to seepage. It is interesting to look at data from 2008 to 2009 in which the same fields were used in the study, but the establishment practices were switched between years. What is evident is that one field (DS in 2008 and WS in 2009) had higher infiltration losses (average of 476 and $432 = 452 \text{ mm}$) than the adjacent field (average of 166 and $19 = 93 \text{ mm}$) (Table 4). Assuming these fields have the same soil type and hydraulic conductivity, it suggests that one field had much higher seepage losses. The field with the higher losses was adjacent to a deep (>3 m) drain canal while the other was not. It is likely that the presence of such a deep canal beside a field may have favored higher seepage losses. If this is indeed the case, then DS practices in which the field is flooded for a shorter period of time would tend to minimize seepage losses.

Summary and conclusions

Across years there was no difference in ET_c (averaged 862 mm), seasonal K_c (averaged 1.07), irrigation water delivery (averaged 1839 mm) and calculated percolation

and seepage losses (averaged 269 mm) between the WS and DS systems. While DS did not reduce average ET_c as may have been expected due to differences in early-season water management, our 2007 results suggest that there is potential for reducing ET_c , when rice is planted into existing soil moisture, which reduces the number of irrigation flushes required at the onset of the season to establish the crop. In California, it is not common to DS in this manner due to the heavy clays (which make seedbed preparation a challenge) and little-to-no rainfall during the establishment period; however, in the southern US, where DS is the most common form of establishment, there is often adequate rainfall during this period to establish a crop without irrigation and thus realize irrigation water savings. An analysis of the first month of the season, when the water management between these two practices was different, indicated that K_c and water use were lower in DS systems relative to WS systems when there was only one irrigation flush during this period while two or three irrigation flushes resulted in similar values between the two systems.

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