Takeda, N., López-Galvis, L., Pineda, D., Castilla, A., Takahashi, T., Fukuda, S. and Kensuke, O. 2019. Evaluation of water dynamics of contour-levee irrigation system in sloped rice fields in Colombia. *Agricultural Water Management.* 217 (20 May), pp. 107-118.

Evaluation of water dynamics of contour-levee irrigation system in sloped rice fields in Colombia

Naoya Takeda[a]*, Lorena López-Galvis[a], Dario Pineda[b], Armando Castilla[b], Taro Takahashi[c,d], Shinji Fukuda[e], and Kensuke Okada[a]

[a]Graduate School of Agricultural and Life Sciences, University of Tokyo, 1-1-1 Yayoi, Bunkyo, Tokyo 113-8657, Japan

[b]Federación Nacional de Arroceros (FEDEARROZ), Cra. 4 Sur No. 62-98, Ibagué, Tolima, Colombia

[c]Sustainable Agriculture Sciences Department, Rothamsted Research, North Wyke, Okehampton, Devon, EX20 2SB, UK

[d]Bristol Veterinary School, University of Bristol, Langford House, Langford, Somerset, BS40 5DU, UK

[e]Institute of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan

*Corresponding Author: Naoya Takeda

E-mail: take708gym@gmail.com; Tel.: +81 42 465 2638

ABSTRACT

Contour-levee irrigation system is commonly used for rice cultivation in Latin American and Caribbean countries, but its water dynamics in commercial farm field settings are yet to be fully determined. This study aimed to investigate the water dynamics of the contour-levee irrigation system by analyzing conventional irrigation practices and by quantifying water balance and additionally to examine potential toposequential effects. Field experiments with different irrigation intervals were conducted on three commercial farms in Ibagué, Colombia for two seasons from 2017 to 2018. Irrigation and runoff water flows were constantly measured during the crop cycle using Parshall flumes with water level sensors. Percolation rate and field water table were measured using percolators and piezometers installed along the toposequence. The results showed that conventional irrigation management was highly flexible depending on soil permeability, rainfall, and agronomic factors, not particularly paying attention to ensure the flooded conditions during flowering period. The water balance resulted in the irrigation accounting for 76% of the total water input, whereas the runoff, ET, and percolation accounted for 40%, 21%, and 31% on overall average with considerable variation among the three farms. Percolation rates and duration with standing water did not show a clear and consistent tendency among the toposequential positions, but the percolation rate was significantly different among the farms corresponding to soil permeability. Consequently, clear toposequential effects on the water dynamics or on grain yield were not observed at the study site. To our knowledge, this study is the first to elucidate detailed water dynamics of contour-levee irrigation system in farm fields including toposequential difference.

Keywords: Colombia; rice; contour-levee irrigation system; water balance; toposequential effects

1. Introduction

Rice is one of the most important food crop providing 19% of the global human per capita energy, but there are concerns regarding the sustainability of its production because of the large water requirement of up to 2–3 times more than that required by other cereals (McLean et al., 2013). Therefore, various water-saving rice cultivation systems such as saturated soil culture (the soil is maintained at saturated water conditions) and alternate drying and wetting (AWD; the soil is allowed to dry out for a few days after disappearance of standing water before the next irrigation instead of continuously flooding) have been developed and adopted by farmers (Tabbal et al., 2002).

Among the rice producing countries, those in the Latin American and Caribbean (LAC) region have relatively recently started rice cultivation. Nevertheless their production has been increasing remarkably from 7,986,000 Mg in 1961 to 28,092,000 Mg in 2009 (Zorrilla et al., 2012) and is expected to rise with an annual yield increase of around 2% by 2050 (Ray et al., 2013). Rice cultivation in the region has highly intensified; irrigated cultivation system accounts for 59% of the total rice production and the larger (15–50 ha on average) mechanized farms accounts for 94% (McLean et al., 2013). Thus, along with the expansion of rice production highly relying on irrigation, further efficient use of irrigation water would be necessary for sustainable rice production.

In the LAC region, contour-levee irrigation system is a common land-management and irrigation practice for lowland rice cultivation in sloped fields. For example in Colombia, the cultivation system accounts for 70.1% of the irrigated rice area according to National Federation of Rice Producers (FEDEARROZ in Spanish) (FEDEARROZ, 2017). Rice farmers construct levees (bunds) along the contour lines to hold water within the plot (Pineda and Montaña, 2015). Irrigation is started after sowing and is intermittently applied from an inlet at the highest side of the plot, and the water flows down and drains out through an outlet at the lowest side as runoff (Fig. 1). Similar practices of the contour-levee irrigation system are adopted in other major irrigated rice producing areas in the LAC region such as those in Argentina (Marano and Filippi, 2015), Brazil (Takamiya and Tsutsui, 2000), and Uruguay (Battallo et al., 2013).

Although the construction of contour-levees holds irrigation water within the plot to a certain extent, the runoff through the outlet due to the slope of the field might generally cause significant water loss from the plot, leading to high irrigation water requirement. The contour-levee irrigation system is also practiced in Arkansas and Mississippi in the US, and the irrigation water input was reported to range widely from 406 to 1430 mm (Henry et al., 2016). In Uruguay, 1250 mm is considered to be the standard volume allotted for irrigation in the rice sector, but the actual average irrigation water amount applied at the farm-scale is uncertain (Pittelkow et al., 2016). However, to the best of our knowledge, no studies have examined the detailed water balance and dynamics of the contour-levee irrigation system on farm fields. Since observations in experimental fields do not encompass farmers' economic behavior and agricultural practices can differ from those in commercial farms (Takahashi et al., 2018), agricultural strategies must be evaluatiedat the scale reflecting the commercial producers' decision-makings (McGonigle et al., 2014). Therefore, it is essential to reveal the water dynamics of the contour-levee irrigation system in farm fields to elucidate efficient irrigation strategies applicable to actual farms.

Apart from the topographical conditions and construction of contour levees, the intermittent flush irrigation practice under the contour-levee irrigation system is close to AWD irrigation management (Chirinda et al., 2017). AWD was developed by the International Rice Research Institution (IRRI) and has been used in irrigated lowlands, mainly in Asia as a water-saving crop management strategy for lowland rice (Bouman and Lampayan, 2009). In many cases, the irrigation water requirement of AWD is lower than that of continuous flooding (CF) by approximately 30% (Bouman and Tuong, 2001; Chapagain et al., 2011) or even less than half of that of CF (Sudhir-Yadav et al., 2011). A reduction in both irrigation time and percolation loss could contribute to lowering the irrigation requirement (Tan et al., 2013). The grain yield with AWD was similar to or slightly higher than that with CF (Belder et al., 2004; Belder et al., 2005; Cabangon et al., 2004), although a relatively small yield reduction was also observed in other cases (Chapagain et al., 2011; Tabbal et al., 2002). Furthermore, it was reported that in CF, 45% of the water input was productively used by transpiration and 10 and 45% lost by evaporation and percolation, respectively (Bouman et al., 2007). However, for AWD under flat lowland conditions ET, percolation, and runoff loss account for 40–60%, 30–50%, and 0–15% of the total water input, respectively (Cabangon et al., 2004; Lu et al., 2016; Sudhir-Yadav et al., 2011). Consequently, water loss via percolation, which is affected mainly by soil permeability and groundwater table, is usually the focus in AWD to adjust site-specific irrigation management and avoid yield reduction by saving water. Since a high runoff amount is anticipated, percolation might be less important with the contour-levee irrigation system. Quantification of the water balance in the contour-levee irrigation system has not been conducted yet, and it would be important to identify the aspects of conventional irrigation practices that need to be improved to enhance water use efficiency.

In addition, there are potential concerns that positions along a sloped field might be different in soil fertility and water availability, and the variability of resources may lead to within-field variations in plant growth. This spatial heterogeneity along the slope is called toposequential effects and has been reported mainly for a series of flat paddy fields located along the slope in Asia (Boling et al., 2008; Tsubo et al., 2006) and in rice fields of inland valleys in Africa (Touré et al., 2009). The runoff transporting sediments over the toposequence often results in more fertile soil conditions in the lower than in the higher positions (Boling et al., 2008; Homma et al., 2003). In addition, the lower positions tend to store more water and thus, have higher water availability than the higher positions do (Hseu and Chen, 1996; Samson et al., 2004; Tsubo et al., 2005), which was demonstrated as more days with standing water on the soil surface (Boling et al., 2008; Tsubo et al., 2006) in the lower position of the slope. Tsubo et al. (2005; 2006) also reported that the higher percolation rates at higher positions were due to the lighter soil texture. Consequently, variations in crop growth have been observed along the toposequence and lower positions tend to have higher yields (Boling et al., 2008; Samson et al., 2004; Tsubo et al., 2006). The timing of the disappearance of standing water around flowering period was reported to considerably affect the rice productivity (Samson et al., 2004; Tsubo et al., 2006), and therefore, adjustment of crop management strategies according to the toposequential positions would be necessary which have not been conducted so far.

Therefore, in this study, the water dynamics of the contour-levee irrigation system were investigated by analyzing the characteristics of farmers' irrigation practices and by quantifying the water balance in commercial farms with different soil properties and wide range of irrigation practices. Additionally, the significance of the toposequential effects was examined by measuring percolation rates, field water table and grain yield across the toposequence. Ibagué, the capital of the Department of Tolima, Colombia, was chosen as the target site because it is an intensive rice producing regions in Colombia owing to its fertile alluvial soils where the contour-levee irrigation system is commonly practiced (FEDEARROZ, 2017).

2. Materials and Methods

2.1. Study area

Field experiments were conducted on three commercial farms—Farm A (4°22′N, 75°09′W, 940 m), Farm B (4°19′N, 75°04′W, 719 m), and Farm C (4°25′N, 75°09′W, 992 m)—in Ibagué municipality of the Department of Tolima in Colombia for two growing seasons from 2017 to 2018 (2017A and 2017B). Rice fields in the region are generally sloped and that of the targeted farms was approximately 1–3%. Ibagué features a tropical rainforest climate under the Köppen climate system leading to 1691 mm of annual rainfall with bimodal rainfall pattern as well as to 24.0, 28.8, and 19.1 °C of the daily mean, maximum, and minimum temperatures on 20-year average. Weather data was also collected over the period of the experiments by a weather station (Climate Station Vantage Pro 2, Davis Instruments, CA, USA) installed in each farm field, shown in Fig. 2. The typical soil type of the farmlands in the region is Oxisol or Ultisol, which is characterized by moderate levels of organic matter; low levels of phosphorous, nitrogen and pH; and high natural fertility due to its alluvial fan sediments (Castro-González and Lima, 2016). Intact soil samples were collected by creating a soil pit (1 × 1 × 1 m^3) at the center of each farm and then using a soil core sampler (100 cm^3) at the middle depth of the 0–15, 15–30, 30–45, 45–60, 60–85, and 85–110 cm soil layers with two replications in 2016. The soil samples were analyzed using constant head permeability test (saturated hydraulic conductivity [Ks]), pressure chamber method (volumetric water content at different water potential), and Walkley–Black method (organic carbon content). The inorganic nitrogen content was obtained as the sum of NH_4^+-N and NO_3^--N extracted using 2N KCl solution and NH_4^+-N content was measured using indophenol blue method after reduction by cadmium coil using a Technicon Autoanalyzer II (Seal Analytical, Southampton, UK). The soil properties analyzed are summarized in Table 1.

2.2. Experimental design

The experiments were conducted in a plot of each farm with irrigation treatments consisting of three different intervals between irrigations. A “vertical bund” of approximately 30 cm height was constructed along the slope to separate the irrigation treatments in the experimental plots. The total area of the experimental plot in each farm ranged approximately from 1 to 2 ha, while the distance across the slope and degree of the slope were 373 m and 1.9% for Farm A, 205 m and 2.9% for Farm B, and 165 m and 3.0% for Farm C, respectively. A popular rice variety in this region, Fedearroz60, was directly dry-seeded into the soil at a 130 kg ha^{-1} sowing rate by using a non-till drill seeder with a fertilizer applicator. The seeding was performed at 19 cm between rows and 12 kg N ha^{-1} basal fertilizer application. Sowing dates and other phenological events are summarized in Table 2. Irrigation management in each farm was conducted based on three intervals in days between irrigations as the irrigation treatments, (2–4 days [A, short], 4–7 days [B, conventional], and 6–10 days [C, long]) as shown in Table 3. N fertilizer application followed the conventional practice of each farm consisting of 6 splits including basal application, summarized in Table 4. Fertilizers for nutrient elements other than nitrogen were applied according to the conventional management practice of each farm.

2.3. Irrigation and runoff measurement

The irrigation and runoff (water flow at the outlet) were also measured at the inlet and outlet of each irrigation management by using a hand-made Parshall flume and water level sensor (eTape Liquid Level Sensor, Milone Technologies, NJ, USA) for both 2017A and 2017B (Fig. 3). The Parshall flume is an open channel equipment in which water flows horizontally. The water level sensor is a ruler-shaped sensor with a resistive output that varies with the water level. The water flow rate (Q in L s^{-1}) can be determined by the water table in the Parshall flume (H in cm) using equation (1) under the assumption of flat and horizontal water movement (Nevada State Engineer’s Office, 1986). The equation was determined based on a preliminary experiment on another farm near Ibague (data not shown). The water table in the Parshall flume was measured using a water level sensor attached to the side wall of the Parshall flume with a 10-minute recording interval.

$$Q = 0.2578 \times H^2 + 0.0052 \times H \qquad (1)$$

The water table in the Parshall flume was assumed to be the same during the 10-minute intervals, and daily irrigation and runoff amounts were obtained by summing up values for the day. The results were analyzed to calculate the seasonal amount of irrigation and runoff by summing up the values obtained over the growth season. The number of irrigation events over the crop cycle was also counted based on the recording.

2.4. Field water table and percolation rate measurement

The field water table depth (cm in relation to the soil surface) and the rate of percolation were measured in irrigation B in the three farms in 2017B at different positions along the toposequence (Upper, Middle, and Lower). Perforated PVC tubes to measure the field water table both above and below the soil surface (piezometer) and PVC tubes without perforation and with a lid to measure the percolation (percolator) were installed at a representative point halfway between the contour levees for each position. All the PVC tubes had a diameter of 6 cm, and the lengths were 40–80 cm for the piezometers and 50 cm for the percolators. The water table inside the piezometers and percolators was measured using a water level sensor mentioned above with a 10-minute recording interval. The piezometer and the percolator at each location were installed close to each other within a 50-cm distance. For the percolator, water was refilled to the level of field water table occasionally when the field had standing water. The installation method is shown in Fig. 4 and is similar to the setting of Tsubo et al. (2005), except for the sensors. The daily percolation rate (mm day^{-1}) under saturated water conditions was then estimated from the recordings of the percolator as the daily difference in the water table within the percolator. The difference was estimated only when the field water table shown in the piezometer was higher than -25 cm to confirm that the soil at a depth of -30 cm (the depth at which percolators were installed) is saturated. Then, the average of the daily percolation rates was calculated as the percolation rate at each toposequential position. To analyze the field water availability across the slope, cumulative duration with standing water (the field water table above the soil surface [0 cm]) was calculated by multiplying the number of observations by the interval of observation (10 minutes) as the number of days for each piezometer in each farm.

2.5. Water balance analysis

Seasonal water balance was analyzed using irrigation, runoff, and rainfall data in 2017A and additionally using evapotranspiration and percolation data in 2017B. The evapotranspiration was estimated as follows: the reference evapotranspiration (ETo) was first calculated using the Makkink method (Makkink, 1957) from the weather data at each farm. Daily crop evapotranspiration (ETc) was then calculated by multiplying ETo by the rice crop coefficients (Kc) derived by Allen et al. (1998): initial growth (0–55 DAE) – Kc initial = 1.05; mid-season growth stage (55–95 DAE) – Kc mid = 1.20; and late-season growth stage (95–120 DAE) – Kc end = 0.75. Seasonal ETc (ET) was then calculated as the water balance component over the crop cycle. The seasonal total percolation was calculated in two ways. First, it was estimated by subtracting the seasonal runoff and ET from the total water input for each irrigation treatment ("percolation from the balance"), assuming changes in the water stored in the soil and net horizontal seepage flows are negligible. Second, sum of the daily percolation rate measured using the percolator (Section 2.4) was calculated over the crop cycle and averaged across the toposequential positions as water balance component ("percolation observed"). For 2017B, these two seasonal percolation estimates were compared to confirm whether the components were balanced.

2.6 Grain yield measurement

Gain yield was measured at harvest by threshing rice plants from an area of 2×2 m^2 at four positions along the toposequence—T1, T2, T3, and T4 positions (T1 was the highest elevation and T4 the lowest) for each irrigation treatment. The grain samples were dried in a forced-air circulation oven at 70 °C for 72 hours, and the dry weight was measured. Grain yield was then calculated at 14% grain moisture content.

2.7 Statistical analysis

To examine the significance of toposequential effects, following statistical tests were conducted using R statistical software version 3.4.1 (R Core Team, 2017) with the significant level set at $p < 0.05$. Analysis of variance (ANOVA) was conducted across the farms on the percolation rate and on the duration with standing water with factors of farm and toposequence. For grain yield, ANOVA was performed in each farm and each season with a factor of toposequence. Subsequently, Fisher's least significant difference (LSD) test was conducted for the significant factors in those ANOVA analyses using a package "agricolae" (Felipe de Mendiburu, 2017).

3. Results

3.1. Characteristics of conventional irrigation managements

The timing and amount of irrigation managements and changes of field water table depth throughout the growing season 2017B in irrigation treatment B (conventional) are shown in Fig. 5. The observed irrigation schedule coincided well with the timing when the field water table dropped below the soil surface in all the farms. Both the frequency and amount of water for each irrigation event were higher in Farm B than in other two farms. The irrigation schedules in Farm A and Farm C were relatively similar except for the intense irrigation immediately before 30 DAE in Farm C. In terms of the irrigation schedule associated with phenological stages, it was observed that the irrigation pattern did not change even in the flowering period. The changes in the field water table revealed a faster drying rate for the soil and a larger fluctuation of the water table in Farm B, slower and smaller fluctuations in Farm C, and intermediate fluctuations in Farm A. The water table at Middle position in Farm A showed extremely dried conditions during the crop cycle, because the small spot where the equipment was installed resulted in exceptionally dry-prone conditions due to imperfect leveling, based on our field observation.

The average irrigation amount (mm) and duration (hours) of each irrigation event and the number of irrigation events during the cropping season are summarized in Table 5. Since the irrigation treatment was based on the frequency, the seasonal total irrigation amounts did not always follow the order of the irrigation treatments. Nevertheless, the number of irrigation events and the cumulative duration of irrigation throughout the season indicated that the irrigation treatments were correctly implemented in most cases. However, the differences between B and C in Farm B 2017A and between A and B in Farm C 2017B were small and the orders were reversed. The average irrigation amount of each event was slightly less and the duration of each irrigation was shorter in Farm A than in the other two farms. Farm B had the highest number of irrigation events, the longest duration of each irrigation at mostly >10 hours, and the largest irrigation amount for each event of the three farms, resulting in a considerably higher total irrigation amount throughout the season which reached around 3000 mm. In Farm C, the irrigation amount was obviously higher in 2017A than it was in 2017B, despite the similar seasonal rainfall, probably because of the overestimation of the water depth inside the Parshall flume caused by the sedimentation at the bottom in 2017A. However, the irrigation duration and number of events were similar between seasons in Farm C.

3.2. Seasonal water balance

The measured and estimated components of the water balance and their ratio over the total water input are summarized in Table 6. The seasonal irrigation amount was considerably different among the farms, ranging from 468 to 3835 mm with an average of 1930 mm. Together with the rainfall during the cropping season, the total water input was >1000 mm for all the observations and reached 4637 mm in Farm B with an overall average of 2539 mm. A larger portion of the water input was from irrigation, accounting for 76% of the total water input on average, than from rainfall. The irrigation water input was considerably higher in Farm B than it was in the other two farms.

In addition to the high variation in the total water input, the seasonal runoff amount also varied considerably ranging from 227 to 2610 mm and was much higher in Farm B than it was in the other two farms (Table 6). In Farm A and Farm C, the seasonal runoff was mostly <1000 mm. It should be noted that the measured runoff volume in Farm B in 2017A for irrigation treatments B and C were particularly unreliable because of the unexpected cut-inflows of irrigation water from the plot next to our experimental plot, which was measured only at the outlets of irrigation treatments B and C. The unexpected flows only increased the runoff, resulting in a runoff ratio higher than 100% (highlighted in grey), which is completely unrealistic and, thus, was excluded from the calculation of the average water balance components of the farms. Therefore, the seasonal runoff amount was 1009 ± 170 mm (mean ± SE) across the farms. Subsequently, the seasonal observed and calculated percolation amounts were compared, based on the water balance, with the estimated ET in 2017B (Table 6). The estimated ET was relatively stable compared to the other water balance components, ranging narrowly from 483 to 571 mm. The seasonal percolation from the water balance varied considerably among the irrigation treatments in each farm and did not always correspond with the observed volume in irrigation B. The observed seasonal percolation volume was highest in Farm B at 2026 mm, followed by Farm A and Farm C at 618 and 117 mm, respectively, on average over the toposequential positions. Consequently, runoff, ET, and percolation accounted for 40, 21, and 31% of the average total water input, respectively, in the contour-levee irrigation system (the averages were not exactly balanced because of the number of observations for each item).

3.3. Toposequential effects on water dynamics and on grain yield

The toposequential positions did not have a significant effect on percolation rates across the farms, but the percolation rates averaged over the toposequence were significantly different among the farms with the highest rate in Farm B (Table 7). As a result, farm average percolation rates ranged 2.3–62.8 mm day^{-1}. Even though the difference in percolation rate among toposequential positions was not significant, lower position had the lowest rate in each farm.

The duration with standing water widely ranged 1.6–89.2 days across the toposequence and the farms (Table 7). As mentioned in Section 3.1, Middle position in Farm A had exceptionally dried conditions and resulted in the extremely short duration. There was no significant difference or consistent tendency in the duration with standing water over the toposequence across the farms. Moreover, the duration was not significantly different among the farms unlike the percolation rate, though that in Farm C was relatively longer than in the other two farms despite that the total observation period was shortest among the farms. Relationships between the percolation rate and the duration with standing water were not very clear across the toposequence. Nevertheless, smaller percolation rates corresponded with longer duration with standing water as farm-averaged values, though Farm B had a similar duration to Farm A despite of its much higher percolation rate.

Finally, the grain yield associated with the toposequential positions ranged 3.8–6.6 t ha^{-1} across the farms and seasons (Fig. 7). The toposequential positions showed a significant difference in grain yield only in Farm B 2017A and Farm A 2017B, where the upper positions tended to have higher grain yield than did the lower positions. However, the grain yield was not clearly or consistently different among toposequential positions across the farms and seasons.

4. Discussions

4.1. Conventional irrigation management affected by soil property, rainfall, and agronomic factors

This study included three farms with different soil water permeability as seen in the Ks values varying from zero to over 100 mm day^{-1} (Table 1), and we discovered that the conventional irrigation practices were diverse among the farms (Fig. 5). The more frequent irrigation with larger water amounts for individual irrigation events observed in Farm B 2017B can be explained by its highly permeable soil, which was demonstrated by both the Ks and high fluctuation of the field water table depth. In contrast, Farm C 2017B was less frequently irrigated, because the farm soil showed lower permeability than that of the other farms. The soil in Farm A had medium permeability and, therefore, demonstrated an intermediate field water table pattern but was more frequently irrigated than was Farm C.

Naturally, rainfall events would reduce irrigation application. Generally, the number of irrigation was negatively correlated with the seasonal rainfall amount when it is compared between the seasons in each farm, though irrigation B in Farm C exceptional (Table 5). In addition, the reduction in the number of irrigation in relation to the increment in the seasonal rainfall amount was largest in Farm C and lowest in Farm B, indicating the similar effect of the soil water permeability as mentioned above. It is rational that a rainfall event is more influential on irrigation practice in an impermeable soil since the rainfall water would keep the soil saturation for a longer period. Therefore, it was demonstrated that their decision on irrigation application could be affected by rainfall as well as by its interaction with the soil property.

Although soil permeability and rainfall were the main factors affecting irrigation management, the interview with the irrigation managers revealed other agronomic factors that influenced their decision on irrigation. For instance, the intensive irrigation before 30 DAE in Farm C

2017B (Fig. 5) was performed to suppress weeds (personal communication with the irrigation manager of Farm C), in accordance with the recommendation of AWD practice (Richards and Sander, 2014). In addition, depending on the weather, one or two irrigations were applied between the sowing and emergence periods to aid emergence, which were not measured in this study. Furthermore, the flowering period was not a particular focus, as shown in Fig. 5, although rice is known to be susceptible to drought stress especially during that period (Boonjung and Fukai, 1996; Davatgar et al., 2009; Lilley and Fukai, 1994). Therefore, the rice crop was probably exposed to drought stress around the flowering period to some extent under the conventional irrigation management judging from the chart of the field water table. For AWD, -10 kPa soil water potential in the root zone has been reported as the safe threshold for re-irrigation to avoid yield reduction (Bouman and Tuong, 2001), and it is recommended that flooded conditions should be maintained particularly around the flowering period (Richards and Sander, 2014). Thus, protecting rice from exposure to drought stress by allocating additional irrigation water during the flowering period would improve the irrigation efficiency of the target site.

4.2. Water balance of contour-levee irrigation system characterized by large irrigation and runoff

To our knowledge, the water balance of the actual contour-levee irrigation system was revealed for the first time and exhibited different characteristics compared to the AWD practices in flat fields. The absolute values and ratios of each water balance component compared with those reported in previous studies, as well as the whole water balance of the contour-levee irrigation system, are discussed below.

The contour-levee irrigation system exhibited a considerably high total water input of 2539 mm including 1930 mm of irrigation, which accounted for 76% of the total input (Table 6). Previous studies have shown that the total water input including rainfall typically ranged from 600 to 1500 mm and irrigation accounted for 200–1000 mm in AWD practices in lowland, puddled, and transplanted conditions (Belder et al., 2005; Cabangon et al., 2004; de Vries et al., 2010; Sudhir-Yadav et al., 2011; Tabbal et al., 2002). The ratio of irrigation to total water input also varies widely from approximately 10 to up to 100% depending on the amount of seasonal rainfall, but the ratio usually decreases rapidly, following a certain amount of rainfall, typically leading to <50% with rainfall over 500 mm (Cabangon et al., 2004; Lu et al., 2016; Zhang et al., 2012). Focusing on Farm A and Farm C farms, the total water input was mostly similar to that of AWD, but the irrigation water requirement of the contour-levee irrigation system was high even when rainfall was not scarce.

Regarding water outflows, the high runoff ratio that accounted for 40% of the total input was remarkable compared to that of the AWD practices in other regions (Table 6). The average seasonal runoff in this study was much higher than that of AWD. Normally, the runoff of AWD in flat fields is less than 200 mm over a crop cycle (Cabangon et al., 2004; Sudhir-Yadav et al., 2011), although an experiment in Brazil with intermittent irrigation management recorded 215–449 mm (de Avila et al., 2015). The observed high runoff amount was expectedly caused by the sloped conditions and closely agrees with studies conducted in Arkansas and Mississippi in the US, which reported that the contour-levee irrigation system required twice as much or more irrigation water than that required for the zero-grade irrigation system in flat fields (similar to the irrigated lowland system in Asia) (Massey et al., 2014; Smith et al., 2007).

ET is reported to be affected by numerous factors but mainly by climatic conditions, and it ranges from approximately 350–700 mm over the crop cycle (Belder et al., 2005; Lu et al., 2016; Sudhir-Yadav et al., 2011). The ET in in this study (483–571 mm, Table 6) was lower but not much different from that reported in a humid sub-tropical zone in Brazil under intermittent irrigation management (559–627 mm) (de Avila et al., 2015).

The estimated seasonal percolation from the water balance was the highest in Farm B and the lowest in Farm C, which agreed with the soil characteristics of the three farms. The seasonal percolation amount is known to be highly affected by soil permeability (Belder et al., 2007). For instance, an average percolation of 274 mm under AWD was reported in silty clay soil in California, USA (Linquist et al., 2015), 369 mm in clay loam soil in Tuanlin, China (Tan et al., 2013), and 422 mm in sandy loam soil in Jilin, China (Lu et al., 2016). Compared to the above studies, in this study, the estimated percolation amounts of the water balance were relatively higher, which could be attributed to the lack of puddling practice, which significantly reduces percolation (Sudhir-Yadav et al., 2011; Tuong et al., 1994). Farm B, in particular, showed higher percolation than that in the other farms because of its highly permeable soil without puddling and longer irrigation period, which maintained the saturation for a relatively long period despite the soil permeability.

The amount of percolation measured using the percolator was roughly in agreement with the amounts estimated from the water balance in Farm A, underestimated in Farm C, and overestimated in Farm B. For Farm C, some cracks were observed in the field during some periods in the season that could have increased the seasonal percolation amount of the entire field, which did not occur in the percolator. In Farm B, the soil layer immediately below the bottom of the percolator often contained many rocks and, therefore, the water could have percolated more easily than did the water in the entire plot, possibly leading to the higher observed than estimated amount from the balance. Generally, the large variation in the seasonal percolation amount from the balance could have been derived partly from measurement errors in the observation of irrigation and runoff water flows, which likely caused the discrepancy with the observed amounts, to a certain extent. Nevertheless, the magnitude of the relationship of the seasonal percolation amounts among the farms was similar, and the averages across the farms were close between the values of the water balance and those of the percolator, indicating that the components were acceptably balanced.

Finally, overall water balance of contour-levee irrigation system was compared with that of AWD and also of CF (Fig. 6), resulted in remarkably higher irrigation input and runoff water loss.

Since the other components, rainfall, ET, and percolation were not largely different, the high irrigation input was applied mainly to compensate the large runoff water loss. It should be noted that the irrigation and runoff components in contour-levee irrigation system had large variability due to the small sample size as well as to the diverse soil properties and thus investigating further contour-levee irrigation systems is demanded in order to compare the irrigation systems more precisely. Nevertheless, avoiding runoff water loss by revising the irrigation management would essentially contribute to reducing the high irrigation input, leading to improved water use efficiency of the contour-levee irrigation system at the plot scale.

4.3. Insignificant toposequential effects within a plot under contour-levee irrigation system

The observed percolation rates along the toposequence were not clearly different among the positions in this study, but agreed to a certain extent with a lower percolation rate in lower positions reported in the previous studies (Tsubo et al. 2005; 2006). The result showed that although a relatively high variation in the percolation rates occurred among the toposequential positions, a significant and consistent difference was observed only among the farms. The tendency in percolation rates among the farms was coinciding with that in the permeability of the soil shown as Ks in Table 1. Thus, the toposequential effects influenced the percolation rate a little but the soil permeability did much more clearly in this study.

Consequently, the duration with standing water did not show a clear tendency over the toposequence (Table 7). Percolation rates would negatively affect the duration from the perspective of water balance, but did not clearly exhibit such an expected negative correlation. The presence of the intermittent flush irrigation in this study might have mitigated the difference in the duration among the toposequential positions or among the farms. For instance, the relatively long duration in Farm B compared to its considerably high percolation rate can be attributed to the long duration of irrigation itself (Table 5). Under rainfed conditions, disappearance of standing water were often observed was often earlier in the upper positions than in the lower positions (Inthavong et al., 2011; Tsubo et al., 2006), resulting in longer days without standing water (Boling et al., 2008; Tsubo et al., 2006) or lower mean levels of the field water table in the upper positions (Inthavong et al., 2011; Touré et al., 2009; Tsubo et al., 2006), in general. The number of days with standing water has been reported to range from 22 to 44 days with flush irrigation management, depending on the severity of the irrigation threshold and weather in China (Cabangon et al., 2003). The range of duration in the present study (36.3–51.2 days on farm average) was longer than the previous study but still compatible.

The lack of clear toposequential effects on the water dynamics in this study could be explained by the following reasons. First, both the toposequence scale and slope degree were considered as factors determining the extent of toposequential effects, with the scale exerting a higher influence. A steeper slope of over 5% with similar length along the toposequence of up to 100 m did not cause clear toposequential effects in previous studies either (Boling et al., 2008; Oo et al., 2012). On the other hand, toposequential effects were more commonly observed with a longer distance along the toposequence ranging from several hundred meters to kilometers, despite a gentle slope of approximately 1–2%, similar to this study (Boling et al., 2008; Hseu and Chen, 1996; Tsubo et al., 2006). Therefore, with the contour-levee system in gently sloped fields around Ibague, plots of similar scales to those in this study (1–2 ha) are less likely to have toposequential effects, but larger plots of 1 km or more along the toposequence would have significant effects. Second, the location of the fields in this study was relatively far from a river at the bottom of a valley, which might have alleviated toposequential effects on the water dynamics. Typical areas where toposequential differences in water dynamics were reported were located at lower positions in a river valley or close to water sources such as a river or the sea (Homma et al., 2003; Hseu and Chen, 1996; Touré et al., 2009; Yamauchi, 1992;

Worou et al., 2013). In such situations, irrigation water might not adequately drain out of the plot but stay at the lower part of the plots with sediments, and percolation might also be smaller because of a shallow groundwater table.

Ultimately, the grain yield was not significantly affected by the toposequential positions, except for two cases (Farm A 2017B and Farm B 2017A) or did not correspond to the toposequence consistently across the farms and seasons (Fig. 7). This finding disagreed with the previous studies reporting higher yields together with the higher water availability in lower positions (Boling et al., 2008; Samson et al., 2004) but agreed with the insignificant difference in the water dynamics among the toposequential positions in this study. The two cases with significant effects of the toposequence in this study had large seasonal rainfall amounts and resulted in higher grain yields in the upper positions. Tsubo et al. (2006) also partly observed similar higher grain yields in upper positions and attributed them to flooding damages in lower positions. Since well-drained conditions in the contour-levee irrigation system in this study were demonstrated by the high seasonal runoff (Table 6) and the field water table frequently reaching below the soil surface (Fig. 5), such negative effects of excessive water in the lower positions are not likely to have occurred in this study. Nevertheless, observation of the water dynamics focusing on the period between sowing and emergence together with plant emergence rate along the toposequence might provide further clues, since soil water conditions during that period particularly affect crop establishment. In conclusion, clear toposequential effects on water dynamics or on grain yield were not confirmed in this study.

4.4. Implications for whole-farm irrigation management

The medium to large farms in the Central rice growing region in Colombia consist of multiple plots (typically 5–20). Usually, only a few plots are irrigated from the irrigation canal directly, and the remaining plots receive the excess water from adjustment plots slightly higher than the recipient plots.

This plot-to-plot irrigation seems to be the common practice of the contour-levee irrigation system. It is arguable whether the high ratio of runoff water in each plot could be justified in such conventional water management. In fact, long duration is required for each irrigation in the conventional plot-to-plot management (Table 5) and presumably contributed to larger water loss via percolation (Section 4.2). Flexible and precise irrigation management of each plot for the amount and timing of the irrigation could only be possible if each plot was independently connected by an irrigation canal, which is particularly important for the further water saving technologies on a plot scale (Guerra et al., 1998). For example, the sparse irrigation during the flowering period in this study (Section 4.1) cannot be easily overcome using the plot-to-plot irrigation practice. Therefore, it is recommended that irrigation should be individually managed among the plots of the whole farm by minimizing the runoff from each plot to optimally allocate water depending on the crop growth stage in the plot.

5. Conclusion

Aiming at revealing water dynamics of contour-levee irrigation system, field experiments were conducted in three commercial farms in Ibagué, Colombia with different irrigation intervals. The conventional irrigation management in each farm was analyzed and found to be highly affected by soil permeability and rainfall but also by agronomic factors. The result of this analysis indicated that allocating more irrigation water during the flowering period would enhance productivity. Water balance of the contour-levee irrigation system was quantified and resulted in remarkably high irrigation input: it reached an average of 1930 mm, and the considerable water loss via runoff accounted for approximately 40% of the total water input. Duration with standing water and percolation rate were additionally compared along the toposequence but not significantly different or consistent among the farms in this study. This observation was probably due to the relatively small scale of the plots and the large distance between the location and water sources such as rivers or the bottom of inland valleys. Furthermore, clear toposequential effects on the grain yield were not confirmed either. This study elucidated the detailed water dynamics of contour-levee irrigation system at plot scale in commercial farms in Ibagué, Colombia including the characteristics of the conventional irrigation management and the water balance together not accompanied with significant toposequential effects, which have not been reported to date. To improve the irrigation management and thus water use efficiency, individual irrigation management of each plot of the whole farm is recommended by minimizing the runoff from each plot. Furthermore, water should be allocated optimally depending on the crop growth stage in the plot, rather than the currently followed whole-farm plot-to-plot irrigation management over sequential plots.

Acknowledgments

Part of this research was conducted under the Science and Technology Research Partnership for Sustainable Development (SATREPS) Project “Development and Adoption of Latin American Low-input Rice Production System through Genetic Improvement and Advanced Field-management Technologies” supported by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA).

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements, FAO Irrigation and Drainage paper 56. Rome. https://doi.org/10.1016/j.eja.2010.12.001

Battallo, C., Queheille, N., Uraga, R., Gonnet, D., Hill, M., Roel, A., Cantou, G., Martinez, M., Pippolo, D., 2013. Guía De Buenas Prácticas En El Cultivo De Arroz En Uruguay.

Belder, P., Bouman, B.A.M., Spiertz, J.H.J., 2007. Exploring options for water savings in lowland rice using a modelling approach. Agric. Syst. 92, 91–114. https://doi.org/10.1016/j.agsy.2006.03.001

Belder, P., Spiertz, J.H.J., Bouman, B.A.M., Lu, G., Tuong, T.P., 2005. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. F. Crop. Res. 93, 169–185. https://doi.org/10.1016/j.fcr.2004.09.022.

Boling, A.A., Tuong, T.P., Suganda, H., Konboon, Y., Harnpichitvitaya, D., Bouman, B.A.M., Franco, D.T., 2008. The effect of toposequence position on soil properties, hydrology, and yield of rainfed lowland rice in Southeast Asia. F. Crop. Res. 106, 22–33. https://doi.org/10.1016/j.fcr.2007.10.013

Boonjung, H., Fukai, S., 1996. Effects of soil water deficit at different growth stages on rice growth and yield under upland conditions. 2. Phenology, biomass production and yield. F. Crop. Res. 48, 47–55. https://doi.org/10.1016/0378-4290(96)00039-1.

Bouman, B.A.M., Tuong, T.P., 2001. Field water management to save water and increase its productivity in irrigated lowland rice. Agric. Water Manag. 1615, 1–20. https://doi.org/10.1016/S0378-3774(00)00128-1.

Bouman, B.A.M., Feng, L., Tuong, T.P., Lu, G., Wang, H., Feng, Y., 2007. Exploring options to grow rice using less water in northern China using a modelling approach. II. Quantifying yield, water balance components, and water productivity. Agric. Water Manag. 88, 23–33. https://doi.org/10.1016/j.agwat.2006.10.005

Bouman, B.A.M., Lampayan, R.M., 2009. Alternate Wetting Drying (AWD). IRRI Rice Factsheet.

Cabangon, R., Lu, G., Tuong, T.P., Bouman, B.A.M., Feng, Y., Zhichuan, Z., 2003. Irrigation management effects on yield and water productivity of inbred and aerobic rice varieties in Kaifeng, in: Proceedings of the First International Yellow River Forum on River Basin Management. The Yellow River Conservancy Publishing House, Zhengzhou, Henan, China, Vol. 2, pp. 65–76.

Cabangon, R.J., Tuong, T.P., Castillo, E.G., Bao, L.X., Lu, G., Wang, G., Cui, Y., Bouman, B.A.M., Li, Y., Chen, C., Wang, J., 2004. Effect of irrigation method and N-fertilizer management on rice yield, water productivity and nutrient-use efficiencies in typical lowland rice conditions in China. Paddy Water Environ. 2, 195–206. https://doi.org/10.1007/s10333-004-0062-3

Castro-González, M., Lima, A., 2016. Temporal shifts of nitrite reducing communities in a rice field soil in Ibague (Colombia). Agron. Colomb. 34, 82–91. https://doi.org/10.15446/agron.colomb.v34n1.52993

Chirinda, N., Arenas, L., Loaiza, S., Trujillo, C., Katto, M., Chaparro, P., Nuñez, J., Arango, J., Martinez-Baron, D., Loboguerrero, A.M., Lopez-Lavalle, L.A.B., Avila, I., Guzmán, M., Peters, M., Twyman, J., García, M., Serna, L., Escobar, D., Arora, D., Tapasco, J., Mazabel, Lady, Correa, F., Ishitani, M., Silva, M. Da, Graterol, E., Jaramillo, S., Pinto, A., Zuluaga, A., Lozano, N., Byrnes, R., LaHue, G., Alvarez, C., Rao, I., Barahona, R., 2017. Novel technological and management options for accelerating transformational changes in rice and livestock systems. Sustain. 9. https://doi.org/10.3390/su9111891

Davatgar, N., Neishabouri, M.R., Sepaskhah, A.R., Soltani, A., 2009. Physiological and morphological responses of rice (*Oryza sativa* L.) to varying water stress management strategies. Int. J. Plant Prod. 3, 19–32.

de Avila, L.A., Martini, L.F.D., Mezzomo, R.F., Refatti, J.P., Campos, R., Cezimbra, D.M., Machado, S.L.O., Massey, J.H., Carlesso, R., Marchesan, E., 2015. Rice water use efficiency and yield under continuous and intermittent irrigation. Agron. J. 107, 442–448. https://doi.org/10.2134/agronj14.0080

de Vries, M.E., Rodenburg, J., Bado, B.V., Sow, A., Leffelaar, P.A., Giller, K.E., 2010. Rice production with less irrigation water is possible in a Sahelian environment. F. Crop. Res. 116, 154–164. https://doi.org/10.1016/j.fcr.2009.12.006

FEDEARROZ, 2017. Ⅳ CENSO NACIONAL ARROCERO 2016. Bogotá, Colombia. http://www.fedearroz.com.co/doc_economia/Libro%20Censo%20General.pdf

Felipe de Mendiburu, 2017. agricolae: Statistical Procedures for Agricultural Research. R package version 1.2-8. https://CRAN.R-project.org/package=agricolae

Guerra, L.C., Bhuiyan, S.I., Tuong, T.P., Barker, R., 1998. Producing more rice with less water from irrigated systems, IRRI Discussion Paper Series. Manila (Philippines).

Henry, C.G., Hirsh, S.L., Anders, M.M., Vories, E.D., Reba, M.L., Watkins, K.B., Hardke, J.T., 2016. Annual irrigation water use for Arkansas rice production. J. Irrig. Drain. Eng. 142, 1–5. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001068

Homma, K., Horie, T., Shiraiwa, T., Supapoj, N., Matsumoto, N., Kabaki, N., 2003. Toposequential variation in soil fertility and rice productivity of rainfed lowland paddy fields in mini-watershed (Nong) in Northeast Thailand. Plant Prod. Sci. https://doi.org/10.1626/pps.6.147

Hseu, Z., Chen, Z., 1996. Quantifying soil hydromorphology of a rice-growing ultisol toposequence in Taiwan. Soil Sci. Soc. Am. J. 270–278.

Inthavong, T., Fukai, S., Tsubo, M., 2011. Spatial variations in water availability, soil fertility and grain yield in rainfed lowland rice: A case study from Savannakhet Province, Lao PDR. Plant Prod. Sci. 14, 184–195. https://doi.org/10.1626/pps.14.184

Lilley, J.M., Fukai, S., 1994. Effect of timing and severity of water deficit on four diverse rice cultivars III. Phenological development, crop growth and grain yield. F. Crop. Res. 37, 215–223. https://doi.org/10.1016/0378-4290(94)90100-7

Linquist, B., Snyder, R., Anderson, F., Espino, L., Inglese, G., Marras, S., Moratiel, R., Mutters, R., Nicolosi, P., Rejmanek, H., Russo, A., Shapland, T., Song, Z., Swelam, A., Tindula, G., Hill, J., 2015. Water balances and evapotranspiration in water- and dry-seeded rice systems. Irrig. Sci. 33, 375–385. https://doi.org/10.1007/s00271-015-0474-4

Lu, W., Cheng, W., Zhang, Z., Xin, X., Wang, X., 2016. Differences in rice water consumption and yield under four irrigation schedules in central Jilin Province, China. Paddy Water Environ. 14, 473–480. https://doi.org/10.1007/s10333-015-0516-9

Makkink, G.F., 1957. Testing the Penman formula by means of lysimeters. J. Inst. Water Eng. 11, 277–288.

Massey, J.H., Walker, T.W., Anders, M.M., Smith, M.C., Avila, L.A., 2014. Farmer adaptation of intermittent flooding using multiple-inlet rice irrigation in Mississippi. Agric. Water Manag. 146, 297–304. https://doi.org/10.1016/j.agwat.2014.08.023

Marano, R.P., Filippi, R.A., 2015. Water Footprint in paddy rice systems. Its determination in the provinces of Santa Fe and Entre Ríos, Argentina. Ecol. Indic. 56, 229–236. http://doi.org/10.1016/j.ecolind.2015.03.027

McGonigle, D.F., Burke, S.P., Collins, A.L., Gartner, R., Haft, M.R., Harris, R.C., Haygarth, P.M., Hedges, M.C., Hiscock, K.M., Lovett, A.A., 2014. Developing demonstration test catchments as a platform for transdisciplinary land management research in England and Wales. Environ. Sci. Process. Impact. 16, 1618–1628. http://doi.org/10.1039/c3em00658a

McLean, J., Hardy, B., Hettel, G., 2013. Rice Almanac, 4th edition, IRRI, Los Baños, Philippines. https://doi.org/10.1093/aob/mcg189

Nevada State Engineer's Office, 1986. Common methods of measuring water as practiced in Western States. State of Nevada State Engineer's Office, Carson City, NV, USA.

Oo, A.Z., Kimura, S.D., Win, K.T., Huu, N.X., Nguyen, L., Cadisch, G., 2012. Effect of toposequence position on soil properties and crop yield of paddy rice in Northern Mountainous Region, Vietnam. JIFS 9, 59–65.

Pineda, D., Montaña, H., 2015. Principios Básicos Para El Manejo Eficiente Del Agua En El Cultivo De Arroz En Colombia. FEDEARROZ, Bogotá, Colombia.

Pittelkow, C.M., Zorrilla, G., Terra, J., Riccetto, S., Macedo, I., Bonilla, C., Roel, A., 2016. Sustainability of rice intensification in Uruguay from 1993 to 2013. Glob. Food Sec. 9, 10–18. http://doi.org/10.1016/j.gfs.2016.05.003

R Core Team 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield trends are insufficient to double global crop production by 2050. PLoS ONE 8(6): e66428. http://doi.org/10.1371/journal.pone.0066428

Richards, M., Sander, B.O., 2014. Alternate wetting and drying in irrigated rice - Implementation guidance for policymakers and investors. Pract. Br. Clim. Agric.

Samson, B.K., Ali, A., Rashid, M.A., Mazid, M.A., Wade, L.J., 2004. Topographic position influences water availability in rainfed lowland rice at Rajshahi, Northwest Bangladesh. Plant Prod. Sci. 7, 101–103. https://doi.org/10.1626/pps.7.101

Smith, M.C., Massey, J.H., Branson, J., Epting, J.W., Pennington, D., Tacker, P.L., Thomas, J., Vories, E.D., Wilson, C., 2007. Water use estimates for various rice production systems in Mississippi and Arkansas. Irrig. Sci. 25, 141–147. https://doi.org/10.1007/s00271-006-0041-0

Sudhir-Yadav, Humphreys, E., Kukal, S.S., Gill, G., Rangarajan, R., 2011. Effect of water management on dry seeded and puddled transplanted rice. Part 2: Water balance and water productivity. F. Crop. Res. 120, 123–132. https://doi.org/10.1016/j.fcr.2010.09.003

Tabbal, D.F., Bouman, B.A.M., Bhuiyan, S.I., Sibayan, E.B., Sattar, M.A., 2002. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric. Water Manag. 56, 93–112. https://doi.org/10.1016/S0378-3774(02)00007-0

Takahashi, T., Harris, P., Blackwell, M.S.A., Cardenas, L.M., Collins, A.L., Dungait, J.A.J., Hawkins, J.M.B., Misselbrook, T.H., McAuliffe, G.A., McFadzean, J.N., Murray, P.J., Orr, R.J., Rivero, M.J., Wu, L., Lee, M.R.F., 2018. Roles of instrumented farm-scale trials in trade-off assessments of pasture-based ruminant production systems. Animal 12, 1766–1776. http://doi.org/10.1017/S1751731118000502

Takamiya, K., and Tsutsui, H., 2000. Rice and irrigation in Latin America. Rural Environ. Eng. 38, 5–19.

Tan, X., Shao, D., Liu, H., Yang, F., Xiao, C., Yang, H., 2013. Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. Paddy Water Environ. 11, 381–395. https://doi.org/10.1007/s10333-012-0328-0

Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K., Kiepe, P., 2009. Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. F. Crop. Res. 114, 304–310. https://doi.org/10.1016/j.fcr.2009.08.015

Tsubo, M., Basnayake, J., Fukai, S., Sihathep, V., Siyavong, P., Sipaseuth, Chanphengsay, M., 2006. Toposequential effects on water balance and productivity in rainfed lowland rice ecosystem in Southern Laos. F. Crop. Res. 97, 209–220. https://doi.org/10.1016/j.fcr.2005.10.004

Tsubo, M., Fukai, S., Basnayake, J., To, P.T., Bouman, B., Harnpichitvitaya, D., 2005. Estimating percolation and lateral water flow on sloping land in rainfed lowland rice ecosystem. Plant Prod. Sci. 8, 354–357. https://doi.org/10.1626/pps.8.354

Tuong, T.P., Wopereis, M.C.S., Marquez, J.A., Kropff, M.J., 1994. Mechanisms and control of percolation losses in irrigated puddled rice fields. Soil Sci. Soc. am. J. 58, 1794–1803. https://doi.org/10.2136/sssaj1994.03615995005800060031x.

Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., Ewert, F., 2013. Spatial and temporal variation in yield of rainfed lowland rice in inland valley as affected by fertilizer application and bunding in North-West Benin. Agric. Water Manag. 126, 119–124. https://doi.org/10.1016/j.agwat.2013.04.007.

Yamauchi, M., 1992. Growth of rice plants in soils of toposequence in Nigeria. Jpn. J. Trop. Agr. 36, 94–98.

Zhang, Y., Tang, Q., Peng, S., Xing, D., Qin, J., Laza, R.C., Punzalan, B.R., 2012. Water use efficiency and physiological response of rice cultivars under alternate wetting and drying conditions. Sci. World J. 2012, 10 pages. https://doi.org/10.1100/2012/287907

Zorrilla, G., Martínez, C., Berrío, L., Corredor, E., Carmona, L., Pulver, E., 2012. Improving rice production systems in Latin America and the Caribbean, in: Hershey, Clair H. (Ed.), Eco-Efficiency: from vision to reality. International Center for Tropical Agriculture (CIAT), Cali, pp. 161–170.

Figure legends

Fig. 1. Picture of contour-levee irrigation system with arrows showing the constructed levees and flush irrigation is applied from the inlet at the upper side (right-hand side in the picture)

Fig. 2. Observed weather data from 2017A to 2017B in Farm B as a representative

Fig. 3. Parshall flume (left) and water level sensor (right) for measuring irrigation and runoff

Fig. 4. Installation of equipment in field

Fig. 5. Conventional irrigation management (irrigation B, blue bar), rainfall (red bar), and field water table across toposequence (green lines) over crop cycles (S: sowing, E: emergence, F: flowering, H: harvest) in Farm A (A), Farm B (B), and Farm C (C) in 2017B

Fig. 6. Water balance compared among irrigation systems (AWD, CF, and Contour-levee [Contour]) regarding water inputs (Rainfall and Irrigation in upper side of the figure) and outputs (Runoff, ET, and Percolation in lower side of the figure)

Fig. 7. Grain yield across toposequential positions in Farm A–C in 2017A and 2017B

Tables

Table 1 Summary of analyzed soil property in Farm A–C sampled before sowing in 2017A

Table 2 Sowing dates and phenology in Farm A–C in 2017A and 2017B

Table 3 Irrigation treatments as three intervals between irrigations (short[A], conventional[B], and long[C]) for each farm

Table 4 Conventional N fertilizer management in Farm A–C

Table 5 Observed irrigation amount, duration, and number of irrigation events in Farm A–C in 2017A and 2017B

Table 6 Seasonal water balance components in Irrigation A–C on Farm A–C in 2017A and 2017B

Table 7 Observed percolation rates and duration with standing water across the toposequential positions in Farm A–C in 2017B

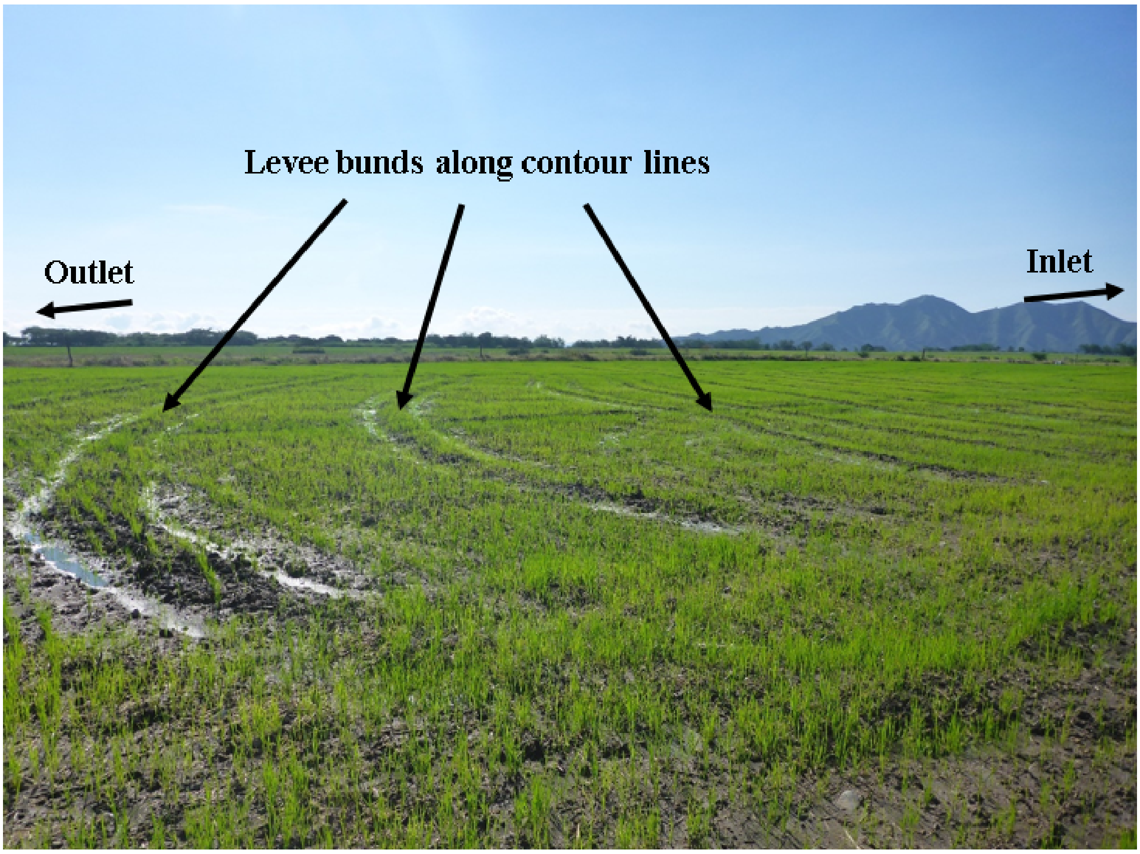

Fig. 1

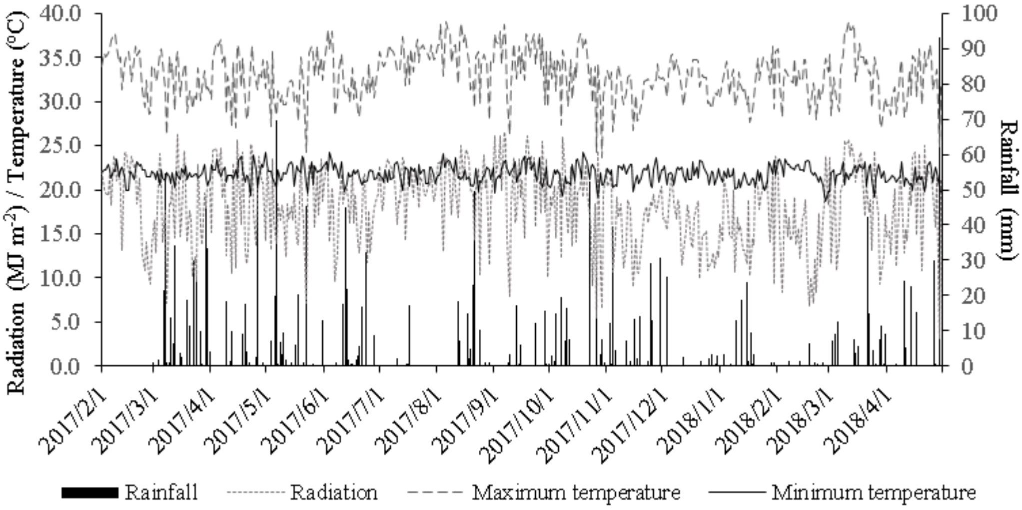
Radiation (MJ m-2) / Temperature (°C)
Rainfall (mm)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
100
90
80
70
60
50
40
30
20
10
0
2017/2/1
2017/3/1
2017/4/1
2017/5/1
2017/6/1
2017/7/1
2017/8/1
2017/9/1
2017/10/1
2017/11/1
2017/12/1
2018/1/1
2018/2/1
2018/3/1
2018/4/1
Rainfall
Radiation
Maximum temperature
Minimum temperature

Fig. 2.

Fig. 3

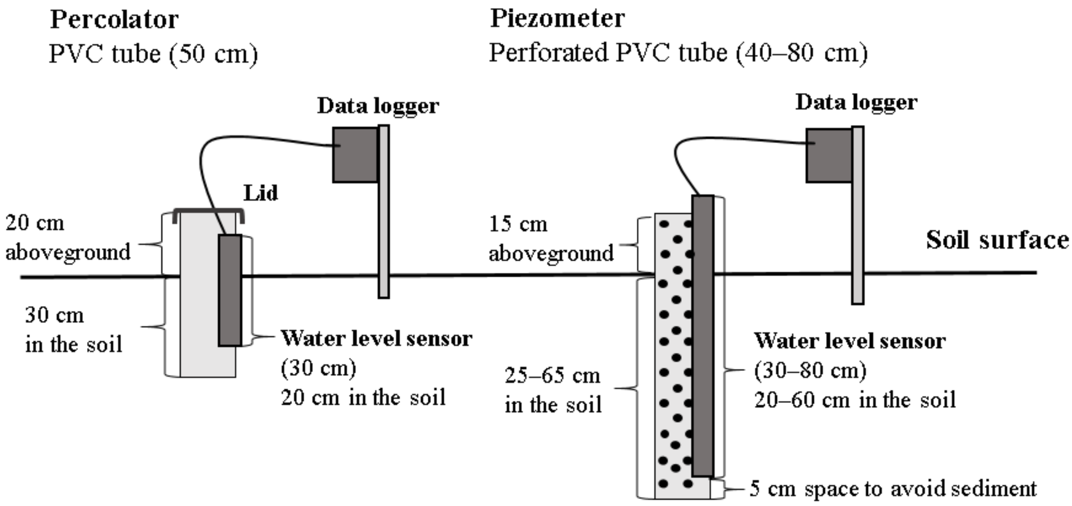
Percolator
PVC tube (50 cm)
Piezometer
Perforated PVC tube (40–80 cm)
Data logger
Data logger
Lid
20 cm
aboveground
30 cm
in the soil
Water level sensor
(30 cm)
20 cm in the soil
15 cm
aboveground
Soil surface
25–65 cm
in the soil
Water level sensor
(30–80 cm)
20–60 cm in the soil
5 cm space to avoid sediment

Fig. 4


(A) Farm A 2017B
S
E
F
H
Field water table (cm)
Irrigation / rainfall (mm)
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
200
180
160
140
120
100
80
60
40
20
0
2017/9/14
2017/9/29
2017/10/14
2017/10/29
2017/11/13
2017/11/28
2017/12/13
2017/12/28
2018/1/12
2018/1/27
Field water table
Rainfall
Irrigation
Upper (T1)
Middle (T2)
Lower (T4)
(B) Farm B 2017B
S
E
F
H
Field water table (cm)
Irrigation/rainfall (mm)
2017/12/7
2017/12/22
2018/1/6
2018/1/21
2018/2/5
2018/2/20
2018/3/7
2018/3/22
2018/4/6
2018/4/21
Field water table
Rainfall
Irrigation
Upper (T1)
Middle (T2)
Lower (T4)
(C) Farm C 2017B
S
E
F
H
Field water table (cm)
Irrigation/rainfall (mm)
2017/11/7
2017/11/22
2017/12/7
2017/12/22
2018/1/6
2018/1/21
2018/2/5
2018/2/20
2018/3/7
2018/3/22
2018/4/6
Field water table
Rainfall
Irrigation
Upper (T1)
Middle (T2)
Lower (T4)

Fig. 5

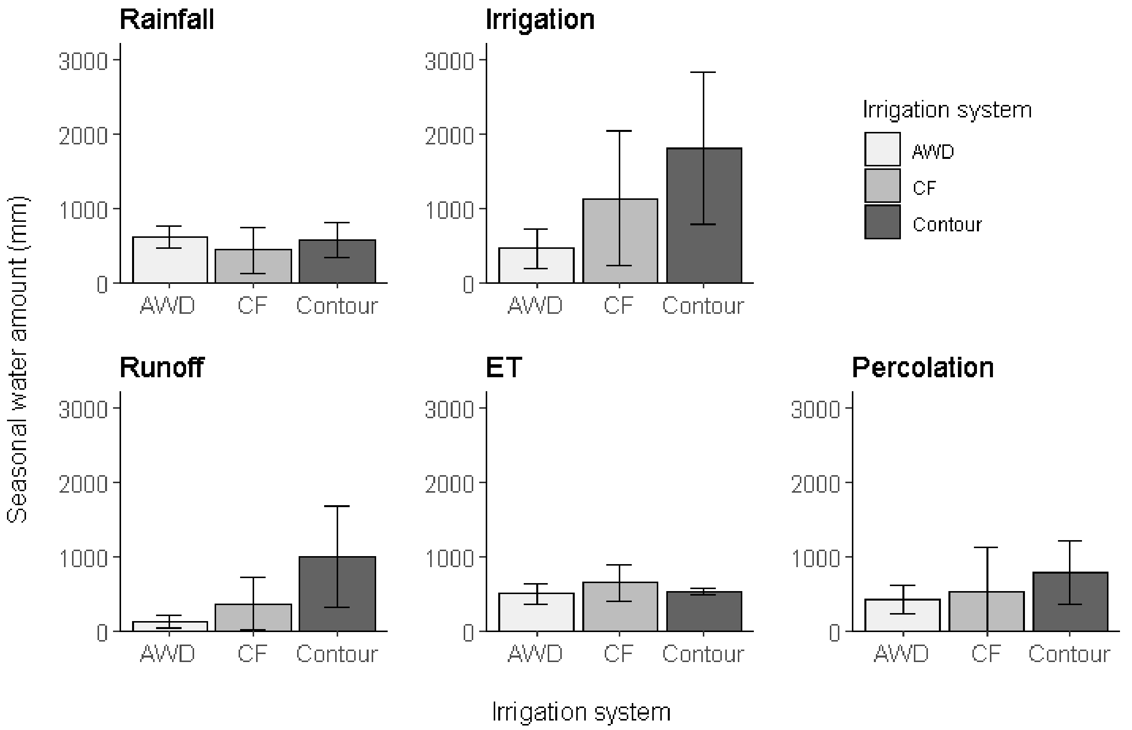

Fig. 6

* Data for AWD and CF was retrieved from Lu et al. (2016); de Avlia et al. (2015); Linquist et al. (2015); Tan et al. (2013); Sudhir-Yadav et al. (2011); Cabangon et al. (2004)

** Percolation from balance (Table 6) was used for the average seasonal percolation of Contour

*** Error bars indicate standard deviation (sample sizes are 24, 22, and 16 for AWD, CF, and Contour)

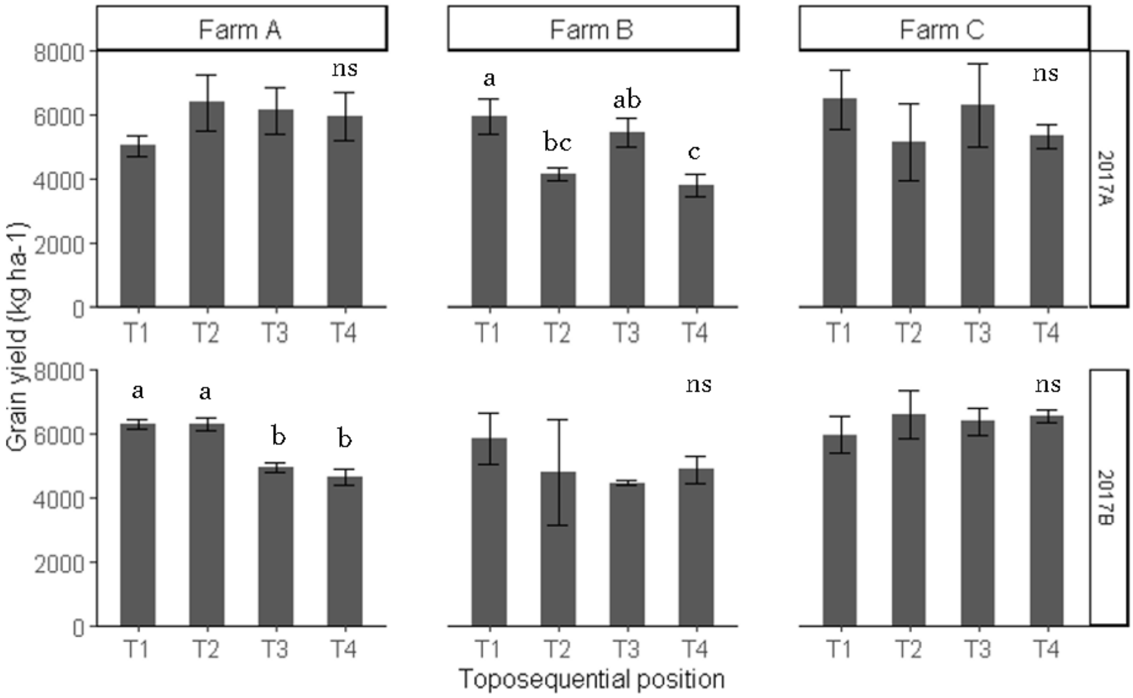

Fig. 7

*different letters in each graph indicate significant difference as determined by LSD test

Table 1

Farm	Depth (cm)	Bulk density (g cm^{-3})	Soil volumetric water content (mm mm^{-1})			Saturated hydraulic conductivity (mm day^{-1})	Soil organic matter (g kg^{-1})	Inorganic nitrogen (mg kg^{-1})
			Permanent wilting point	Field capacity	Saturation			
Farm A	0-15	1.57	0.306	0.351	0.416	0.0	23.5	16.6
	15-30	1.50	0.377	0.408	0.482	7.2	9.6	7.3
	30-45	1.49	0.376	0.409	0.459	0.0	2.4	5.7
	45-60	1.46	0.354	0.403	0.470	4.8	1.3	6.4
	60-85	1.41	0.322	0.385	0.468	0.0	1.2	5.2
	85-110	1.44	0.330	0.394	0.444	0.0	1.0	4.9
Farm B	0-15	1.42	0.257	0.321	0.447	111.7	25.6	10.0
	15-30	1.45	0.293	0.379	0.447	62.2	16.3	9.4
	30-45	1.59	0.258	0.322	0.395	49.9	13.3	9.6
	45-60	1.44	0.316	0.382	0.451	358.1	9.6	5.2
	60-85	1.12	0.425	0.519	0.583	167.7	9.6	7.4
	85-110	1.16	0.406	0.499	0.566	2.4	7.9	4.6
Farm C	0-15	1.69	0.274	0.319	0.370	0.0	19.9	10.8
	15-30	1.59	0.326	0.362	0.433	0.0	11.8	8.8
	30-45	1.47	0.374	0.408	0.458	0.0	9.7	7.7
	45-60	1.51	0.350	0.379	0.443	0.0	8.2	13.7
	60-85	1.48	0.373	0.397	0.476	0.0	2.4	14.4
	85-110	1.38	0.395	0.427	0.486	0.0	2.2	6.1

Table 2

Farm	Season	Sowing	Emergence	Flowering	Harvest
Farm A	2017A	14-Feb-17	2-Mar-17	31-May-17	6-Jul-17
	2017B	19-Sep-17	1-Oct-17	28-Dec-17	30-Jan-18
Farm B	2017A	2-Feb-17	22-Feb-17	31-May-17	4-Jul-17
	2017B	12-Dec-17	28-Dec-17	28-Mar-18	25-Apr-18
Farm C	2017A	20-Apr-17	28-Apr-17	2-Aug-17	6-Sep-17
	2017B	14-Nov-17	24-Nov-17	26-Feb-18	2-Apr-18

Table 3

Farm	Irrigation interval (days)		
	A (short)	B (conventional)	C (long)
Farm A	3	5	7
Farm B	2	4	6
Farm C	4	7	10

Table 3

Farm	Nitrogen application (kg ha^{-1})						
	Basal (at sowing)	**1st (15 DAE)**	**2nd (25 DAE)**	**3rd (35 DAE)**	**4th (55 DAE)**	**5th (70 DAE)**	**Total**
Farm A	12	40	56	34	34	23	199
Farm B	12	50	50	50	46	23	231
Farm C	12	40	50	50	46	24	222

Table 5

Farm	Season	Rainfall (mm)	Irrigation treatment	Irrigation amount (mm)			Duration of irrigation (hour)			No. of irrigation events
				Average	SE	Season total	Average	SE	Season total	
Farm A	**2017A**	**705**	**A**	53.3	5.1	1608	5.9	0.5	174	30
			B	43.8	4.3	1031	5.6	0.5	128	23
			C	44.6	4.6	956	6.1	0.6	133	21
	2017B	**931**	**A**	84.3	8.4	1436	7.2	0.7	116	17
			B	52.9	5.3	907	7.2	0.6	112	17
			C	31.1	3.0	468	5.9	0.6	89	15
Farm B	**2017A**	**802**	**A**	86.9	7.3	2961	12.3	1.0	432	34
			B	86.1	7.9	2154	10.8	0.9	272	25
			C	147.5	12.8	3835	11.4	1.0	297	26
	2017B	**293**	**A**	53.2	4.9	2408	10.2	1.0	503	45
			B	70.6	6.1	2838	10.2	0.9	408	40
			C	119.8	12.3	3833	9.3	0.9	278	32
Farm C	**2017A**	**407**	**A**	71.5	7.3	2727	10.0	0.9	383	38
			B	106.4	12.9	2875	8.5	0.8	223	27
			C	96.3	13.4	1931	9.0	1.0	181	20
	2017B	**518**	**A**	27.0	2.5	732	10.6	0.9	288	27
			B	45.0	4.9	1265	11.5	1.0	322	28
			C	85.6	10.6	772	13.9	1.3	125	9

Table 6

Farm	Season	Irrigation Treatment	Rainfall		Irrigation		Total input	Runoff		ET		Percolation from balance		Percolation observed (SE)
			(mm)	(%)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)
Farm A	**2017A**	**A**	705	30	1608	70	2313	982	42					
		B	705	41	1031	59	1736	537	31					
		C	705	42	956	58	1661	547	33					
	2017B	**A**	931	39	1436	61	2366	648	27	542	23	1176	50	
		B	931	51	907	49	1837	709	39	542	30	586	32	618 (67)
		C	931	67	468	33	1399	227	16	542	39	630	45	
Farm B	**2017A**	**A**	802	21	2961	79	3764	2610	69					
		B	802	27	2154	73	2956	3020	102					
		C	802	17	3835	83	4637	5104	110					
	2017B	**A**	293	11	2408	89	2701	1255	46	571	21	875	32	
		B	293	9	2834	91	3128	1857	59	571	18	700	22	2026 (316)
		C	293	7	3833	93	4126	1843	45	571	14	1712	41	
Farm C	**2017A**	**A**	407	13	2727	87	3134	1025	33					
		B	407	12	2875	88	3282	1814	55					
		C	407	17	1931	83	2338	658	28					
	2017B	**A**	518	41	732	59	1250	393	31	483	39	373	30	
		B	518	29	1265	71	1782	563	32	483	27	736	41	117 (43)

	C	518	40	772	60	1289	485	38	483	37	322	25	
Total	**Average**	609	24	1930	76	2539	1009	40	532	21	790	31	920
	SE	54	4	252	4	236	170	3	13	3	143	3	571

* Values in the cells highlighted by grey contained the cut-in flows and were overestimated

** Percentage is in comparison with the total water input

Table 7

Farm	Total days observed	Percolation rate (mm day^{-1})			Duration with standing water (days)		
		Toposequence		Farm ave.	Toposequence		Farm ave.
Farm A	**118**	**Upper**	12.6		**Upper**	59.9	
		Middle	27.6	16.7 **b**	**Middle**	1.6	36.6
		Lower	10.0		**Lower**	48.4	
Farm B	**111**	**Upper**	94.2		**Upper**	25.1	
		Middle	57.4	62.8 **a**	**Middle**	36.0	36.3
		Lower	36.9		**Lower**	47.7	
Farm C	**101**	**Upper**	1.7		**Upper**	29.2	
		Middle	4.8	2.3 **b**	**Middle**	89.2	51.2
		Lower	0.5		**Lower**	35.0	
ANOVA	**Factor**		**F-value**			**F-value**	
	Toposequence		1.07^{ns}			0.02^{ns}	
	Farm		9.80*			0.20^{ns}	

*different letters attached to the values in columns indicate significant difference as determined by LSD test

*P < 0.05, **P < 0.01, ***P < 0.0001; ns, not significant.