Estimating Soil Water Contents from Field Water Tables for Potential Rice Irrigation Criteria under Contour-Levee Irrigation Systems

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Contour-levee irrigation systems are commonly used in rice cultivation in Latin American and the Caribbean countries, but research-based criteria for irrigation timing have not yet been determined under field conditions. In this study, we determined the relationship between soil volumetric water content (SWC) and field water table (FWT) for potential use in developing practical irrigation criteria based on FWT. Field experiments were conducted at four farms in Ibagué, Colombia from 2017 to 2018. The SWC at different soil depths and the FWT were constantly measured over the crop cycle using soil moisture sensors and piezometers with water level sensors, respectively. The resulting relationships were fitted with linear, plateau models and validated with satisfactory prediction performances. The FWT at actual irrigation timings was observed and compared with the FWT at field capacity at 10 cm soil depth (reference FWT) using the validated relationship. The observed range of threshold FTWs (~46.2 to ~9.2 cm) was comparable to the reference FWTs except one field (~21.4 to ~12.9 cm). Although developing practical irrigation criteria as FWT still requires thresholds of SWC under a target contour-levee irrigation system, this study demonstrated the relationships between FWT and SWC in fields in Colombia.

Keywords: contour-levee irrigation, farm management, field water level, soil water content, water-use efficiency

INTRODUCTION

Rice is a very important food crop, providing 19% of global human per capita energy (McLean et al., 2013). However, it is a highly water-demanding crop, and the total water input to rice fields in a cropping season is up to 2–3 times more than that for other cereals. Therefore various water-saving rice cultivation systems such as saturated soil culture, where soil is maintained at saturated water conditions, and alternate drying and wetting (AWD), where flooded conditions and semi-dried conditions were alternately managed by the intermittent irrigation, have been developed and adopted by farmers in regions where fresh water is scarce (Tabbal et al., 2002).

Latin American and the Caribbean countries began engaging in rice cultivation relatively later than Asian countries, but its production and consumption has grown rapidly. The region’s annual rice consumption per capita was about 9 kg of milled rice in 1924–28 but increased to 30 kg in 2008–10 (McLean et al., 2013). In response to this rising demand, rice production in the region has increased remarkably from under 7,986,000 t in 1961 to almost 28,092,000 t in 2009 (Zorrilla et al., 2012) and expected to rise accompanied with the annual yield increase by around 2% by 2050 (Ray et al., 2013). In the region, contour-levee irrigation systems are a common land-management and irrigation practice for lowland rice cultivation in sloped fields, as shown in Fig. 1. The farmers construct levees along contour to hold irrigated water within the plot (Pineda and Montaña, 2015). Irrigation begins after sowing and is intermittently applied from an inlet at the highest side of the plot, from which it flows across the plot and drains through an outlet at the lowest side. These levees help hold irrigation water to a certain extent, but a significant amount is lost via runoff through the outlet due to the fields’ overall slope. Although the water budget of these systems has not yet been determined, sloped contour-levee fields were shown to consume at least double the irrigation water of flat rice fields in the United States (Smith et al., 2007; Massey et al., 2014). Thus, more efficient irrigation practices are required in contour-levee irrigation systems to reduce water losses via runoff.

Other than the details of contour levee construction, the intermittent irrigation practices used in the contour-levee irrigation system are similar to the AWD irrigation method developed by the International Rice Research Institute (IRRI) and applied to irrigated lowlands in many Asian countries as a water-conservation measure for lowland rice production (Bouman and Lampayan, 2009). In
this approach, irrigation is applied when the field water table (FWT) is reduced to between −15 and −20 cm depth and discontinued when the water table rises to 5 cm above the soil surface; this is monitored using perforated plastic or bamboo tubes (typically 30 cm long with a 15 cm diameter) installed in the field (Richards and Sander, 2014). However, the AWD irrigation threshold should be adjusted depending on soil type and other conditions (Bouman and Lampayan, 2009).

The safest and most effective threshold for AWD irrigation has been tested and discussed in many agronomic studies. Sudhir-Yadav et al. (2011) examined AWD with soil water potential thresholds based on soil matric water potential at minimum −70 kPa under clay loam soil and observed significant yield reductions only at −40 kPa. Similarly, Feng et al. (2007) conducted flush irrigation at −10, −30, and −70 kPa and observed clearly lower yields in the treatment at −70 kPa. Lampayan et al. (2015) compared water table thresholds of 15, 25, and 30 cm below the soil surface under clay soil conditions with both shallow and deep groundwater tables in the Philippines. No significant differences in grain yield were confirmed with soil water potential mostly higher than −30 kPa, even though the deeper threshold produced consistently lower yields. Bouman and Tuong (2001) summarized previous AWD studies and reported that soil matric water potential thresholds of −10 to −30 kPa at 10–20 cm soil depth would prevent large yield reductions. Yang et al. (2017) suggested a moderate AWD threshold based on previous research, in which soil matric water potential higher than −20 kPa and a FWT ranging from 8–25 cm below the soil surface did not cause significant yield reductions. Overall, an AWD threshold of higher than −30 kPa of soil matric water potential at a soil depth of 10–20 cm (“safe AWD” in this paper) can be expected to avoid significant yield reductions, although the corresponding FWT varies among different studies.

In contrast to AWD practices, proper irrigation criteria have yet to be standardized for the intermittent flush irrigation used with the contour-levee system in Latin America, and the Caribbean region. Even though it is recommended by National Federation of Rice Producers (Spanish acronym FEDEARROZ, 2015) in Colombia for example that irrigation should maintain soil saturation levels, in practice, managers apply irrigation by visual judgement alone based on the apparent dryness of the soil surface. In order to manage irrigation more efficiently, practical irrigation criteria based on a site-specific FWT can be adopted in a similar manner as AWD in Asia using the safe-AWD threshold (depending on local soils). The soil matric water potential can be calculated (using the soil water retention curve) from soil volumetric water content (SWC), which can be measured directly using field sensors. Thus, determining the local relationships between FWT and SWC would enable the establishment of proper irrigation criteria. When adjusted for the contour-levee irrigation system in the region, this approach could be easily adopted, helping rice farmers manage irrigation more efficiently. Thus, in this study we estimated SWC at different soil depths using actual FWTs using farmers’ field conditions in the central rice growing region of Colombia as an example, observed FWTs at actual irrigation timings in the farms with the contour-levee irrigation system, and compared them with reference FWTs corresponding to safe AWD practices in Asia derived by the estimated relationships.

MATERIALS AND METHODS

Study area

The experiments were conducted from August 2017 to April 2018 at four farms in rural parts of Ibagué Municipality in the Department of Tolima: Farm A (4°22′N, 75°09′W), Farm B (4°19′N, 75°04′W), Farm C (4°25′N, 75°09′W), and Farm D (4°22′N, 75°05′W). In the municipality spreads along mountain slopes at a central altitude of 1,285 m. Annual rainfall averages 1,691 mm with a bimodal distribution. Annual average daily mean, maximum, and minimum temperatures are 24.0, 28.8, and 19.1 °C, respectively. Rice fields in the region are generally not flat; those of the targeted farms sloped at about 2%. The area of the plot for this study in each farm ranged approximately from 1 to 2 ha. Typical agricultural soil in the region is characterized by moderate levels of organic matter, low levels of phosphorous, nitrogen, and pH, and high natural fertility due to alluvial fan sediments (Castro-González and Lima, 2016).

Soil analysis

We took intact soil samples from a soil core (100 cm³) at the middle depth of the 0–15 cm soil layers, with two replications, near the center of each farm. The soil texture was analyzed using the hydrometer method (texture) and classified based on the soil texture triangle (Ditzler et al., 2017). In addition, the samples were analyzed by the constant head permeability test (saturated hydraulic conductivity) and the pressure chamber method (volumetric water content at different water potential); results are given in Table 1.

Cultivation information

Popular rice varieties in this region, Fedearroz60 was used in Farm A, Farm B, and Farm C as well as Fedearroz67 in Farm D. In the region of the study area, rice is typically cultivated twice a year before the rainy
seasons. The sowing dates of the target plots in this study were 19 Sept., 12 Dec., 14 Nov., and 12 July in 2017 in Farm A, Farm B, Farm C, and Farm D respectively. Rice seeds were 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 for the entire plot including the levee bunds. The seeding was performed at 17 cm between rows and 12 kg N ha$^{-1}$ basal fertilizer application. Although the weather conditions matter, the conventional irrigation management was principally based on the interval days between irrigations, which were 4 days in Farm B, 5 days in Farm A and Farm D, and 7 days in Farm C according to the local farmers. Additional N fertilizer was applied by broadcasting with five splits and the total N input ranged 200 to 230 kg ha$^{-1}$ among the farms. As a result, the grain yield on a dry weight basis was 4.7, 5.2, 5.4, and 4.5 t ha$^{-1}$ in Farm A, Farm B, Farm C, and Farm D for the season of this study.

Measurement of field water table and soil water content

Hydrological variables, SWC and FWT were measured at a representative point halfway between the contour levees around the center of each farm over the crop cycle. To measure the SWC, we used moisture sensors (EC-5, Decagon Devices, Inc., Washington, USA) installed in the field at 5, 10, and 20 cm soils depth with a 10-min recording interval. To measure the FWT, we installed perforated PVC tubes (basic piezometers) 6 cm in diameter and 40–80 cm long depending on local conditions. A ruler-shaped water level sensor (eTape Liquid Level Sensor, Milone Technologies, New Jersey, USA) inside each of these tubes recorded the FWT with a 10-min recording interval. All hydrological measurement equipment was installed within a 50-cm radius (Fig. 2). Our methods followed those of Tsobo et al. (2005) except for the choice of sensors. Equipment installation was conducted after crop establishment (a few weeks after rice emergence) and the recording continued until harvest.

Estimation of the relationship between field water table and soil water content

To establish the relationship between FWT and SWC over each farm’s crop cycle, we divided the data equally into calibration and validation batches. For calibration, the relationships between SWC and the FWT were fitted to the following linear-plateau equation for each depth by non-linear regression (“nls” function in R):

$$SWC = A + B \times (FWT - C)$$

where $A$ is the upper limit of the SWC (the value at the plateau), $B$ is the slope of the linear curve, and $C$ is the threshold of the FWT before a reduction in the SWC (the threshold between the plateau and the linear curve). For model fitting, the observed data below the lower limit of the water level sensor in the piezometer were excluded.

Validation was conducted by graphical comparison of the SWC values and several statistical indicators, principally following the hydrological model evaluation by Moriasi et al. (2007). First, we plotted the observed and estimated SWC over the second half of the crop season,
then calculated the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR) as indices, along with the ratio of the root mean square error to the average of measured data (RRMSE, %). All the statistical analysis was conducted using the statistical software R version 3.4.1 (R Core Team, 2017).

**Observation of the current farmers’ irrigation thresholds and reference field water tables**

The current farmers’ irrigation criteria were quantified as the threshold of the FWT. The same water level sensors used as soil piezometers were also installed in the irrigation canals of each farm, where they recorded the timing of irrigation events as large increases in the canal’s water table. Then, the corresponding FWT just before irrigation events was manually sampled from the record of the data logger. Average and standard deviation (SD) of the sampled FWTs were calculated for each farm as the current farmers’ irrigation threshold.

We set the reference FWT based on the SWC at field capacity based on the soil analysis (equivalent to −33 kPa of soil matric water potential, Table 1), following the safe-AWD practice defined above. The fitted relationship at 10 cm soil depth was used to estimate the corresponding FWT, following previous research and reflecting the actual root zone existing in the soil shallower than 20 cm.

**RESULTS AND DISCUSSION**

**Relationship between field water table and soil water content at different depths**

The calibrated relationship between the FWT and the SWC fitted well with the linear-plateau model, with distinctive parameters for all farms’ soil depths, although the observations generally had high variation around the fitted lines (Fig. 3). Some outliers were observed at Farm C (Fig. 3c), but as the other data points were far more numerous, the curve fitting was scarcely affected. As for validation, the estimated SWC agreed well with the observed SWC without any unusual patterns in the predicted performance over the crop cycle, indicating that the estimated relationships can be used throughout the season.

Of the estimated model parameters, A (upper limit of the SWC) was generally higher at Farm C but did not have a clear relationship with depth (Table 2). Compared with the SWC at saturation based on the soil analysis, the estimated upper limits were lower at Farm A and Farm B, but higher at Farm C and Farm D (Table 1), partly because the regression estimated these parameters as the middle of the values around the upper limit to reduce error (Fig. 3). This discrepancy could also be attributed to spatial variations in soil properties between farms and to measurement errors.

The slope of the fitted curve for parameter B also did not exhibit a clear tendency among the soil depths, though Farm B had relatively high values. Parameter C, the threshold of the FWT, where the SWC starts decreasing, decreased in deeper soil layers, especially at 20 cm soil depth. This clearly reflects the longer saturation period in lower soil layers during drying. The estimated thresholds were relatively low at Farm A and Farm B but did not obviously correspond with the soil texture among the farms (Table 1).

According to the criteria for evaluating indices of model prediction performance suggested by Moriasi et al. (2007), all PBIAS values in this study were very good (<10%), NSE and RSR were very good or good (>0.65 and <0.6, respectively) at Farm A and Farm B, and some NSE and RSR values at Farm C and Farm D were not satisfactory (<0.5 and >0.7, respectively) (Table 3). Nevertheless, the estimated relationships at 10 cm soil depth at all four farms had at least satisfactory values for the three indices. The RRMSE values were generally lower than 10%, also indicating good model performance considering that prior rice cultivation modeling studies attempting to simulate soil water tension via soil water conditions generally produced RRMSE values over 50%, often over 100% (Belder et al., 2007; Feng et al., 2007; Sudhir-Yadav et al., 2012). One reason for the errors in validation is the lower limit of the water level sensors in the piezometers: especially at Farm B, the FWT often dropped below the water table sensor’s lower limit due to the high soil water permeability, resulting in discrepancies between the estimated and observed SWC (Fig. 3b). Installation of longer PVC tubes and water level sensors could have resulted in better validation performance, but the soil conditions at Farm B (abundant rocks in deeper soil layers) did not allow for this.

Overall, the relationship between FWT and SWC was satisfactorily estimated and validated for each farm at each soil depth, although the differences in soil characteristics between farms were not clearly reflected in these relationships. The estimated relationships can be used to establish irrigation criteria with regard to the FWT to target a particular SWC or matric water potential.

**Observed field water tables of farmers’ irrigation thresholds and reference field water tables**

The observed FWT at the timing of re-irrigation averaged over the crop season ranged from −46.2 to −9.2 at the four farms (Table 4). The FWT was relatively deeper at Farm A and Farm B but shallower at Farm C and Farm D. At Farm B, the FWT was often at the lower limit of the water level sensor’s range when the plot was re-irrigated, indicating that the actual threshold would be even lower. In addition, considerable variation in the current irrigation criteria was observed in SD over 10 cm at all the farms (Table 4). Thus, introduction of irrigation criteria based on FWTs would make irrigation management more stable and efficient.

The reference FWT at the field capacity ranged from −12.9 to −21.4 cm and similar to the observed thresholds (Table 4). The notable exception was Farm C, where the threshold was estimated to be considerably deeper than the observable range of the FWT. According to the field observation of the soil in Farm C at the monitoring devices’ location and at the soil-sampling location, the soil water retention characteristics could be relatively different between the two locations, producing the discrepancy in SWC at saturation mentioned above. Applying the lower value of the SWC at the field capacity from the soil analy-
sis could have resulted in the exceptionally deep threshold of the FWT estimated from the relationship. Although we found no clear tendency in the reference FWT in relation to soil characteristics, further research on deriving realistic values of corresponding FWTs in clay-rich soil conditions similar to Farm C might indicate a relationship between FWTs at a specific SWC threshold and soil properties. Overall, the range of the reference FWTs for the contour-levee irrigation system used in Ibagué was close to that recommended for AWD practices in Asia (15–20 cm soil depth) (Richards and Sander, 2014) and to reports of safe-AWD thresholds from 10–25 cm soil depth (Lampayan et al., 2015; Yang et al., 2017).

Elucidating the threshold of SWC under the contou-
CONCLUSION

In this study we established empirical relationships between the FWT and the SWC under the contour-levee irrigation system at four rice farms with distinct soil properties in Ibagué, Colombia. The prediction performance was satisfactory for the practical estimation of SWC under actual field conditions. Subsequently, we observed FWTs at the irrigation timings on the farms and the averaged FWT threshold over the crop season ranged from −46.2 to −9.2 cm with relatively high variation shown in the SD over 10 cm at all the farms. The reference FWTs at field capacity were derived with the validated relationships, resulting in the range from −12.9 to −21.4 cm with an exception of Farm C. The reference FWTs were comparable to the observed current farmers’ irrigation thresholds and also close to the AWD practices in Asia. Development of irrigation criteria still requires further research on SWC thresholds under contour-levee irrigation systems. Overall, this study demonstrated empirical relationships between FWT and SWC under field conditions in Colombia, which can be utilized to develop practical irrigation criteria for rice growing in the contour-levee irrigation system.

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