Developing Automatic Water Table Control System for Reducing Greenhouse Gas Emissions from Paddy Fields

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Abstract. Water table in rice fields play important role to mitigate greenhouse gas (GHG) emissions from paddy fields. Continuous flooding by maintenance water table 2-5 cm above soil surface is not effective and release more GHG emissions. System of Rice Intensification (SRI) as alternative rice farming apply intermittent irrigation by maintaining lower water table is proven can reduce GHG emissions reducing productivity significantly. The objectives of this study were to develop automatic water table control system for SRI application and then evaluate the performances. The control system was developed based on fuzzy logic algorithms using the mini PC of Raspberry Pi. Based on laboratory and field tests, the developed system was working well as indicated by lower MAPE (mean absolute percentage error) values. MAPE values for simulation and field tests were 16.88% and 15.80%, respectively. This system can save irrigation water up to 42.54% without reducing productivity significantly when compared to manual irrigation systems.

1. Introduction
Rice (Oryza sativa L) is the primary staple food in Indonesia and it covers the largest agricultural area. The total area was 8.1 million ha with rice production was 70.8 million tons in 2014. Its production decreased 0.6% in 2013 [1]. In Indonesia, paddy rice is known as cultivated plant with more water need, thus continuous flooding irrigation is applied by keeping water depth 2-5 cm above the soil surface. Irrigation consumes highest fresh water in agriculture by up to 89% following by fisheries (7%), domestic and industrial (4%) and livestock (0.2%) [2]. More water consumed for irrigation does not always have positive correlation to the increase in yield and biomass production as reported by previous studies [3, 4, 5]. On the other hand, sustainability of rice cultivation is threatened as raising water resource competition in rice production affected by regional climate change [6]. In addition, inefficiency of continuous flooding irrigation increases by more water loss from surface runoff, seepage and percolation [7].

Flooding water continuously in rice field promotes anaerobic soil condition that will contribute to negative effect to the environment by releasing greenhouse gas emissions particularly methane (CH₄) [8, 9]. More CH₄ concentration in the atmosphere contributes to global warming. CH₄ is produced by methanogens during organic matter decomposition in the soil, under an environment where the oxygen and sulfate are scarce in anaerobic soil condition [10, 11, 12]. In fact, N₂O is also emitted from paddy field with different characteristic to CH₄ emission. N₂O gas is primarily produced from the nitrification and denitrification processes in soil by microbial [13]. It is emitted more to the atmosphere when aerobic
soil condition with less water availability in the fields. Both N$_2$O and CH$_4$ are two of contributors to global warming from paddy fields and their level contribution represented by global warming potential (GWP) [14].

Currently, the system of rice intensification (SRI) is known as promising rice farming with more benefits compare to that conventional farming. SRI is well-known as a set of crop management practices by changing the management of plants, soil, water, and nutrients for increasing rice productivity. Many critics were addressed to SRI [15,16,17], however, its benefits have been validated in 42 countries of Asia, Africa and Latin America including in Indonesia [18]. Here, water irrigation is supplied by applying intermittent irrigation in which the field is allowed to dry during particular time instead of keeping them continuously flooded. Intermittent irrigation is also known as a mitigation option for greenhouse gas emissions including CH$_4$ and N$_2$O gasses from paddy fields [19,20,21].

Crucial factor in SRI application is to determine optimal water management during planting season. Water management is needed to maintain water table within a proper soil moisture range [22]. Soil moisture conditions in SRI paddy field usually should be kept around saturation level to air-entry level. In addition, optimal water table also can be used as mitigation strategy to reduce CH$_4$ and N$_2$O emissions. Achieving this condition is not easy and to be the limitations in disseminating SRI in Indonesia as well as developing irrigation water control system [23]. Fuzzy based control system is promising method to control water table in paddy field since it has ability to solve complex system problems that can’t be solved by conventional control system such as on-off system [24]. Fuzzy based control system adopts fuzzy logic by means specific mathematical model is not needed. Fuzzy logic works based on the rules that have been extracted from human knowledge as expert [25]. In addition, it has more accuracy compare to another control systems [26]. Therefore, the objectives of the current study were to develop fuzzy based water table control system and then to evaluate the performances.

2. Methodology

2.1. Experimental Design

Automatic water table control system was developed in the pot experiment during Feb – Aug 2017 in field laboratory of Dept Civil and Environmental Engineering in Bogor. There were four pots prepared in which only one pot was controlled by developed fuzzy-based control system (PS). The developed water table control system was used to control optimal water table that was determined by previous study [27]. Based on this study, dry regime was the best regime to mitigate greenhouse gas emissions from paddy field. This regime reduced by 34% of global warming potential compared to that flooding regime. In the dry regime, water table was kept at 0 cm water depth from the beginning to 20 days after transplanting, then the water was drained at -5 cm water depth until one week before harvesting time, and finally the water was drained until harvesting time. For comparison, there were three uncontrolled pots (P1, P2, P3).

2.2. Field Measurements

Water table was measured by calibrated E-Tape water level sensor. Meanwhile, weather parameters were measured by a Davis weather station consisting of a rain gauge, pyranometer, air temperature, humidity, air pressure, and wind speed and direction sensors with the interval measurement was 30 minutes. Plant growth parameters consisted of plant height, number of tillers/hill and number of panicles/hill that was measured every week. Collected data were then used in analyzing water balance for water control simulation process according to the following equation [28]:

\[
WL_i = WL_{i-1} + P + I - ETc - DP - RO - D
\]

where WL is water depth (mm), P is precipitation (mm), I is irrigation (mm), ETc is crop evapotranspiration (mm), DP is percolation (mm), RO is runoff (mm) and D is drainage (mm).
2.3. Fuzzy based control system

The fuzzy logic program was developed using Python code. The benefits of python code are large library and have provided modules to facilitate users and have a clear grammar [29]. Inference system was used based on sugeno reference with minimum implication function since it’s more efficient and proper for mathematical analysis [30]. Here, we used 15 rules for decision matrix as presented in table 1.

| Error   | Very Low | Low  | Zero | High | Very High |
|---------|----------|------|------|------|-----------|
| Delta Error |
| Negative | High     | Medium | Stop | Low  | Medium    |
|          | Irrigate | Irrigate | Stop | Drainage | Drainage |
| Zero     | High     | Low   | Stop | Low  | High      |
|          | Irrigate | Irrigate | Stop | Drainage | Drainage |
| Positive | Medium   | Low   | Stop | Low  | High      |
|          | Irrigate | Irrigate | Stop | Drainage | Drainage |

**Table 1. Decision matrix for output fuzzy system**

![Figure 1. Schematic of fuzzy based water table control system](image1)

![Figure 2. Layout fuzzy based water table control system in the field](image2)

For the hardware, we used Raspberry Pi microcontroller equipped with analog-digital converter (ADC). Solenoid valve was used as actuators in both irrigate and drainage system to keep expected water table (set point). Based on figure 1, actual water table will be measured by E-Tape water level sensor, then its value will be compared to the set point and we will get error and delta error. According to error and delta error values, fuzzy logic program (in fuzzy logic controller) determine degree of membership and decision matrix based on the rules. The output of fuzzy logic controller then will be
sent to the relay and give order to open/close solenoid valve in both irrigate and drainage gates. Layout fuzzy based water table control system in the field can be referred to figure 2.

The performance of system either for simulation and field test was evaluated based on the following mean absolute percentage error (MAPE) [31]:

\[ MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{X_a - X_i}{X_a} \right| \times 100\% \]  \hspace{1cm} (2)

where \( n \) is number of data, \( X_i \) is reference data (set point) in cm and \( X_a \) is actual data (cm). The system can be accepted when MAPE value lower than 25%.

3. Results and discussion

3.1. Sensor Calibration and monitored data

The output of E-Tape water level sensor is voltage and it has negative correlation to water depth as presented in calibration graph (figure 3). It has strong correlation as indicated by \( R^2 \) of 0.96 (>0.90), thus the sensor can be used to measure water depth precisely. The interval measurement of this sensor was 200–400 mV with water depth in between 0–30 cm. However, the sensor output was less sensitive when water depth less than 5 cm, thus water depth should be designed to be higher than 5 cm in the field.

![Figure 3. Calibrated water table sensor](image)

Dynamic changes of weather parameters such as air temperature, relative humidity, solar radiation and reference evapotranspiration are shown in figure 4. In left side showed that daily maximum, average and minimum air temperatures fluctuated and their trend had a negative correlation to relative humidity. The maximum air temperature was relatively higher than 30oC and it reached maximum by 36.4oC occurred on 10 April 2017. However, the trend was declined and dropped on 10 May 2017. The same situation also happened on average and minimum air temperature that indicated declining trend. During planting season, the average air temperature was 26.6oC with minimum air temperature was 20.1oC. Meanwhile, the interval of relative humidity was 68.6% to 92.3% and the trend was also slightly declined. Maximum relative humidity occurred when maximum air temperature lower than that 30oC. On the other hand, minimum relative humidity occurred when maximum air temperature lower than 30oC. It was indicated that when air temperature reaches peak, actual vapor pressure increased, thus relative humidity decreased.

Figure 4b (right side) shows dynamic changes of solar radiation and evapotranspiration during planting season. They had a positive correlation by means solar radiation had direct effect on reference evapotranspiration. It is indicated that solar radiation is the main factor in the process of evapotranspiration both from soil and plant surfaces [32]. In addition, a sensitivity analysis of evapotranspiration model showed that solar radiation strongly governs evapotranspiration [33]. During
planting season, their trend was slightly declined as well as air temperature and relative humidity. Maximum solar radiation and reference evapotranspiration were 20.14 MJ/m²/d and 5.03 mm, respectively. This event occurred when air temperature reaches peak on 10 April 2017.

![Image](image)

**Figure 4.** Monitored data: a) Air temperature and relative humidity, b) solar radiation and reference evapotranspiration

### 3.2. Performance of developed control system

Performance of fuzzy based water table control system in both simulation and field testing was shown in figure 5 and figure 6, respectively. The simulation was conducted during 18 minutes with initial water table was 1.91 cm. Figure 5 showed that the system can reach expected water table 1 cm in the early simulation during 18 seconds. Then, when set point was set to be 0 cm, actual water table can be reached that set point during 10 seconds. Overall, actual water table was closed to the set point indicated that the system was working well. In addition, the simulation reached MAPE by 16.88% (<25%) indicated that the system showed good performance and can be applied in the field. However, over and underestimation frequently occurred when the set point was set to be -5 cm.

![Image](image)

**Figure 5.** Simulation of the developed control system
The performance of the developed system was also satisfied in the field test during 112 trial days. Actual water table was close to the set point particularly in the early planting season (0-30 days after transplanting). However, its values over fluctuated when high precipitation occurred. This event occurred several times particularly in during 40-44 days after transplanting and 84-96 days after transplanting as shown in figure 6. For set point above ground (during 0-32 days after transplanting), MAPE was 26.41%, meanwhile when set point was set below ground MAPE was 11.79%. In general, MAPE of this system was 15.80% (<25%) that indicated the system can be accepted and it was worked effectively.

3.3. Plant growth and water efficiency

Plant growths among pots were comparable and not significantly different as indicated by plant height and tiller numbers in figure 7. Plant height for controllable pot (PS) was 145.6 cm in 15 weeks after transplanting. This high was higher than that uncontrollable pot P1 and P2 and slightly lower than that pot P2. PS also produced moderate tiller numbers by 30 tillers in which it was more than those P2 and P3 and less than that P1. However, controllable pot produced heaviest biomass that indicated water was supplied efficiently for fulfilling plant water requirement, thus it evapotranspiration rate highest (table 2). This finding was supported by the previous study that has reported evapotranspiration rate under intermittent irrigation with SRI higher than that conventional rice farming with continuous flooding irrigation [34].

![Figure 6. Performance of developed control system on field testing](image)

**Figure 6.** Performance of developed control system on field testing

![Figure 7. Plant growth: a) plant height, b) tiller numbers](image)

**Figure 7.** Plant growth: a) plant height, b) tiller numbers
Table 2. Calculation of water balance and water use efficiency between pots experiment

| Pot                  | Irrigation (mm) | Drainage (mm) | Precipitation (mm) | ETc (mm)   | Percolation/Runoff (mm) |
|----------------------|-----------------|---------------|--------------------|------------|-------------------------|
| PS (controlled pot)  | 256.29          | 295.36        | 1386.40            | 312.98     | 1034.35                 |
| P1 (uncontrolled pot)| 436.00          | 112.00        | 1386.40            | 136.72     | 1201.87                 |
| P2 (uncontrolled pot)| 455.00          | 12.00         | 1386.40            | 136.72     | 1392.68                 |
| P3 (uncontrolled pot)| 447.00          | 155.00        | 1386.40            | 208.53     | 1241.68                 |
| Water saving (%)     | 42.54%          |               |                    |            | 42.57%                  |

The developed system was more efficient in water use as presented in table 2. The system can save water by average of 42.54%. Also, the controllable water table can significantly reduce water loss due to percolation/runoff by 42.57%. Although supplied less water, crop evapotranspiration (ETc) was highest among pots that indicated the system was effective in utilization of water irrigation. Different ETc values in each plot gave different yield. For application in wider fields, it is recommended to develop proper drainage system such as subsurface drainage to keep expected water table, thus water input from precipitation can be well managed.

4. Conclusion and recommendation
The developed fuzzy based water table control system was effective. The performance was acceptable as indicated by MAPE (mean absolute percentage error) values lower than 25%. MAPE values for simulation and field tests were 16.88% and 23.06%, respectively. This system can save irrigation water up to 42.54% without reducing productivity significantly when compared to manual irrigation systems. For application in wider fields, it is recommended to develop proper drainage system such as subsurface drainage to keep expected water table, thus water input from precipitation can be well managed.

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