AUTOMATIC SUBSURFACE IRRIGATION AND DRAINAGE USING SHEET-PIPE TYPED MOLE DRAIN

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ABSTRACT

Sheet-pipe is a sort of perforated mole-drain used mainly to draw the excess of water from a water-logged paddy field. During installation, sheet-pipe is inserted horizontally into the soil at a certain depth using heavy machine called mole-drainer. After a heavy rainfall, the groundwater can decrease faster and be maintained at expected levels. As the soil aeration is getting better and soil salinity decrease due to leaching, better growth and higher productivity can be achieved. This paper reports plan and progress of sheet-pipe installation in Indonesia. A conceptual design of automatic irrigation and drainage using the sheet-pipe is described with the objective to minimize irrigation and drainage rates to maintain the groundwater at expected levels. Water flow model is developed to figure out profiles of the groundwater level and patterns of the drained water. And, combined with a controller model to determine the appropriate rate of returned flow from to drainage to the irrigation canals. Compared the field without sheet-pipe, the paddy field installed with sheet-pipe drained faster and could manage groundwater level ±5 cm right after a heavy rainfall ceased. Pattern of infiltration rate formed parabolic curve with the maximum value of 0.94 cm/h. Drainage rate also formed parabolic curve with the maximum and average values 0.899 m^2/h and 0.758 m^2/h, respectively. The profile of groundwater level was horizontally flat but then curved as closer toward the sheet-pipe. Soil salinity reduced to 0.42 mS/cm while productivity increased 6%. Further plans are to develop remote control system and install it in laboratory and field experiments.

Keywords: Paddy field, sheet-pipe, irrigation, drainage, water level, water-use efficiency, water productivity.

1. INTRODUCTION

Indonesia has a vast swampland accounted for 43.7 million hectares, and out of it, about 9.8 million hectares have been identified potential to develop as paddy fields [1]. Currently, more than 1 million hectares of the swampland has been converted into paddy fields [2] and cultivated at least one time every year. In general, the paddy fields inundated with water due to a frequent and high intensity of the rainfall with a periodic sea tide [3]. This paddy field also faces saline or acidic soils with low percolation due to the high content of heavy clays [4]. Land preparation usually starts after passing the peak of the rainy season. With low agricultural inputs as traditionally practiced by the local farmers, the averaged land productivity is about 3 t/ha of the wet paddy but with intensive treatments and better water management can attain more than 5 t/ha [5]. Low productivities of the paddy fields in swamplands have been reported elsewhere [6] [7] [8].

An effective drainage system is imperative to maintain the groundwater level preferable for the optimum growth of the plants. A combination of surface and subsurface drainage can intensify land utilization and increase yield increase, which, in turn, gain additional farmers' income [9]. Design criteria and practices and viable alternatives are available for the improvement of subsurface agricultural drainage systems to meet the demands

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of modern agriculture [10]. A shallow subsurface drainage system with a drain depth of 0.3 m and drain spacing of 8 m can increase yield and facilitate safe harvest while avoiding pre-monsoonal rainfall damage [11]. A subsurface drainage system can reduce salinity by about 80% in the topsoil (20 cm depth) [12].

In Japan, land consolidation and drainage improvement for farm mechanization in paddy fields began during the 1960s. It was not easy to use big machines in the muddy conditions caused by the clayey soil and heavy rainfall during the harvesting period. Several investigations were carried out by many researchers, and factors relating to drainage were clarified. Not only surface drainage but also under drainage was planned. However, drainage was not always enough, because the clayey surface soil was impermeable to ponding water. It became clear that under drainage for a clayey paddy field for the harvest is quite different from under drainage for an ordinary field. Field and soil characteristics, as well as water conditions, should be scrutinized before planning drainage improvement for farm mechanization [17].

On irrigated lands, drainpipe performance is often below standard due to clogging, siltation and root growth inside the pipe., an innovative pipe–envelope concept was tested on a 50-ha pilot area in Harran, Turkey, in 2015 and 2016. The new concept, HYDROLUIS, consists of a corrugated inner pipe with three rows of perforations at the top and an unperforated outer pipe that covers about 2/3 of the inner pipe leaving only the unperforated bottom part of the inner pipe in contact with the soil. The main advantages of the new concept are that it works for a wide range of soil textures, and there is better protection against root growth inside the pipe. The new concept was compared with a geotextile envelope, a gravel envelope, and a control with no envelope. The HYDROLUIS and gravel envelopes had a significantly lower entrance resistance compared to the geotextile, the best drain performance, and no signs of sedimentation nor of root growth inside the pipe. The production costs of the HYDROLUIS envelope are comparable to those of pre-wrapped synthetic envelopes and considerably lower than gravel envelopes. It can be concluded that the HYDROLUIS envelope is a promising alternative for sand/gravel or synthetic envelopes in irrigated lands [13].

Many studies have been conducted on the role and importance of subsurface drainage in groundwater table control to discover new techniques and more economical solutions, particularly relating to different pipes, envelope materials, and their installation. This research was conducted to investigate the applicability of rice husk in drainage as a drain envelope material s compared with a standard sand and gravel envelopes. Some of the physical and hydraulic properties of rice husk such as bulk density, void ratio, gradation curve, and hydraulic conductivity were measured. A physical model that simulated a part of the drain trench enabling groundwater table control was used to simulate land drainage in the laboratory and to test filtration and water conductivity of a rice husk envelope. The experiments were carried out in two soils that required envelope material based on standard methods. The results of this study showed that hydraulic conductivity of the rice husk even under large loads was high enough to guarantee its hydraulic function as an envelope. Furthermore, the rice husk envelopes had proper function compared to mineral envelopes [14].

Since 1993, the Red River of the North Valley in North Dakota (ND) and Minnesota (MN), in the USA has experienced increased annual rainfall which has caused localized seasonal Soil waterlogging and inhibited crop yield potential in the unique, high water table clay soils of the region. Subsurface (tile) drainage has been increasingly considered by farmers to help reduce excess water in the crop root zone. Producers desire to manage the water table for optimizing yield and trafficability of the field. The objective of this research was to evaluate differences in soil penetration resistance and water table depth between subsurface (drained) and non-subsurface drained treatments (undrained), using water control structures, in fallow, and cropped soybean (*Glycine max* L. Merr.) and wheat (*Triticum aestivum* L. emend. Thell.) cultivars on a

Fargo-Ryan silty clay soil near Fargo, ND, USA in 2009 and 2010. The experimental design was a randomized complete block in a split-plot arrangement with four replicates.

The whole plot treatments were drained and undrained (control structures opened and closed, respectively). Soil penetrometer readings and water table depth were measured weekly. Yields of each crop were not different comparing drained and undrained treatments in 2009 and 2010. The depth-averaged drained penetration resistance was 1,211 kPa compared with 1,097 kPa for undrained treatment, averaged across 2009 and 2010. The depth-averaged drained penetration resistance values for fallow, soybean, and wheat were 1,077, 1,137, and 1,420 kPa, respectively. The undrained values for fallow, soybean, and wheat were 1,001, 1,021, and 1,267 kPa, respectively, all significantly lower than the drained treatments, indicating that the drained soil is capable of a higher load carrying capacity compared to the undrained soil. The average depth to the water table was greater on drained soil compared to the undrained soil both early and late in the growing season. Forty-two percent of the variation in the penetration resistance can be explained by the level of the water table below the surface. Water control structures can be used to manage the water table level and soil penetrations resistance. The ability for land managers to enter drained fields with farm equipment earlier lengthens the growing season and potentially increase crop yields in this region [15].

The study revealed the performance of subsurface drainage systems for the long-term sustainability of irrigated agriculture. The performance of subsurface drainage systems was evaluated based on drain spacing equations for disposal of effluent and hydraulic characteristics. Three important synthetic envelopes, HG 22, SAPP 240 and CAN 2 were tested in the laboratory using sand tank model and permeability apparatus to compare their performances in terms of entrance resistance and hydraulic conductivity of soil envelope system. The hydraulic conductivity for SAPP 240 filter was found the highest and entrance resistance the lowest. Performance of four unsteady state drain spacing equations viz. Glover-Dumm, Van Schilfgaarde, Integrated Hooghoudt, and Modified Glover equations were also tested to evaluate disposal efficiency of excess water. The percentage deviation between predicted drain spacing and actual spacing was -33.31% to -31.55%, 9.40% to 17.07%, 11.84% to 20.83% and 6.10% to 14.62% for Glover-Dumm, Van Schilfgaarde, Integrated Hooghoudt, and Modified Glover equations, respectively. Modified Glover equation showed minimum deviation from actual drain spacing due to its versatile applicability. Therefore, the Modified Glover equation with SAPP 240 filter was recommended for the subsurface drainage system in sandy soil texture areas [16].

Modern technology of subsurface drainage known as the sheet-pipe system has been developed in Japan for 20 years ago. Merits of this system among others are fast installation process and easy to operate and the paddy field installed with this system is readily arable with many other crops beside paddy. This system has been introduced in Indonesia since 2018 under cooperation among JICA, Ministry of Agriculture, Kyouwa Kensetsu Kogyo Co., Ltd, Yamaguchi University and Bogor Agricultural University. This paper reports development plan and progress of the implementation with special attention given to a field experiment conducted in 2018/2019 located in the Rice Research and Development Centre belongs to the Ministry of Agriculture of the Republic Indonesia.

2. DEVELOPMENT PLAN AND PROGRESS

2.1. Sheet-pipe

As shown in **Figure 1,** Sheet Pipe (SP) is a sort of perforated sheet made of High-Density Polyethylene (HDP) that can be formed into a pipe using a sheet-pipe roller that inserts pin E into the socket B. There are 22 holes per 3 cm along its length (see, E+F). The diameter of one hole is 2 mm, and that of the pipe is 5 cm with its thickness 1 mm. The sheet pipe is manufactured by Polymer Japan and produced in two types, SP50-1 t (1 mm thickness) and SP50-0.7t (0.7 mm thickness). The sheet pipe is packed in the form of a sheet roll having 100 m length per roll.
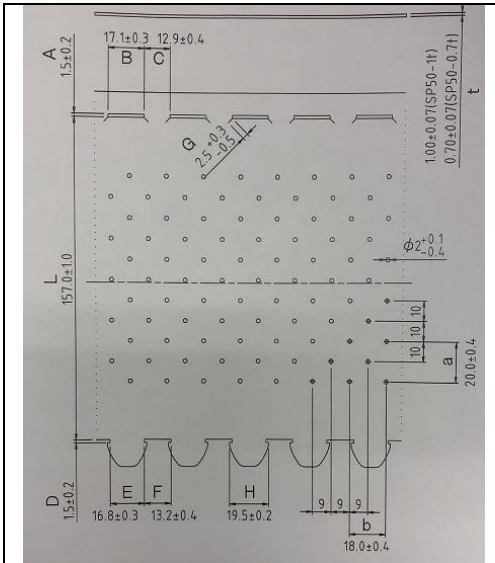
Figure 1. Sheet-pipe Specification

2.2. Conceptual Design

Sheet-pipe used formerly to draw the excess water from the water-logged farmlands. It is inserted horizontally into the soil at a specific deep (±50 cm) using a heavy machine called mole drainer. The installation is very fast around 3 days per hectare on a field having a length of 100 m with a spacing of 4 m. **Figure 2** shows a conceptual design of automatic control of subsurface irrigation and drainage with the sheep-pipe system.
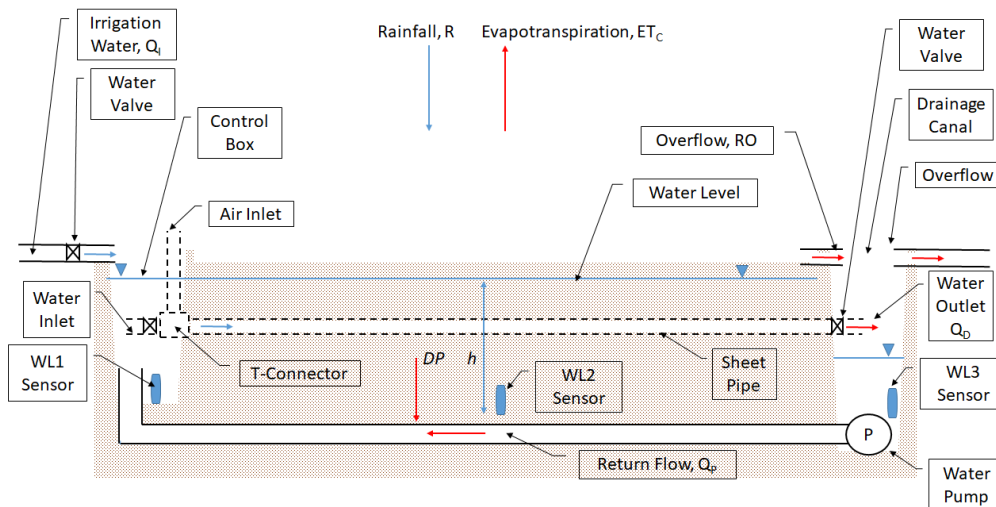

Figure 2. Conceptual Design

Referred to **Figure 2,** the following is a short explanation of the operating mechanism:

(a) The main target is to maintain the water level in the farmland (WL2) at a specific range.

(b) The farmland receives the water from occasional Rainfall and the Control Box.

(c) The Control Box receives the water from the Irrigation Canal and the Drainage Canal.

(d) The water from the Irrigation Canal is regulated with a floating-type Water Valve (WV1).

4

(e) The water from the Drainage Canal is pumped operated by an electrical switch referred to the water level in the Control Box (WL1) and in the Drainage Canal (WL3).

(f) In general, the control mechanism is as follows:

  (i) When WL2 is higher than the highest limit, WV1 closes, and WV2 opens.
  (ii) When WL2 is lower than the lowest limit, WV1 opens, and WV2 closes.
  (iii) When WL1 is higher than the highest limit, the Pump is off.
  (iv) When WL1 is lower than the lowest limit, the Pump is on.
  (v) When WL3 is lower than the lowest limit, the Pump is off.

(g) Rainfall and evapotranspiration are measured intensively and used for water balance analysis.

2.3. Performance Indicators

Performance indicators to be sought, among others, are groundwater level, hydrograph, infiltration and drainage patterns, leaching effectiveness, irrigation efficiency, and water productivity.

2.4. Implementation Plan and Progress

1) First Stage in 2018/2019:

   a. Box experiment in the laboratory to characterize the decrease of water level profiles and drainage flow;
   b. A field experiment in a paddy field to characterize groundwater level (GWL), hydrograph, infiltration, and drainage patterns and leaching effectiveness.

2) Second Stage in 2019/2020

   a. Field monitoring and measurements of irrigation efficiency and water productivity
   b. Box experiment in the laboratory to test the performance of the control system.
   c. Engineering design of the automatic control system in field scale.

3) Third Stage in 2010/2021

   a. Installation and monitoring of the control system in the field.
   b. Field monitoring and measurements of irrigation efficiency and water productivity

3. FIELD EXPERIMENT IN THE FIRST STAGE

3.1. Location

The investigated site is located inside the Indonesia Centre for Rice Research belongs to the Ministry of Agriculture, the Republic of Indonesia in Sukamandi District, Subang Regency, West Java, Indonesia (**Figure 3**) with the elevation is about 13 m from the sea level.

There are 2 investigated plots. The first plot (P1) located at 6°20'48.19"S and 107°39'2.00"E is the common paddy field without SP having an area of 1.12 ha with its perimeter 426 m; and the second plot (P2) located at 6°20'46.33"S and 107°39'4.01"E was the paddy field which has been installed with SP having an area of 1.1 ha with its

perimeter 434 ma. A small ridge surrounds each plot. From these plots, the draining water flows to the drainage canal (P3). The base of the drainage canal is the reference level or datum from which the elevations of P1 is 105 cm, and P2 is 104 cm. With this, a small difference (1 cm) both plots can be considered at the same level.

In P2, there are 8 rows of sheet-pipe with a 4 m-lateral distance in each other with the length of each row was about 100 m perpendicular to the irrigation and drainage canals. Sheet pipe was installed using a mole drainer Komatsu SP30 having a high level of accuracy in placing SP horizontally about 40 cm below the soil surface. Each SP has a water valve installed at its lower end that can be used to regulate the draining water manually.
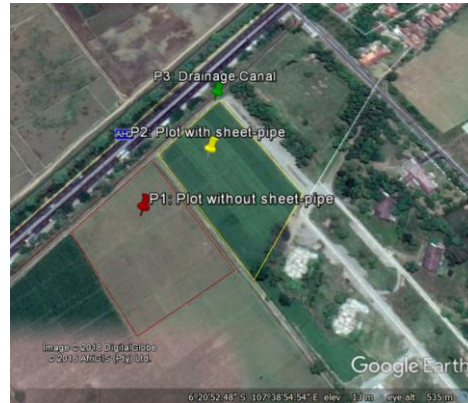
Figure 3. Investigated Paddy Fields

3.2. Field Investigation

Water level (WL) in the 3 points (P1, P2, and P3) were measured intensively using the CTD type WL sensors produced by Meter Group, Inc, WA. The USA. In P1 and P2, the sensor was placed at 70 cm depth from the soil surface or 30 cm below the sheet-pipe; and in P3, the sensor was placed at the bottom of the drainage canal. The sensor can also measure water electrical conductivity (EC) and temperature (Tw) simultaneously. Soil moisture at a depth of 5 cm in P1 and P2 was measured using 5TE produced by the same group that can also measure soil temperature (Ts) and electrical conductivity. Furthermore, the weather data: Rainfall (R) was measured using ECRN-100 Precipitation, Solar Radiation (Rs) using PYR Solar Radiation, and air temperature (Ta) and relative humidity (RH) were measured using EHT RH/Temp.

Acquisitions of weather, water, and soil data use EM50 data logger produced by the same group with a measurement interval of 30 minutes. A field investigation started from May 4th to August 7th, 2018 in which P1 and P2 cultivated with paddy for the second planting season from wet to dry period.

To get a hydrograph unit of a rainfall event, the water flow from the irrigation canal was stopped before the rainfall occurrence to eliminate its influence on the water level. By this, it could be distinguished effects of sheet-pipe on the water level at each rainfall event.

3.3. Data Analysis

As the relation of rainfall and water level was the primary concern of this investigation, data analysis focused on each rainfall event that resulted in a significant rising of water level in both plots. A unit hydrograph consisted of rainfall and water level was depicted to figure out how the water level gave responses to the rainfall. Elapsed times to attain the peaks in the two plots were analyzed and compared to see the differences. Percolation and soil permeability were calculated from the declining section of the hydrograph.

Furthermore, the continuity equation of water flow in a saturated porous medium was applied to figure out the profiles of water level and their changes with time in the plot installed with sheet-pipe. The equation is as follows:

$$\frac{\partial h}{\partial t} = K_s \left(h \frac{\partial^2 h}{\partial x^2} + \frac{\partial h}{\partial x} \frac{\partial h}{\partial x} \right) + p \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(1)$$

Where h is water level (cm), K_s is saturated hydraulic conductivity (cm/h), p is percolation rate (cm/h), x is the distance (cm), and t is time (h) subjected to the following boundary conditions:

$$q(0,t) = p(0,t)\frac{\Delta x}{H-h(0,t)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(2)$$

And,

$$h(L,t) = f(L,t) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3)$$

Where q is horizontal water flux (cm/h), Δx is spatial interval (cm), H is the depth of sheet-pipe from the soil surface (=40 cm), L is length of water flow domain (=200 cm) from the sheet-pipe which is set at x=0 cm, and f is an interpolation function of the measured water level at x=L. Subjected to the initially measured water levels, the equations above were then solved numerically using the explicit scheme of Finite Difference Method.

4. RESULTS AND DISCUSSIONS

4.1. Weathers

During field investigations, there were 6 rainfall events (see **Table 1**) in which the most significant rainfall occurred from May 23rd, 2018 at midnight and lasted

Table 1 Rainfall Events within the Period of Investigation

No	Started	Length (h)	Amount (mm)	Rate (mm/h)
1	20-May-18 04:30	2.0	0.8	0.40
2	21-May-18 02:30	1.5	1.2	0.80
3	22-May-18 00:00	5.5	3.4	0.62
4	23-May-18 00:00	6.0	34.0	5.67
5	23-May-18 20:00	6.0	25.6	4.27
6	25-May-18 06:00	3.5	3.6	1.03

about 6 hours and produced 34 mm of the rainwater with the averaged rate 5.67 mm/h. This rainfall resulted in measurable water inflows into P1, P2, and P3 and will be taken into attention for further analysis in this paper.
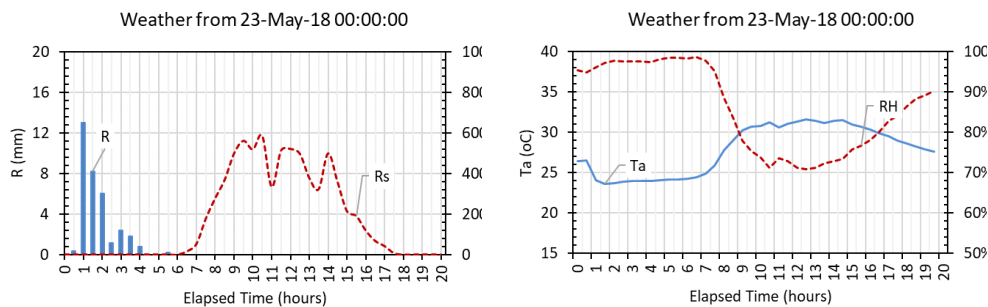

Figure 4. Rainfall (R), Solar Radiation (Rs), Air Temperature (Ta), and Relative Humidity (RH)

As shown in **Figure 4**, the rainfall attained its peak after one hour then gradually decreased with time and stopped after 6 hours. During the rainfall which was still dawn, Rs was very low, and Ta was about 24º C while RH was high closer to 100%. After the rainfall, which was during daylight, Rs increased steeply to reach a maximum value of 600 W/m², and Ta increased above 30 ºC while RH decreased to 70%. About 17:30, Rs reduced to zero at the nighttime.

4.2. Water Level and Soil Moisture

Figure 5 water level and soil moisture fluctuations in P1 and P2. The water level was referred to the bottom of the drainage canal (P3) where is WL fluctuated from 10 cm and reached maximum 40 cm after lasted 8 hours then gradually decreased below 30

cm after lasted 20 hours. The water level in P1 was always higher than that in P2. Even WL in P1 was always above the soil surface while WL in P2 was mostly below the soil surface, which was stable at about 5 cm depth after lasted 10 hours. As also shown in Figure 5, soil moisture in P1 was slightly higher than that in P2, but then similar lasted 8 hours and reached saturation at about 46% of VWC.
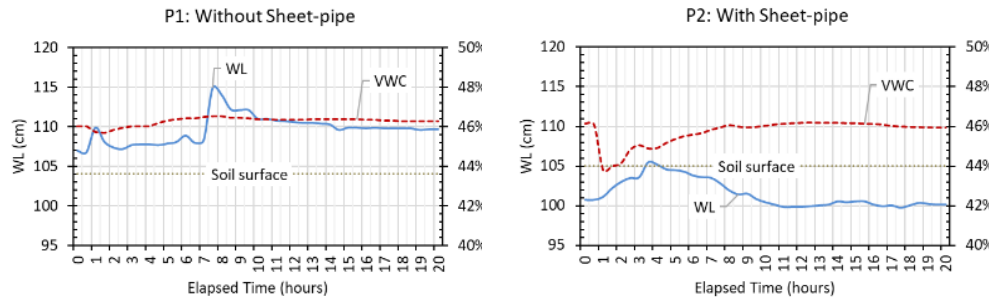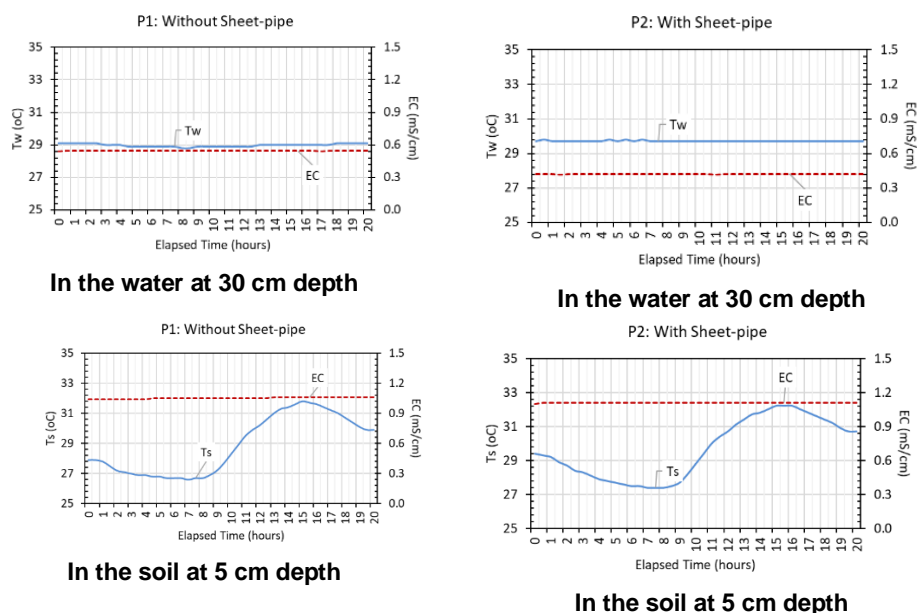

Figure 5. Water Level (WL) and Volumetric Water Content (VWC) in the Plots without Sheet-pipe (P1) and with Sheet-pipe (P2)

4.3.   Temperature and Electrical Conductivity

Figure 6 shows temperature and electrical conductivity in P1 and P2. Water temperature (Tw) were relatively stable in average at 29.0 ℃ in P1 and 29.7 ℃ in P2 compared to soil temperature (Ts) which was oscillated with time because it was close to the atmosphere and influenced by the air temperature (Ta). The minimum and maximum Ts in P1 were 26.6 ℃ and 31.8 ℃, respectively; and those in P2 were 27.4 ℃ and 32.3 ℃, respectively.

Soil EC was relatively stable in average at 1.05 mS/cm in P1 and 1.11 mS/cm in P2 which were not significantly different in each other. These values are more significant than those reported by [9] in the range of 0.6–1 mS/cm in paddy fields under anaerobic condition. While in most uplands under aerobic condition EC is commonly around 0.33 mS/cm [10].
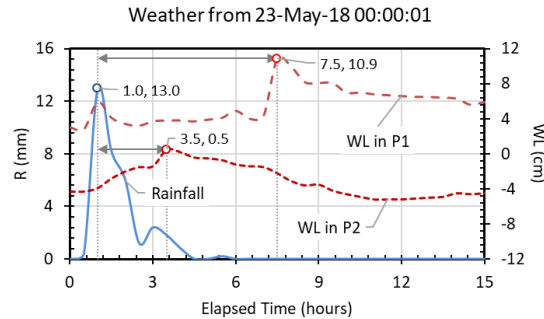

In the water at 30 cm depth

In the water at 30 cm depth

In the soil at 5 cm depth

In the soil at 5 cm depth

Figure 6. Water Temperature (Ts) and Electrical Conductivity (EC) in the Plots without Sheet-pipe (P1) and with Sheet-pipe (P2)

Water EC was 2 times lower than the soil EC. Water EC was relatively stable but that in P1 was slightly higher on average at 0.55 mS/cm than that in P2 at 0.42 mS/cm which might be influenced by the leaching effect while water EC in P3 was 0.25 mS/cm the lowest as the consequence of the accumulation of rainwater and drained water.

4.4. Hydrograph Patterns

Figure 7 shows two hydrographs comparing responses of WL in P1 and P2 to a single rainfall event. The differences are apparent. In P1, the rainwater accumulated mainly on the soil surface and reached the maximum WL at 10.9 cm after lasted 7.5 hours then gradually decrease with time to reach 5.9 cm after lasted 15 hours. While in P2, the maximum WL was only 0.5

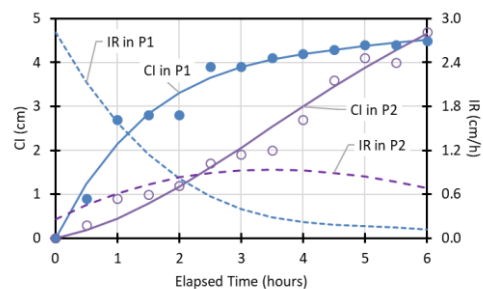**Figure 7. Hydrographs of Rainfall and Water Level**

cm reached after lasted 3.5 hours then gradually decreased below the soil surface and reached -4.5 cm after 15 hours. This decrease indicates that the large part of the rainwater percolated to deeper layers and discharged through the Sheet-pipe.

4.5. Infiltration Patterns

Figure 8 shows the cumulative infiltration (CI) defined here as the accumulation of rainwater entering the soil surface, starting from the maximum WL then percolates to the deeper layers. In P1, the data of CI formed a parabolical curve as commonly occurs in normal plots while in P2, the data formed a slight S-curve in which the total infiltrated water was 4.5 cm. Herewith, both curves are represented by the 4th Polynomial Equation, which gained determination coefficients close to 1 subjected to the time length from 0 to 6 hours. The infiltration rate (IR) which is the first derivative of the polynomial equation formed a typical decreasing pattern in P1 and attained steady rate at 0.121 cm/h while IR in P2 formed a parabolical curve having a maximum value of 0.94 cm/h at elapsed time 3.5 hours.
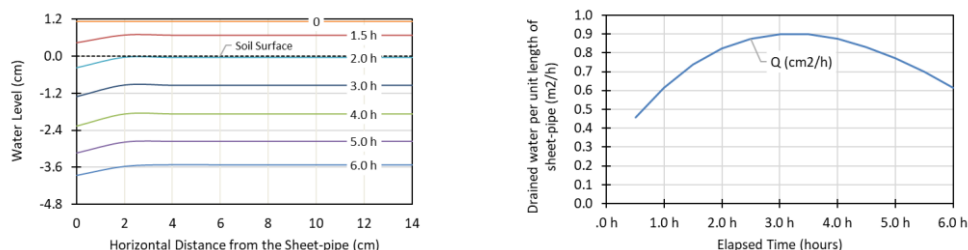
4.6. Water Level Profiles

Figure 9 shows the calculated water level profiles in P2 for several elapsed hours. In general, the WL curves flatted horizontally excepting at the points closer to the sheet-pipe (x=0) are lower, indicating there were outward gradients of water head. Figure 9 also shows the drained water per unit length of sheet pipe, which

Figure 8. Cumulative Infiltration (CI) and Infiltration Rate (PR)

again formed a hyperbolic curve having a maximum value of 0.899 m²/h with an average of 0.758 m²/h.

The results of the analyses show that seepage velocity along the ponded surface water decreases with distance from the ditch, and accordingly, leaching of salts is non-uniform [11].

Figure 9. Profiles of the Water Level in the Paddy Field with Sheet-pipe

5. CONCLUSIONS

The paddy field installed with sheet-pipe can drain faster, and in consequence, its water level can be managed easier, which is an important key to be able to regulate anaerobic and aerobic conditions. Right after a productive rainfall event, the rainwater immediately infiltrates downward, resulting in a parabolic curve of infiltration rate, which differs with a standard infiltration curve. Water level profile is horizontally flat except at the points closer to the sheet-pipe, which is showing the presence of outward gradients of the water head. Soil electrical conductivity was lower due to the leaching effect, which is potential to move unexpected substances commonly found in the wetland.

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