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Technical Paper

Simulation of Oil Palm Root Water Uptake by Using 2D Numerical Soil-Water Flow Model.

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Abstract

The sustainability in oil palm plantation requires a specific information about the oil palm root water uptake. As an introduction, it is find of interest to simulate the root water uptake and water content pattern of oil palm. The study was performed by applying the 2D simulation soil-water flow model to 17th year old oil palm tree located in Siak, Riau with the loam soil type. The climate data during 22 Nov – 22 Dec 2018 was used to predict the evapotranspiration. The simulation over 30 days based on Richard equation illustrated the root water uptake distribution, water content change, pressure head and flow velocity. The most intensive root water uptake occurred in the upper root zone of oil palm tree as an impact of the higher root density. The significant root water uptake in the upper root zone lead to the decreasing of water content and increasing of pressure head. Consequently, there was a change of water flow direction from the wet area in the downward and sideward do dry root zone as the water supply to the oil palm tree. The validation test showed that the simulation performed well (R2 = 0.724 and RMSE = 0.0066).

Keywords : 2D simulation, oil palm, root water uptake, water flow

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Introduction

The lack of water resource in these past decades encourages the implementation of the precision agriculture system towards the sustainability in oil palm plantation (Wijayanti et al., 2018, Santos 2019). The main principal of precision agriculture system is to secure the precise input resource include water in an agricultural system (Saptomo et al. 2002; Duhan et al., 2017). Therefore, it requires a specific information about the oil palm performance regarding the water balance system that affect the water consumption through the plant root water uptake. However, the prediction of root water uptake distribution is still a challenge (Safitri et al., 2018b, Safitri et al., 2019c). The dynamics process that occurs underneath the soil requires need a complex approach that probably difficult to be visualised by the experimental study.

Another method to investigate the soil water dynamics under the plant root system is through the numerical simulations. Numerical simulations are one of an efficient method to predict the water flux under the soil for optimal irrigation management practices (Meshkat et al., 1999, Bufon et al., 2012). It is proven based on many studies that the numerically simulated data agree with observed data such as root water uptake evaluation under different irrigation schemes (De Silva et al., 2008; Safitri et al.2018 (b), Safitri et al. 2019 (b)), the spatio-temporal compensated and uncompensated root water uptake (RWU) patterns evaluation of mature pecan trees in a silty clay loam (Deb et al., 2013), the prediction of water content using numerical model (Hydrus 2D/3D) to investigate and design drip irrigation management practices (Bufon et al., 2012), and the latest for modelling soil water balance and root water uptake in cotton grown under different soil conservation practices in the Indo-Gangetic Plain (Aggarwal et al., 2017).

The 2D numerical soil water flow model is considered to provide the high accuracy of simulation and the complex visualization of plant water balance (Bufon et al., 2012, Albasha et al., 2015, Aggarwal et al., 2017). Therefore, there is a high amount of studies using the 2D numerical soil water flow to predict several parameters of plant water balance performance such as water content and root water uptake (Safitri et al. 2019 (c), De Silva et al., 2008, Deb et al., 2013, Ahmed et al., 2016, Aggarwal et al., 2017), capillary water absorption (Van Belleghem et al., 2016), and also to investigate the performance of irrigation strategies (Bufon et al., 2012, Mguidiche et al., 2015, Han et al., 2015, Autovino et al., 2018).

The most common parameters predicted by the 2D numerical soil water flow model is the water content change and the root water uptake distribution. Mguidiche et al (2015) assessed Soil Water Content (SWC) and Salt Accumulation under an SDI System as an application to a Potato Crop in a Semi-Arid Area of Central Tunisia using Hydrus-2D. Then, the measurements of water uptake of maize roots also taken by Ahmed et al., (2016) as the key function of lateral roots. An interesting case study shown by Guber et al., (2015) that enrolled the investigation of root zone water storage improvement for corn production on Coarse – Textured Soils through the subsurface water retention technology. The 2D numerical soil-water flow model also can be used to perform the growth response to soil water availability for a case study of a mature triploid Populus tomentosa plantation located on the North China Plain (Xi et al., 2016). In paddy fields, a numerical modelling also can be applied to simulate the soil water dynamics in subsurface drained paddies with midseason drainage or alternate wetting and drying management (Darzi-Naftchali et al., 2018). Another example shown by Ahmad et al., (2018) that predict the soil water dynamics and crop water use in a soybean-wheat rotation under chisel tillage in a sandy clay loam soil.

Besides modelling the water balance parameter, the 2D simulation soil-water flow has been applied to predict and visualize the treatment of irrigation. For instance, The 2D simulation water flow model particularly Hydrus – 2D was used to predict soil and plant water status dynamic in olive orchards under different irrigation systems (Autovino et al., 2018). Afterward, Han et al., (2015) used the 2D numerical solution model to evaluate the effects of mulch and irrigation amount on soil water distribution and root zone water balance. The changes in irrigation return flow with gradually intensified water-saving technology also have been identified using HYDRUS for regional water resources management by Hu et al., (2017). An investigation of soil water dynamics was also performed using the 2D simulation soil water flow to better understanding the effect of a drip-irrigated intercropping field under plastic mulch (Li et al., 2015).

Moreover, the 2D simulation of soil water flow also provides the water flow, solute and heat transport as well. In order to assess the performance of drip irrigation with raised beds and full plastic-film mulch of a potato field in a semiarid area, Zhang et al., (2018) adopted the 2D simulation of soil water flow to investigate the pattern of the water flow and heat transport. Another illustration of modelling the nutrient transport by the 2D simulation of soil water flow was performed by Tournier et al., (2015) that simulated the nutrient transport with root uptake as an explicit geometry and unstructured adaptive meshing. Thomas & Abbott (2018) used the 2D simulation of soil water flow to confirm the effects of hedgerows to reduce nitrate flux at hillslope and catchment scales via root uptake and secondary effects. As one of the performance test method, Raij et al., (2016) also applied the 2D simulation of soil water flow to simulate the water flow and multicomponent solute transport in drip-irrigated lysimeters.

Regarding a wide range application of the 2D simulation of soil water flow in various type of plant and climate condition, it is evidenced that the 2D simulation of soil water flow has a good performance of predict and visualize the soil water flow condition. Nonetheless, the simulation in oil palm is still rarely found. One of the study was to observe the silt pit efficiency in conserving soil water in oil palm plantation as simulated by HYDRUS 2D Model (Bohluli et al., 2014). Another study found was to analyze the possible differences in the unsaturated soil hydraulic properties of the stemflow and throughfall areas below an oil palm tree where the soil hydraulic properties were estimated inversely from the measured data using the HYDRUS-2D/3D software package. (Rashid et al., 2015). In alignment with the idea of promoting the sustainable oil palm plantation, the investigation of root water uptake and water content under oil palm tree is highly demanding. As an introduction, through this study, it is find of interest to simulate the root water uptake and water content pattern of oil palm tree using the 2D simulation soil-water flow.

Material & Method

2D Numerical Soil and Water Flow Model

Soil water movement was simulated as water flow in vadose zone under the oil palm tree. The governing equation for water flow is in Eq. 1 (Richard 1931) :

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}[k(\theta)\frac{\partial h}{\partial x}] + \frac{\partial}{\partial z}[k(\theta)\frac{\partial h}{\partial z}] + \frac{\partial k(\theta)}{\partial z} - S \quad (1)$$

where θ is the volumetric water content ($cm^3 \cdot cm^{-3}$), h is the pressure head (cm), S is a sink term (cm^{-3}), and k(θ) is the unsaturated hydraulic conductivity function ($cm \cdot day^{-1}$).

Soil hydraulic properties to support the simulation were approximated by the van Genuchten-Mualem function (Van Genuchten 1980, Muallem 1976,) in Eq. 2.

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}; \ h < 0 \\ \theta_s; \ h \geq 0 \end{cases}$$
$$K(\theta) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad (2)$$
$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r), \ m = 1 - 1/n, n > 1$$

where θ s is the saturated water content ($cm^3 \cdot cm^{-3}$), θ r is the residual water content ($cm^3.cm^{-3}$), Ks is the saturated hydraulic conductivity ($cm.day^{-1}$), Se = degree of saturation, α and n are the shape parameters, and l is the pore connectivity parameter.

Input Data Simulation

The simulation was performed for a 17th year old oil palm which is located in Siak, Riau. The input data that was required to run the simulation consisted of the daily weather data including rainfall, sunshine, solar radiation, wind speed, minimum and maximum temperature and relative humidity, the age of oil palm, and. The weather was collected from the Automatic Weather Station for the period 22 Nov – 22 Dec 2018. The weather data furthermore was used to calculate the reference evapotranspiration (ETo) through the Eq 3 and potential evapotranspiration of 17th year old oil palm through the Eq 4. (Allen et al., 1999, Walter et al., 2000FAO 2006, Pereira et al., 2015, Jensen & Allen 2016). The reference evapotranspiration (ETo) is the main parameter of crop water usage. In this study, the ETo was calculated using the Penman–Monteith equation according to study analysis using Equation below by the standardization for grass crops.

$$ETo = \frac{0.408 \text{ x } \Delta(Rn - G) + \gamma \frac{Cn}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + Cd)} \quad (3)$$

where: ETo = reference evapotranspiration (mm day^{-1}); R_n = net radiation at the crop surface (MJ $m^{-2} day^{-1}$); G = soil heat flux density (MJ $m^{-2} day^{-1}$); T = mean daily air temperature at 2 m height (°C); u_2 = wind speed at 2 m height (m s^{-1}); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); $e_s - e_a$ = saturation vapor pressure deficit (kPa); D = slope vapor pressure curve (kPa $°C^{-1}$); g = psychrometric constant (kPa$°C^{-1}$); Cn = numerator constant for reference type and calculation time step, aerodynamic resistance where the constant was 900 for daily, and 37 for hourly daytime and night-time; Cd = denominator constant for reference type and calculation time step. Bulk surface resistance and aerodynamic resistance where the constant was 0.34 for daily, 0.24 for hourly daytime, and 0.96 for hourly night-time.

$$ETP = kc \text{ x } ETo \quad (4)$$

Where ETP = Potential evapotranspiration (mm/day), kc = corp coefficient; 0.98 for 17th year old oil palm (Safitri et al., 2019a)

Simulation to Visualise the Oil Palm Root Water Uptake

Geometry and Simulation Time Information

Fig. 1 performed the illustration of the oil palm root architecture and the scheme of boundary condition. The 2D numerical soil and water flow was simulated to perform a 17th year old oil palm tree in 2D axisymmetric vertical flow along the root distribution. The root architecture of oil palm tree referred to Safitri et al., (2018a) for length (x) is 450 cm and depth (Z) is 200 cm with the maximum root intensity is 20 cm on the upper root zone. The boundary condition was determined as no flux at the top soil and free drainage on the bottom of root zone. The simulation was run during 30 days in daily time step. The minimum and maximum time step was set for 0.05 and 3 days respectively.

Soil Properties and Water Flow Scheme

The soil type used in this simulation was loam soil. The estimated soil hydraulic properties of loam soil was performed on the Table 1 based on the single porosity model by Van Genuchten – Muallem.

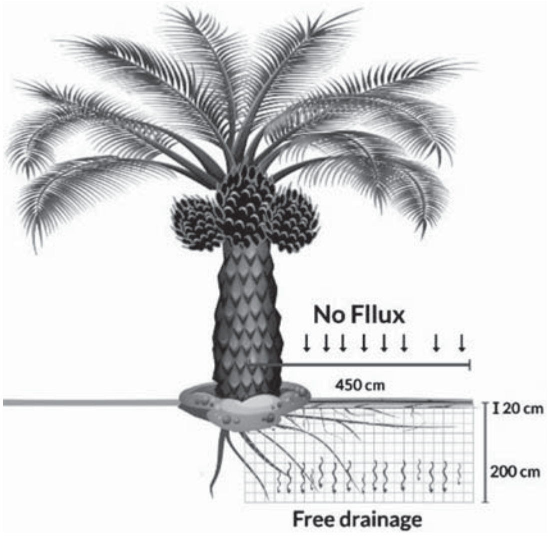
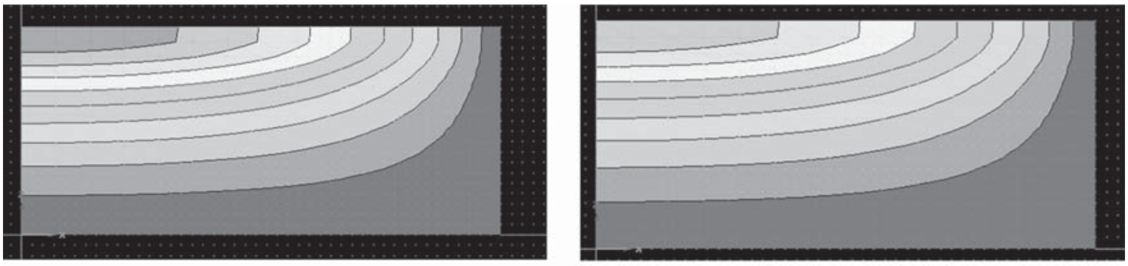


Fig 1. Illustration of oil palm root architecture (Safitri et al., 2018a).

Table 1. Soil hydraulic properties.

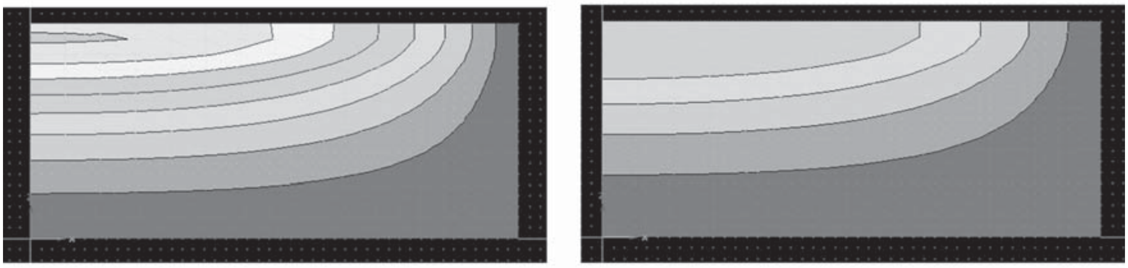
Parameter		Value
Qr	Residual soil water content, q_r	0.078
Qs	Saturated soil water content, q_s	0.43
Alpha	Parameter *a* in the soil water retention function [cm^{-1}]	0.036
n	Parameter *n* in the soil water retention function	1.56
Ks	Saturated hydraulic conductivity, K_s [cm day^{-1}]	24.96
l	Tortuosity parameter in the conductivity function [-]	0.5

The 2D numerical soil and water flow on oil palm tree was run to simulate the water flow and root water uptake of oil palm tree. The Feddes model (Feddes et al., 2004) was applied to perform root water uptake in this simulation. The root water uptake (RWU) was predicted using Eq. 5 (Feddes et al., 2004).



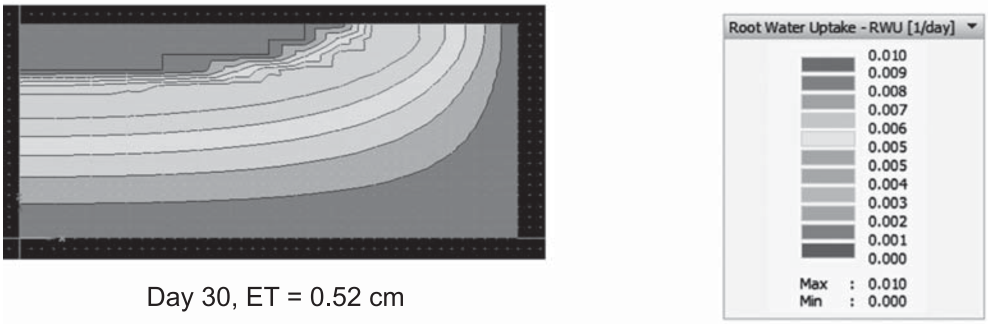
Day 1, ET= 0.43 cm

Day 7, ET = 0.49 cm



Day 16, ET= 0.35 cm

Day 20, ET = 0.255 cm



Day 30, ET = 0.52 cm

Fig 2. Visualisation of root water uptake distribution.

$$S_w\,(h) = \alpha\,(h) \times RLT\,(x,z) \times S_t \times ET_c \qquad (5)$$

Where Sw = root water uptake (cm/day), α(h) = *soil water pressure head* ($0 \leq \alpha \leq 1$), St = length of surface related to transpiration area *(cm),* ETc = potential evapotranspiration (cm/day), RLT(x,z) = normal root water uptake distribution (m-1).

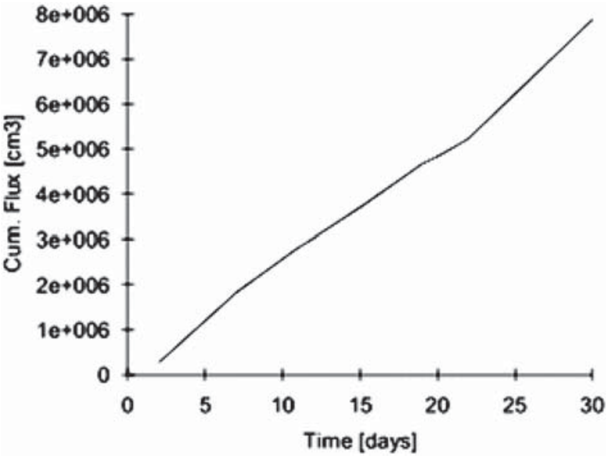


Fig 3. Cumulative potential root water uptake of 17 year old oil palm during 30 days simulation.

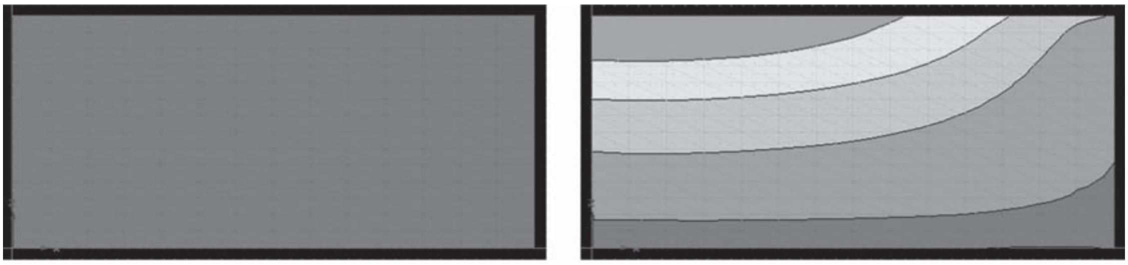
Data validation

The data validation was undertaken by comparing the simulated and observed daily water content data along the root zone area and performed in root mean squared error (RMSE) and coefficient of determination (R^2).

Result and Discussion

Root water uptake distribution

From the visualisation, there is the change of root water uptake pattern and distribution during simulation period. The root water uptake of oil palm on the first day represented the initial condition where there was a degradation of root water uptake along the horizontal and vertical root zone. At the beginning, with the rate of transpiration was 0.43 cm, the upper root zone around the trunk contributed the highest portion of root water uptake. Then, it degraded downward and sideward along the less intensive root distribution. The root water uptake seems to pursue the pattern of the root density that intensive along the 20 cm depth under the soil surface. The root density of oil palm tree varied vertically and horizontally. The tertiary and quarterly roots which have the highest contribution



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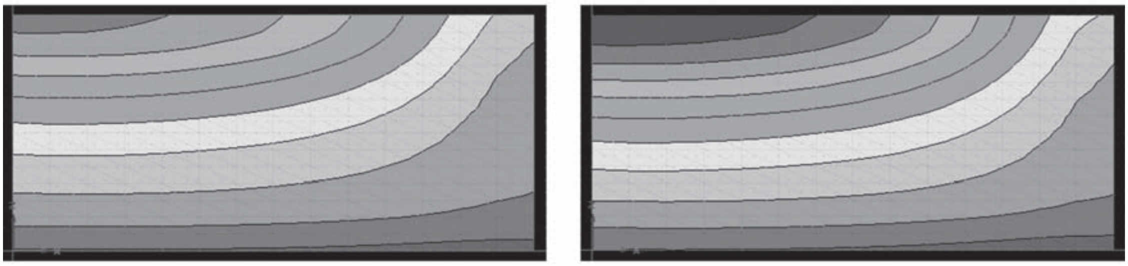

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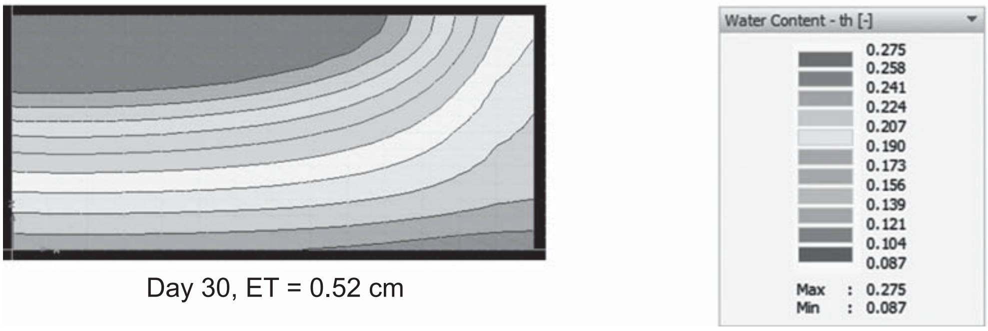


Day 30, ET = 0.52 cm

Fig 4. Water content change distribution along the root zone.

of up taking the water are intensive in upper layer root zone of oil palm tree (Safitri et al., 2018a, Safitri et al., 2019a). Furthermore, on the following days, the pattern of root water uptake on the upper zone changed from high at the beginning, medium at the mid of simulation and low at the end of simulation. Contrary, the root water uptake distribution along the bottom root zone was tending to being steady. Since the root distribution particularly the tertiary and quarterly roots are dense in the upper zone, the root absorption was also intensive at the zone. Without any flux entering the soil surface, the water availability decreased and the root water uptake did too. Otherwise, the less water absorption along the lower root zone kept the water still available during the end of the simulation. Moreover, referred to the Fig 3. The accumulated potential root water uptake of oil pam tree over the 30 days period of simulation was up to 8x10^6 cm^3 which which is similar to 266 litre/day/tree. With the length of radius tree coverage 450 cm, the water consumption over the surface area was equal to 4.2 mm/day.

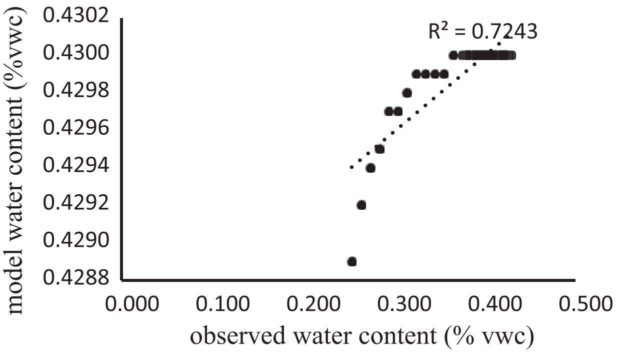
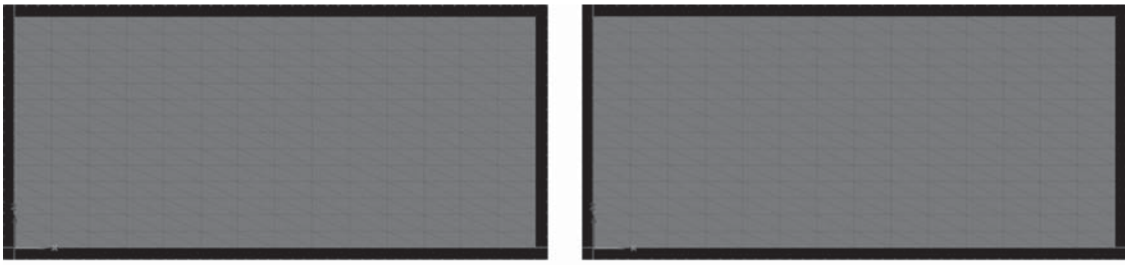


Fig 5. Data validation ; simulated and observed water content.

Water content distribution

Hereafter, the Fig 4 performed the water content change along the root zone of oil palm tree. The first day as the initial condition exposed the red colour that represented the high water content along the root zone. At the 7th day, the pattern transformed to a degrade water content from up to the bottom of root zone. The water content in the upper root zone drying up during the mid and the end of the simulation. Obviously, it was related to the intensive root water uptake without any flux entering the soil surface. Furthermore, the water content in downward change as it contributed to supply the water availability for the upper zone.

The Fig 5 presented the result of data validation by comparing the simulated and observed water



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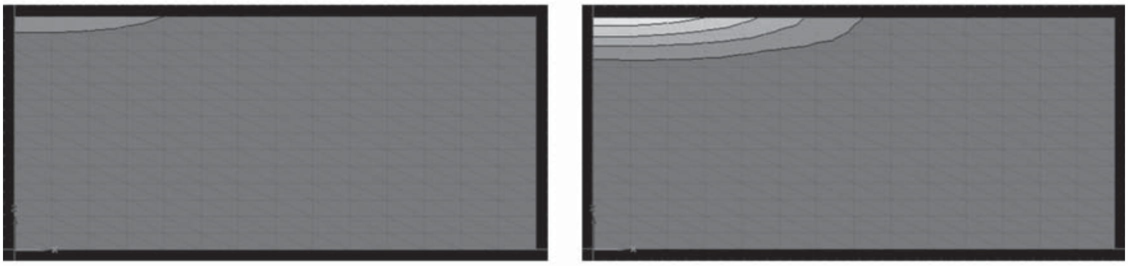

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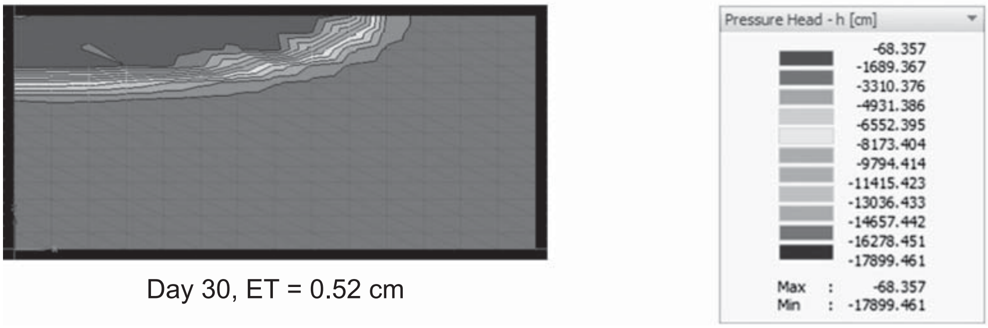


Day 30, ET = 0.52 cm

Fig 6. Pressure head change distribution along the root zone.

content. The observed data was collected from soil moisture measurement along the root zone using the sensor placed in 17th year oil palm during the observation period (22 Nov – 22 Dec 2018). The selected observed data furthermore was compared to simulated data in the same data along the root zone. The result showed that the simulation performed well based on the coefficient of determination ($R^2 = 0.724$) and root mean squeare error (RMSE = 0.0066).

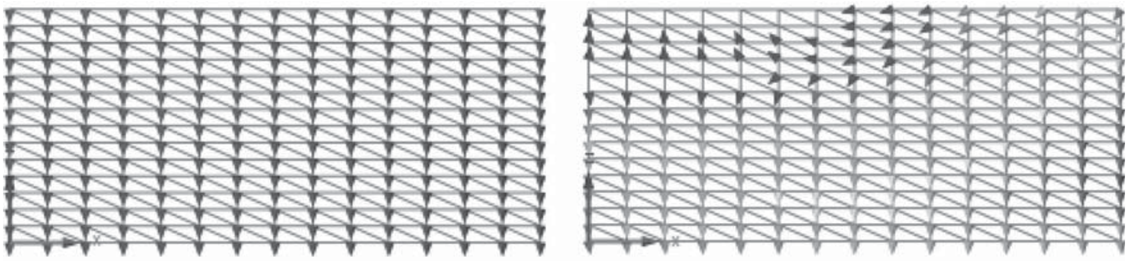
Pressure head distribution and Flow Velocity

The pressure head distribution at the initial condition was under 100 cm that similar to wet condition. There was insignificant difference in pressure head at the beginning. The important change started at the mid period of simulation that occurred only in the upper root zone approach to the oil palm trunk. At the end of simulation period, the pressure head change illustrated the increasing significantly in the upper root zone that represented the diminution of water availability to oil palm tree.

The last simulation's result was evidenced by the flow velocity along the root zone in the Fig 7. The flow velocity pattern of water at the first day represented the gravitational direction. On the following day, there was amount water flow that head to the trunk. The pattern of the flow velocity represented the root water uptake by oil palm tree. The significant pattern change was shown during the end of the simulation. Since there was an important root water uptake and the limited water content around the trunk of oil palm, consequently there was a water movement upward the root zone.

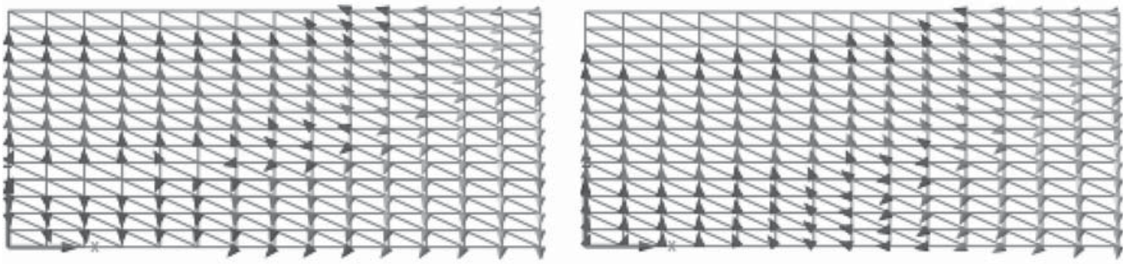
Conclusion

The simulation of 2D numerical soil and water flow model applied to oil palm tree resulted the visualisation of root water uptake distribution along the root zone following by the water content, pressure head and the flow velocity. The most intensive root water uptake occurred in the upper root zone of oil palm tree as an impact of the higher root density. The significant root water uptake in the upper root zone lead to the decreasing of water content and increasing of pressure head in the soil. Consequently, there was a change of water flow direction from the wet area in the downward and sideward do dry root zone as the water supply to the oil palm tree.



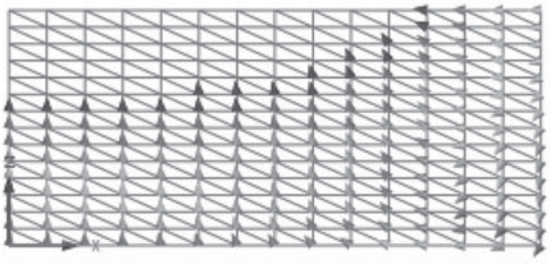
Day 1, ET= 0.43 cm

Day 7, ET = 0.49 cm



Day 16, ET= 0.35 cm

Day 20, ET = 0.255 cm



Day 30, ET = 0.52 cm

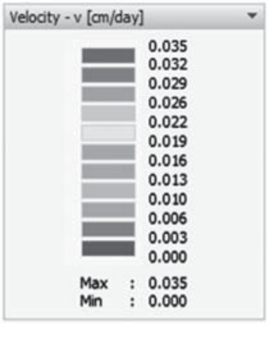


Fig 7. Flow velocity along the root zone.

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