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# The Most Likely Flooded Soil in Terengganu State During Historically Greatest Rainfall Intensity

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### ABSTRACT

Water infiltration in the soil is an essential topic for investigation because soil fully saturated with water forms standing water that leads to flooding on top of the soil. Soil investigation is vital for agricultural study due to the necessity to know soil carrying capacity in holding water, field capacity, and also the soil temperature for biological activities and chemical reactions. However, human urbanization and expansion into previously unexplored soil areas could lead to unnecessary environmental stress, such as floods. Floodwater forms when the rainfall intensity exceeds soil water infiltration. The flood event is crucial since it affects the human livelihood and facility damages. Therefore, a good understanding of soil hydraulic water infiltration helps better understanding the cause of flood occurrence. The current study examines the soil series in Terengganu state with its soil properties concerning the soil water characteristics curve, which indicates the soil's ability to absorb and allow water movement in the ground. The equation used was the improved Richards' equation that can be applied to examine the standing water or floodwater impacts on water infiltration. Also, the unsaturated soil moisture movement conditions can be investigated. The simulation equation verifies with benchmark datasets that was solved on Richards' equation using a different numerical method. The twelve-soil series of Terengganu state subjected to water infiltration study subjected to flooded conditions, by exposing the soil to the highest rainfall identified in the history of Kuala Terengganu from 1985 to early 2023. The results reveal Jambu, Rhu Tapai and Rudua soil series'

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water infiltration rate was greater than the rainfall intensity, whereas other soil series could not accommodate the rainfall intensity. Thus, other soil series areas will likely encounter flooded conditions when exposed to heavy rainfall, as has occurred in history.

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## 1. Introduction

Water supply depends on rainfall [1]. Rainfall scarcity causes drought [2,3], whereas an over-supply of precipitation causes a flood [4,5]. In agriculture, enough rain reduces the need for frequent irrigation, but heavy rainfall damages agricultural production [6,7]. The farm field practices water saving to minimize environmental stress and energy consumption costs, which implies cost reduction; however, during monsoon periods with heavy rainfall, a country like Malaysia experiences over water supply by rains [8]. The incoming abundance of water from rainfall has few pathways of dissipation. The dissipations are evaporation, water infiltration, surface water runoff, and an interception by plant and plant absorption in the root zone. Evaporation refers phase transition from liquid to gas phase that is water vapor but with limited influence on the overall water budget. Soil water infiltration is significant because it has enormous implications on flood and surface runoff [9,10]. After water absorption into the soil, the amount left over at the soil surface is the surface runoff. Water in large quantities on top of the ground contributes to flooding water, soil erosion, etc. [11]. Water intercepted by plants increases the amount of travel time or travel pathways, thus slowing the process of water accumulation downstream, which leads to flood [12]. In addition, the presence of plants often contributes to built-up organic materials on the soil surface, enhancing the entrapment of water, thus increasing water infiltration time and slowing water runoff by increasing the water pathway length at the soil surface. The plant root absorption extracts moisture from the soil [13]; hence, it generates more air space for water infiltration, indirectly increasing the water infiltration rate. Large soil particle size distribution dominated by sand further increase the water infiltration rate [14], and vice versa for soil dominated by clay content. Similarly, a large initial soil moisture content increases the water infiltration rate [15].

Before flood water formation in the downstream river, the rainfall water at the upstream partitions into surface water and the infiltrated soil water. Soil particles in contact with rainfall absorb the water until it is fully saturated [16]. As saturated soil begins to form, it has no leftover space for water absorption; hence, the water rises to cause flood occurrence at the soil surface [17]. Inevitably, soil water infiltration, if not solely, is partly responsible for flood water occurrence.

The current study aims to investigate the influence of soil types in Terengganu in absorbing water from rainfall. In a previous study, the Terengganu soil textures relate to the water required to irrigate the soil at the mass rate sufficient to wet the soil without causing wastage [18]. The study applies water infiltration at a soil moisture content at field capacity [19] for various textures of Terengganu soil. The field capacity is helpful for water saving in agricultural applications [20], but it has no significant importance in flood management. Flood management requires understanding soil water movement mechanisms under water-saturated conditions. A complete understanding requires knowledge of soil absorbing water when it is unsaturated, i.e., dry soil state, in a gradual transition into saturation, i.e., thoroughly wet soil with standing water above the soil surface. Flooded soil is an essential topic for investigation as the flood has almost become an annual event for Terengganu state [21]. Also, flood affects many people's livelihoods in the form of environmental destruction, property damage [22], and so forth. Therefore, the ability to identify the cause of water overflow from the perspective of different soil types in the Terengganu state is a valuable contribution adding to the existing knowledge pool in solving the problem.

## 2. Methodology

Soil types in Terengganu state obtain from the database of the Department of Agriculture, Malaysia [23]. The database provides the necessary information to identify the composition of the soil texture; thus, it helps determine the soil texture [24]. Subsequently, the data allows the estimation of the parameters for the van Genuchten equation [25] for each soil texture. The equation represents the characteristic curve given by,

$$\theta_L(\psi_m) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha\psi_m)^n\right]^{1-1/n}} \quad (1)$$

$$K(\theta_L) = K_s \left(\frac{\theta_L - \theta_r}{\theta_s - \theta_r}\right)^L \left\{1 - \left[1 - \left(\frac{\theta_L - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right]^m\right\}^2 \quad (2)$$

where  $\theta_L(\psi_m)$  is soil moisture content ( $\theta_L$ ,  $m^3 \cdot m^{-3}$ ) that relates to the soil matric suction ( $\psi_m$ , -m),  $K(\theta_L)$  is hydraulic conductivity in unsaturated soil ( $K$ ) varies with the soil moisture content,  $\alpha$  and  $n$  are constant parameters,  $L$  as the constant connectivity parameter,  $\theta_s$  is saturated soil moisture content ( $m^3 \cdot m^{-3}$ ),  $\theta_r$  is residual soil moisture content ( $m^3 \cdot m^{-3}$ ),  $K_s$  is hydraulic conductivity in fully water-saturated soil ( $m \cdot s^{-1}$ ), and  $m = 1 - 1/n$ . Refer to Goh and Noborio [15] for soil parameters that has the greatest influence on water infiltration. Among the soil texture in Terengganu, sand and loamy sand has the greatest  $K_s$ , whereas the lowest goes to clay and clay loam.

Water movement in the soil relies on the mechanisms dictating flow as [26,27],

$$\frac{q_L}{\rho_L} = -K \frac{\partial \psi_m}{\partial z} + K \quad (3)$$

where the first term on the right depends on water movement due to matric suction gradient and the second term on the right is the water flux due to gravitational pull.

Under an unsteady-state or transient water movement environment, the equation governing water flux in the soil is given by Richards' equation [28,29],

$$\frac{\partial \theta_L}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial \psi_m}{\partial z} \right) - \frac{\partial K}{\partial z} \quad (4)$$

Eq. (4) is commonly known as the mix-based Richards' equation that combines soil moisture content and matric suction in a single relation between the equation's left and right sides. However, the equation limits the quantification of water storage between saturated soil moisture content and residual soil moisture content; thus, unable to account for the soil under flooded conditions when soil pressure increases from negative to zero and greater.

For flooded soil, the following equation is employed [30],

$$\rho g [(1-\theta_s)\alpha + \theta_s\beta] \frac{\partial \psi_m}{\partial t} + \frac{\partial \theta_L}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial \psi_m}{\partial z} \right) - \frac{\partial K}{\partial z} \quad (5)$$

where  $\rho$  is soil water density ( $\text{kg}\cdot\text{m}^{-3}$ ),  $g$  is gravity ( $\text{m}\cdot\text{s}^{-1}$ ),  $\alpha$  is soil compressibility ( $\text{m}^{-1}$ ), and  $\beta$  is water compressibility ( $\text{m}^{-1}$ ). The Eq. (5) first term on the left side handles soil pressure when it has standing water, whereas the second term on the left accounts for the unsaturated soil moisture content. The first term on the left side is active during flood soil condition, whereas the second term on the left side is active during unsaturated soil condition.

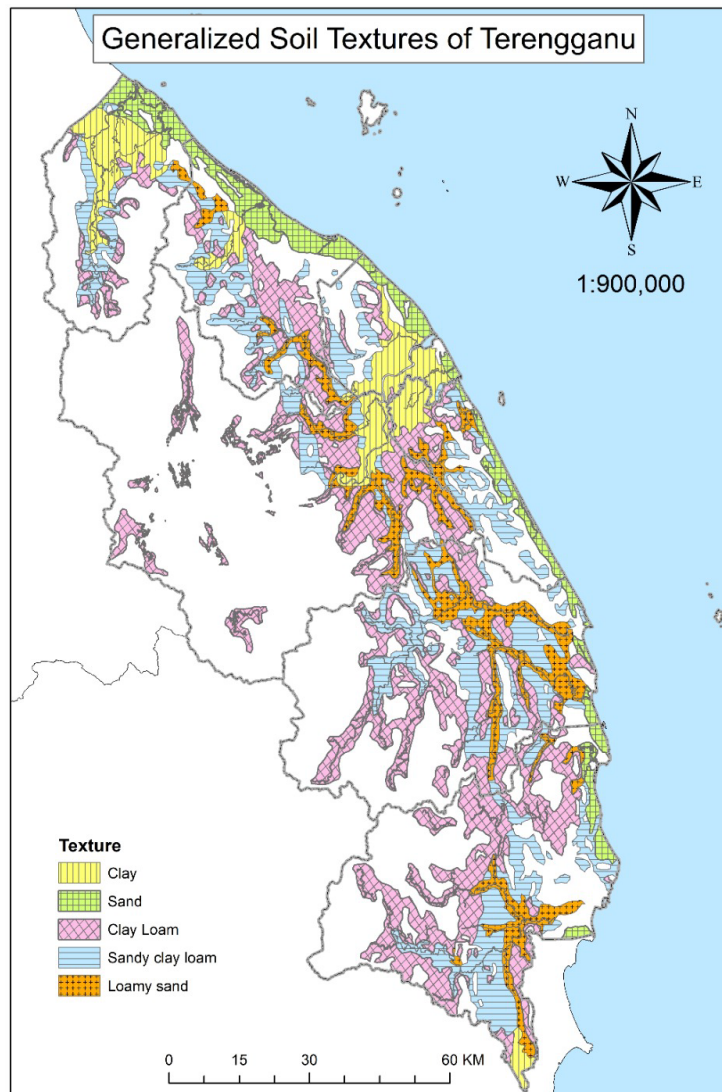
Eq. (5) conserves mass balance. The equation in discretized form of algebra is as follows,

$$\begin{aligned} \rho g [(1-\theta_s)\alpha + \theta_s\beta] & \left[ \frac{\psi_{m(k)}^{n+1} - \psi_{m(k)}^n}{\Delta t} + \frac{\theta_{L(k)}^{n+1} - \theta_{L(k)}^n}{\Delta t} \right] \\ & = \frac{K_{k+\frac{1}{2}} \frac{\psi_{m(k+1)}^n - \psi_{m(k)}^n}{0.5\Delta z_{k+1} + 0.5\Delta z_k} - K_{k-\frac{1}{2}} \frac{\psi_{m(k)}^n - \psi_{m(k-1)}^n}{0.5\Delta z_k + 0.5\Delta z_{k-1}}}{\Delta z_k} - \frac{K_{k+\frac{1}{2}} - K_{k-\frac{1}{2}}}{\Delta z_k} \end{aligned} \quad (6)$$

where the description of the method of discretization from partial differential equation to a set of algebra equations is similar to those reported in previous studies [15,18-20,31].

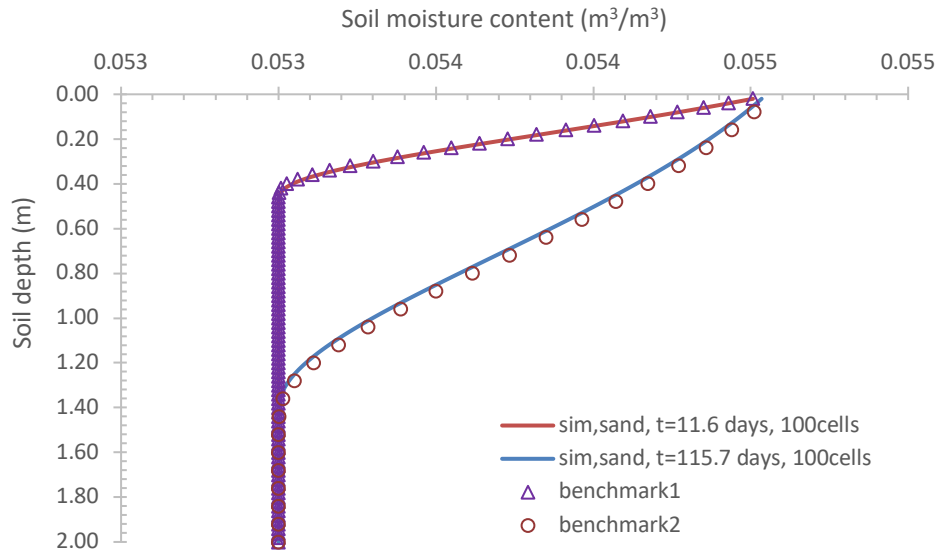
### 3. Results and Discussion

In general, Terengganu state has twelve soil series. The twelve-soil series were Batu Hitam, Jambu, Rhu Tapai, Rudua, Gondang, Tasik, Lubok Kiat, Kampong Pusu, Tok Yong, Jerangau, Tersat, and Kuala Brang Series [18]. A further generalization of the soil series classifies the twelve-soil series into five soil textures. They were clay loam, clay, loamy sand, sandy clay loam, and sand, as shown in Figure 1. The soil texture closely ties the water retention curve, also known as the characteristic curve of the soil. A characteristic curve is a mathematical or graphical relation that illustrates the relationship between soil moisture content and soil pressure. The pressure is commonly known as the soil matric suction. A typical association of this relationship is to expect the soil moisture content to decrease with increasing soil matric suction pressure. Thus, dry soil has the most significant soil matric suction. Similarly, a soil texture with a smaller soil particle size, such as clay, exhibits the greatest value of soil matric suction than that of sandy soil. The characteristic curve is necessary for the water infiltration equation, such as in Eq. (5).

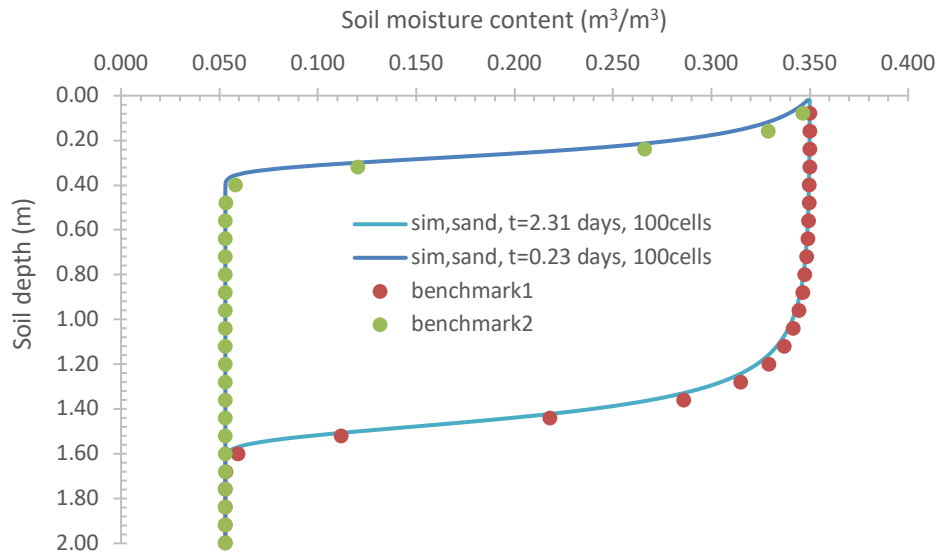


**Fig. 1.** Soil textures distribution in Terengganu State

The inclusion of Eq. (1) and Eq. (2) into Eq. (5) allow the simulation of water infiltration into the soil pressure head greater than zero and also the movement of soil water under unsaturated soil moisture content. Before the simulation uses to investigate any case study, a common practice is to verify the simulation output. The current research verifies the simulation output from Eq. (5) with benchmarking datasets. The result of the comparison shows in Figure 2 for sandy soil. The figure shows water infiltration into sandy soil at field capacity and near water saturation. The water infiltration front at different times, i.e., 11.6 and 115.7 days (Figure 2(a)), and 0.23 and 2.31 days (Figure 2(b)), clearly showed a close approximation between the simulation output and the benchmark datasets.



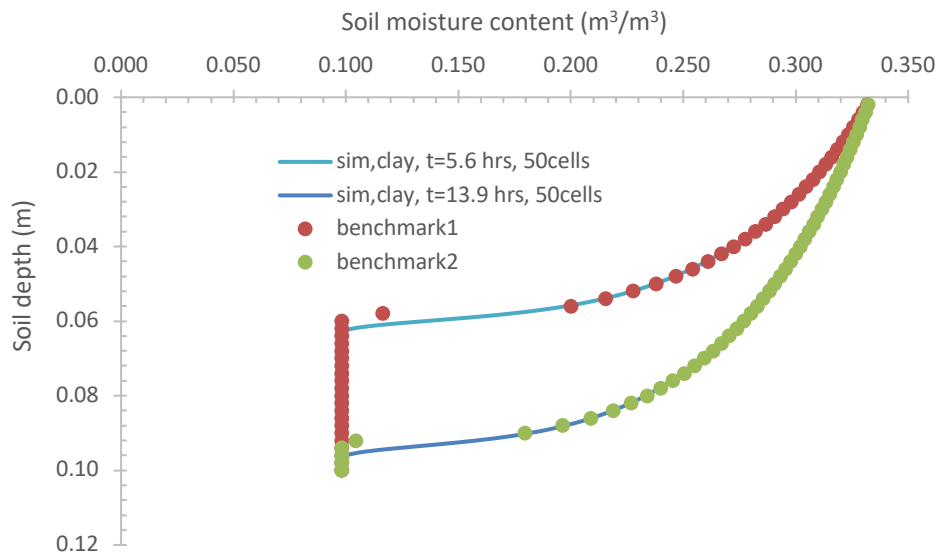
(a)



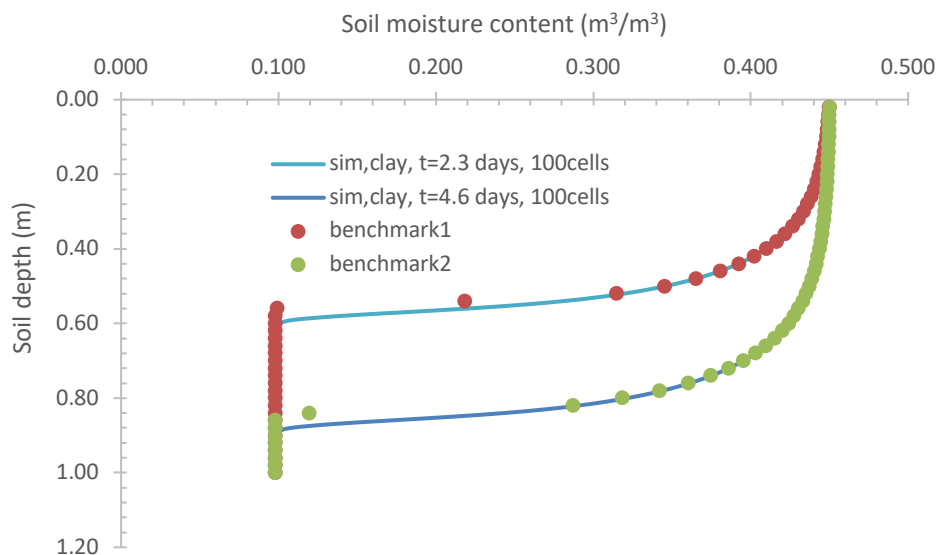
(b)

**Fig. 2.** Sandy soil at (a) field capacity, and (b) near water saturation at the soil surface. The comparison between the simulation results of the water infiltration into sandy soil, Eq. (6), solved by an explicit method, and the water infiltration model (benchmark) solved by an implicit method

Further examination of water infiltration at field capacity and near saturation at the clay soil surface indicates a similar approximation between Eq. (5) and the benchmark datasets (Figure 3). Hence, the findings have verified the simulated results' reliability, allowing further investigation.



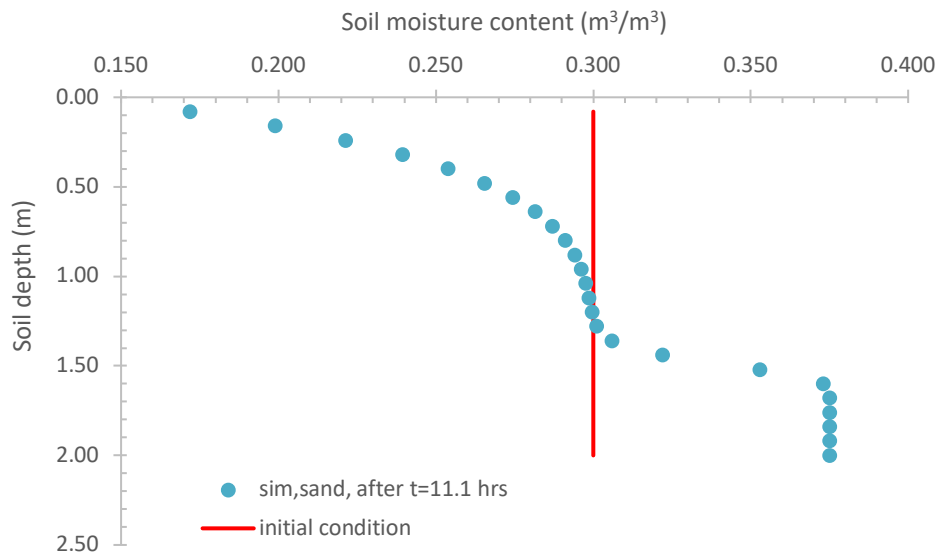
(a)



(b)

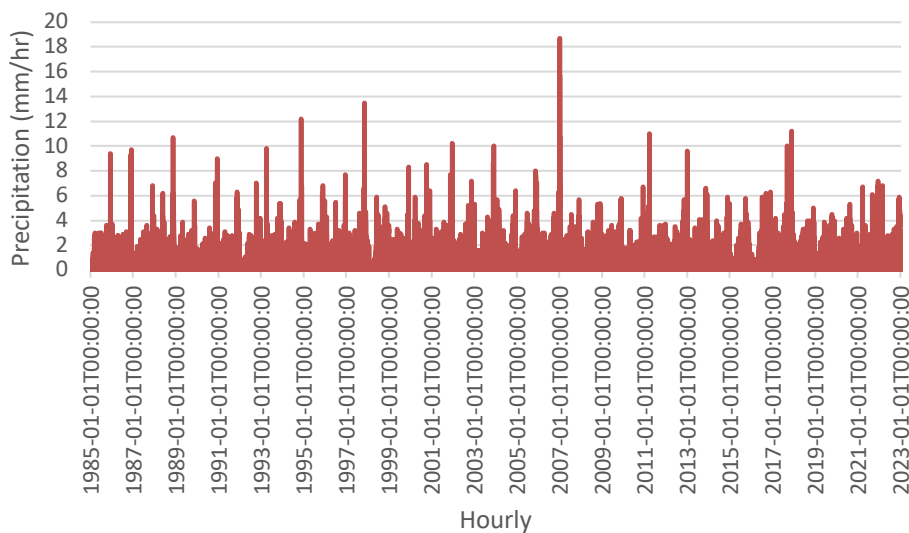
**Fig. 3.** Clay soil at (a) field capacity, and (b) near water saturation at the soil surface. The comparison between the simulation results of the water infiltration into sandy soil, Eq. (6), solved by an explicit method, and the water infiltration model (benchmark), solved by an implicit method

In addition, the model has two physical mechanisms. One is the gravitational attraction of the water to move downward in the soil profile. The mathematical description is by the second term on the right side in Eq. (5). To illustrate the physical mechanism of the soil in graphical illustration, Figure 4 demonstrates the gravitational pull effects on an initially homogenous soil moisture content distributed soil depth. The initial soil moisture content at 0.3 allows for redistributing over the whole soil depth, which is set impermeable at the top and bottom.



**Fig. 4.** Water distribution in the sandy soil profile after simulating 11.1 days from a homogenous soil moisture content of 0.3

Figure 5 is the collection of the hourly water precipitation in Kuala Terengganu from early 1985 to early 2023. At any hour of the day, no rainfall is a typical condition. Almost four decades, 77% of the hourly basis is no rain. The other 23% is the rainy hour. The highest rainfall observed was 18.7 mm/hr in January 2007. Hence, the highest value of the rain is a good testing value that applies to the pressure head (standing water) used on top of the soil. Should the soil type entirely absorb the rainfall water within an hour of precipitation, no standing water or flood appears on top of the ground. Thus, the absorption of soil water is greater than the rainfall intensity.

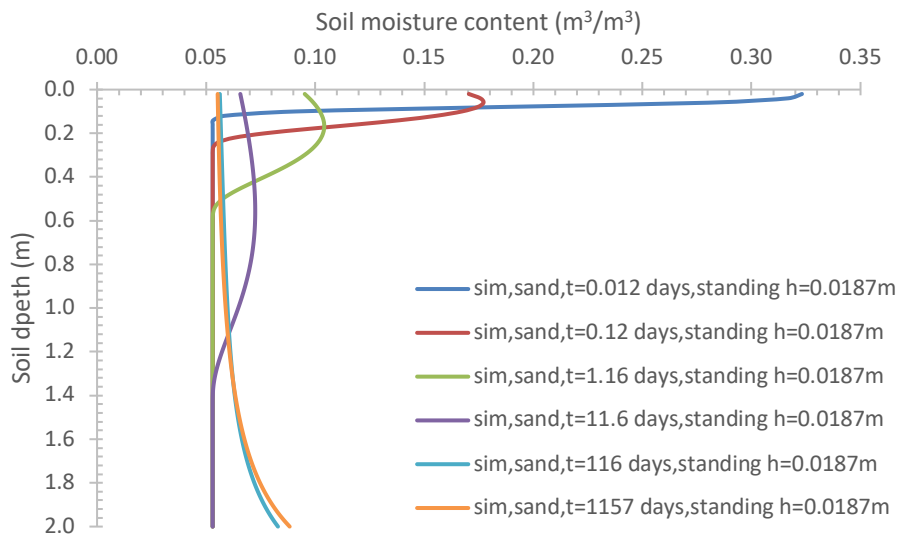


**Fig. 5.** Rainfall almost over four decades from 1985 to early 2023. The hourly rainfall data implies 24 points of rainfall indication for a day

The 18.7 mm pressure head was used as the standing water on the soil surface on all the soil textures of Terengganu soil to investigate the soil water infiltration distribution in the ground (Figure 6). The soil depth used was 2 m, with the bottom boundary impenetrable, while the top was permeable to rainfall that creates standing water. As water penetrates the soil depth, the standing

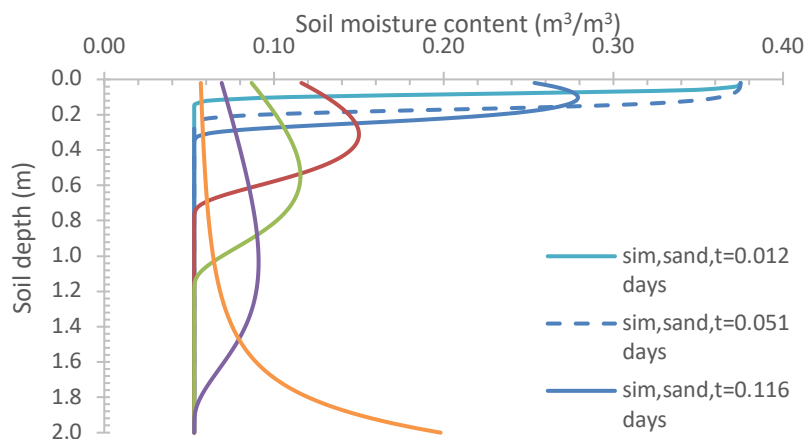


water decreases height, simulating the falling head-water infiltration. A considerable spike in soil moisture content at the near soil surface depth that the soil moisture content reaches over 0.3 at 0.012 days. The area covered by the curve indicates the sum of 18.7 mm amount of rainfall. Once the rain of 18.7 mm had penetrated the soil, the soil surface switched into an impervious surface. Thus, the equal amount of water mass or volume, in this case, allowed it to penetrate deeper into the soil. At 0.12 days, the peak of soil moisture declines in compensation with the rise of soil moisture at the deeper ground.



**Fig. 6.** Water infiltration with 18.7 mm standing water on top of the sandy soil simulated using the falling head method

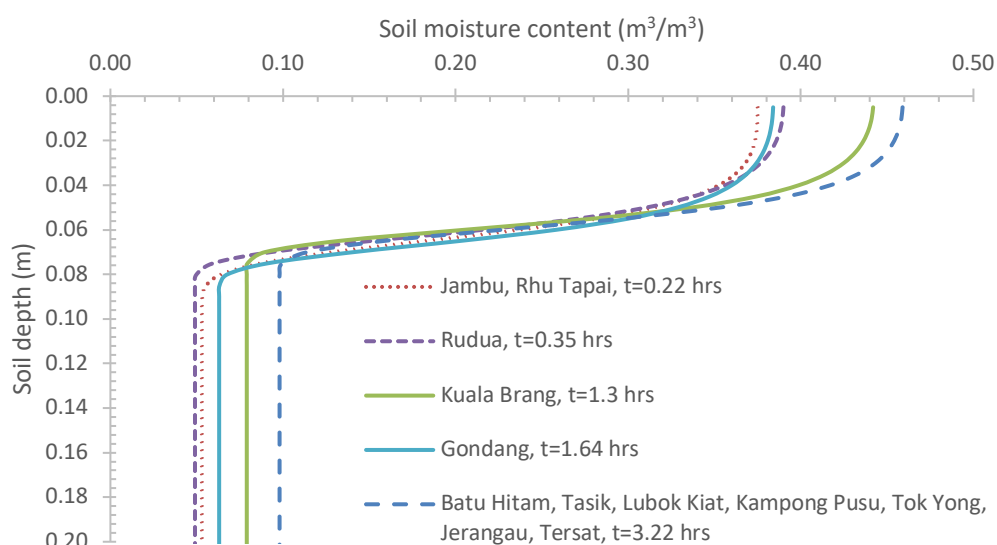
The process of soil water penetration was allowed to continue until 1157 days, which observes an explicit decreasing soil moisture content with soil depth. A repeated simulation with a more considerable standing water height (50 mm) at the surface has shown that a greater volume of water has penetrated the soil with an increased rate of water infiltration, and a similar soil water infiltration profile appears in a shorter time (Figure 7).



**Fig. 7.** Water infiltration with 50 mm standing water on top of the sandy soil simulated using the falling head method. The dashed line indicates the state of simulation that all the standing water (50 mm) has wholly penetrated the ground

Figure 8 demonstrates the water infiltration of 18.7 mm standing water over the topsoil to identify the time required for complete standing water penetration into the soil. Soil series of Jambu dan Rhu Tapai appear to allow the fastest water infiltration into the ground. The observation is the result of the sandy soil texture. Rudua soil series has the second fastest soil water infiltration. The other soil series such as Kuala Brang has a water infiltration time greater than 1 hour. The Batu Hitam, Tasik, Lubok Kiat, Kampong Pusu, Tok Yong, Jerangau, and Tersat soil series have the longest water infiltration time. The longest water infiltration time is the result of clayey soil texture. Given that 18.7 mm/hr is the highest precipitation in the history of Kuala Terengganu, only Jambu, Rhu Tapai and Rudua absorb the entire standing water within an hour.

In contrast, other soil series (Kuala Brang, Gondang, Batu Hitam, Tasik, Lubok Kiat, Kampong Pusu, Tok Yong, Jerangau, and Tersat) will encounter an accumulation of water over the soil surface after an hour of rainfall leading to flood event occurrence. Thus, these soil series will experience a collection of surface water for surface runoff formation and eventually contributes to the creation of flood water on top of the soil. In terms of the water infiltration into the soil depth, all soil series have almost identical soil moisture distribution profiles with only minor apparent distinctions observed on the residual and saturation levels of soil moisture contents.



**Fig. 8.** Time needed for complete penetration of standing water (18.7 mm) into the various soil textures. The water infiltration simulates falling headwater as the water seeps through the ground surface

#### 4. Conclusion

Conventional Richards equation in mix-based form as in discretized form does not accommodate standing water or flood water on top of the soil. The current study improves Richards' equation to study standing water or flood water infiltration into the ground. The study was carried out on all soil series in Terengganu state. The largest rainfall in the history of Kuala Terengganu was applied to the soil surface and study the water infiltration with falling head conditions imposed on the soil surface. The simulation reveals Jambu, Rhu Tapai and Rudua's water infiltration rates are greater, due to greater saturated hydraulic conductivity, than the rainfall intensity, whereas other soil series have water infiltration rates lower than rainfall intensity. Hence, the latter soil series will be vulnerable to surface water accumulation leading to floodwater formation on the soil surface, should the history of

high rainfall intensity repeat itself in the future. In addition, more studies, such as nonhomogeneous soil layers, could be carried out in the future.

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