Final Report: Modelling of Subsurface Drip Irrigation Systems

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SUMMARY

- A HYDRUS model was developed, adopting field derived van Genuchten retention curve parameters for Duplex and Uniform Clay soils.
- Model predictions, with the emitter placed at 20 cm depth, of matric potential were validated with field data showing good agreement. Almost homogenous wetting was predicted by the model for Uniform Clay. For the Duplex soil, there is a greater propensity for soil wetting in the vertical direction compared to lateral wetting. For both soil types, the predicted matric potentials were close to field measured data. The model was further run with emitter placed at 5 cm depth. The results obtained are consistent with expected behaviour in the field.
- A set 42 HYDRUS model runs was conducted to investigate the effects of varying emitter spacing, depth and flow rate on soil wetting. This allowed the evaluation of a set of best-bet options that could be evaluated as follow up studies in the paddock.
- For both soil types, the water lost (water loss) to free drainage is influenced significantly by emitter placement depth, increasing with depth. The average increase in water loss to free drainage is about 18.3% and 7% for Duplex and Uniform clay, respectively. For emitters located at the same depth, delivery rate has a greater influence on water loss compared to spacing.
- The effect of spacing on free drainage loss is insignificant at high delivery rates. At lower delivery rates, although some variability exists, the variation in water loss with emitter spacing is expected to be small, for the emitter spacings considered.
- Qualitative assessment investigating the distribution of the matric potential revealed increased surface wetting for emitters placed at shallower depths. Wetting is most pronounced for the Duplex soil where fully saturated conditions at the surface were predicted above the emitter throughout the simulation period. In this case, closer emitter spacing is advantageous in reducing surface wetting.

INTRODUCTION

Improvements in irrigation system design and management are needed to reduce the incidence of waterlogging and water stress and to potentially improve water and fertiliser efficiencies in duplex red brown earths used by the processing tomato industry in northern Victoria and southern NSW. Computer modelling offers a pragmatic approach to irrigation design as it allows repeat testing of configurations and design variables, in a low-cost desktop approach. It has the advantage of being able to assess differences between multiple combinations of parameters (e.g. emitter delivery rate, spacing and depth) in a cost effective way. "Best bet" outcomes from the simulation modelling can then be tested in later field trials in a more targeted fashion.

The Australian Processing Tomato Research Council Inc (APTRC) and Deakin University (DU) have entered into a Research Agreement with the aim of (i) Developing a computer model to simulate drip irrigation and (ii) Propose optimal irrigation designs (emitter rate, spacing and depth) and water management (frequency and duration of irrigations) strategies to improve water efficiency, in duplex and red brown earths.

The computer model solves the full set of the Richards equation numerically simulating water movement in the saturated/unsaturated zone within the subsurface. Soil hydraulic properties will be prescribed using retention curve (van Genuchten 1980) parameters appropriate for the soil type considered. This soil properties data will be obtained from a separate study. System optimization will be carried out using the technical specifications to be provided by an appointed irrigation supplier.

This document constitutes reporting of work completed under Milestone #2 of the Research Agreement. An Interim Report for the work accomplished for Milestone #1 was submitted on 30 June 2021, which detailed preliminary modelling development including model validation and proposal of a methodology at investigating system optimization. This Final Report details results and proposal for optimal irrigation design.

METHODOLOGY

HYDRUS Modelling

The HYDRUS model (https://www.pc-progress.com/en/Default.aspx?support-hydrus) is a Microsoft Windows based modelling environment for the analysis of water flow and solute transport in variably saturated porous media. The use of the HYDRUS model to evaluate sub-surface drip irrigation systems have been reported internationally (e.g. Simunek *et al.*, 2012) and nationally (e.g. Cote *et al.*, 2003).

The HYDRUS model solves the Richards equation for unsaturated soil. Richards equation adopts the Darcy equation for saturated flow:

$$q = -Ki$$

where q is the flow rate, K is the hydraulic conductivity and i is the hydraulic gradient. In saturated soils:

$$i = \frac{\partial}{\partial z}\left(\frac{p}{\rho g} + z\right)$$

where the hydraulic head $H = \frac{p}{\rho g} + z$ and p is pressure and z is elevation. For unsaturated soils, the hydraulic head is modified as:

$$H = \psi + \mathrm{z}$$

where ψ is the matric potential. The Darcy equation applied to unsaturated soils becomes:

$$\begin{aligned} q &= -K(\psi)\frac{\partial}{\partial z}(\psi + z) \\ &= -K\left(\frac{\partial \psi}{\partial \theta}\frac{\partial \theta}{\partial z}\right) - K \end{aligned}$$

since ψ and water content, θ are uniquely related, and $\frac{\partial \psi}{\partial \theta}$ is the specific water capacity and $\frac{\partial \theta}{\partial z}$ water content gradient in the vertical direction. The application of the Darcy equation for unsaturated soils into the equation of continuity results in the Richards equation solved in HYDRUS:

$$\frac{\partial}{\partial x}\left(K(\psi)\frac{\partial \psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(\psi)\frac{\partial \psi}{\partial y}\right)+\frac{\partial K(\psi)}{\partial z}-S=\frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t}$$

Model setup

To solve flow problems in unsaturated media, the relationship between matric potential and water content is required to characterise the soil material. North (2021) conducted a set of field experiments collecting field soil moisture characteristic data from the two major soil types used by the industry (i.e. duplex RBEs and uniform clays). The data was used to empirically develop retention curves using the formulation proposed by van Genuchten (1978) which is widely used in computer models. In addition, Ks was also estimated in the field, to be 12 cm/d and 46 cm/d for the duplex and uniform clay soils, respectively. Further details on experiments conducted and results obtained can be found in North (2021). The soil properties and Ks values adopted in the HYDRUS model are reported in Table 1. For the Duplex soil, two layers were assumed with the appropriate set of parameters prescribed for the top 15 cm (sity loam) and > 15 cm depth (clay loam) layers, as shown in Table 1. Homogenous soil properties were prescribed for the Uniform Clay soil type.

Table 1 Soil parameters adapted from North (2021) used in HYDRUS modeling

Soil type	**Soil depth**	θ_s	θ_r	**α (cm^{-1})**	***n***	K_s
Duplex RBE (*Chromosol*)	0 -15 cm	0.37	0	0.012	2.3	10
	>15 cm	0.36	0.01	0.005	2.2	10
Uniform clay (*Vertosol*)	> 0	0.38	0.068	0.008	2.0	40

Model Validation

The HYDRUS model was run in two dimensions (2-D). This assumes that the emitter is discharging uniformly along the drip line, and soil wetting can be assessed on a vertical (x-z) plane, perpendicular to the drip line. The assumption of 2-D flow has been validated in field studies (Skaggs *et al.*, 2004) and modelling in 2-D is widely reported in literature (Provenzano, 2007; Hanson *et al.*, 2008; Kandelous *et al.*, 2012). A typical model setup is shown in Fig. 2. The model domain was a vertical (x-z) plane measuring 75 cm wide x 80 cm deep. The boundary conditions adopted in the model were free drainage for the bottom boundary, variable flux for the emitter and zero flux elsewhere. Zero flux conditions are applied to the left and right hand boundaries due to symmetry and to the top surface. Emitters with radius of 1 cm, spaced 50 cm apart and discharging at 1.05 L/hr for 4 hours, once per day, were adopted in the model. The emitter was located 20 cm below the soil surface. The initial matric potential was estimated by trial.

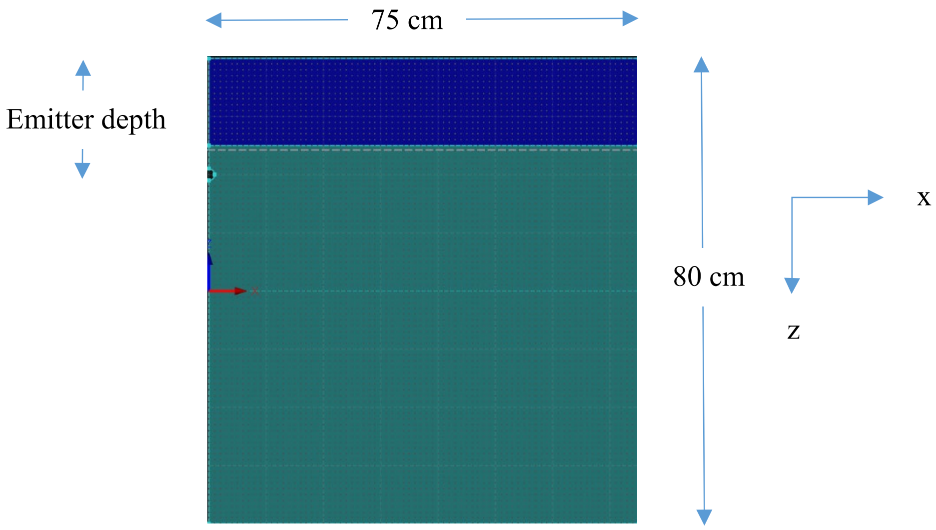


Figure 2. Modelled domain in 2-D for Duplex soil. Top 15 cm layer consists of silty loam underlain by clay loam. Emitter is shown in the clay loam layer.

System optimization

After validating the model against field data, further work in optimising irrigation design was conducted following planned computer simulations for the variation in design parameters shown in Table 2. This series of numerical experiments consider varying emitter delivery rate (discharge), spacing, placement depth and duration of irrigation. The methodology outlined in Table 2 was derived assuming drip lines spaced at 1.5 m apart, and delivery rates (total depth) of not more than 12 mm per day. Emitters placed at 10 cm and 25 cm depth were considered, with emitters spaced at 0.3 m, 0.4 m and 0.5 m apart. This configuration results in watering period ranging from 3.5 h – 18 h, and effective application rates of 0.67 mm/h to 3.33 mm/h. An initial set of 18 experimental runs (Run 1 - 18) was proposed in the Interim Report. This was complemented by an additional 6 experimental runs (Run 19 – 24) for the Duplex soil, by considering emitter discharge of 0.75 L/h. Therefore, a total of 18 experimental runs were conducted for Uniform Clay and 24 experimental runs for Duplex soil, resulting in a total of 42 experimental runs. The additional experimental runs for the Duplex soil were confirmatory. The trend in Duplex soil results were not as clear, likely due to the soil stratification and proximity of the emitter to the interface of the soil types and an additional set of runs was therefore included to establish clearer trends in the model results. Individual configurations were be assessed by quantifying the water loss to free drainage, defined as the cumulative flux across the bottom boundary located 80 cm below ground surface (Fig. 2). This comparison will allow the evaluation of a set of best-bet options that could be evaluated from experimentation in the paddock.

Table 2 Experimental matrix of model simulations to optimise water efficiency and management.

Run	Discharge (L/hr)	Emitter depth (cm)	Spacing (cm)	Duration (hrs)	Delivery (mm/d)	Delivery rate (mm/h)
1	0.5	10	50	18	12.0	0.67
2			40	14	11.7	0.83
3			30	10.5	11.7	1.11
4		25	50	18	12.0	0.67
5			40	14	11.7	0.83
6			30	10.5	11.7	1.11
7	1.05	10	50	8.5	11.9	1.40
8			40	6.75	11.8	1.75
9			30	5	11.7	2.33
10		25	50	8.5	11.9	1.40
11			40	6.75	11.8	1.75
12			30	5	11.7	2.33
13	1.5	10	50	6	12.0	2.00
14			40	4.75	11.9	2.50
15			30	3.5	11.7	3.33
16		25	50	6	12.0	2.00
17			40	4.75	11.9	2.50
18			30	3.5	11.7	3.33
19	0.75	10	50	12	12.0	1.00
20			40	9.5	11.9	1.25
21			30	7	11.7	1.67
22		25	50	12	12.0	1.00
23			40	9.5	11.9	1.25
24			30	7	11.7	1.67

RESULTS

Model Validation

The purpose of model validation was to verify that the model predictions were consistent with field observed data and that the model was able represent the system well. This step is needed to develop confidence in the model and ensure that the model is reasonably capturing the flow within the modelled domain. HYDRUS model results were compared with field data provided by North (2021). The contours in Fig. 2 represent the matric potential conditions averaged over the summer of 2019 – 2020, and were graphed using data collected at three depths each, along the z = 0, cm and 50 cm axes. The emitter is located ~20 cm below surface along the vertical axis of symmetry. The results for Uniform Clay (Fig. 2(a.)) are noticeably uniform. The matric potential ranges from around 0 kPa (at the emitter location) to an average of ~40 kPa at mid-distance to the edge (z = 50 cm), with a small bulb of slightly higher matric potential at mid-depth. The results for the Duplex soil (Fig. 2(b.) show a lesser tendency to wet laterally, with a wetter zone confined generally within a narrow band along the vertical axis passing through the emitter, with increased wetting below the emitter. Significantly, a dry zone is observed in the top right-hand corner of the plot, with pressures of ~200 kPa observed.

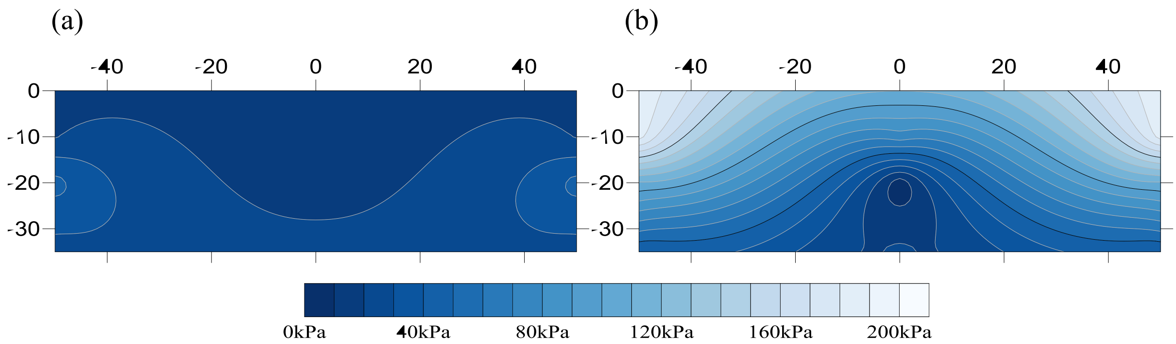


Figure 2. Matric potential obtained from field measurements in (a.) Uniform Clay and (b.) Duplex soil, averaged over the 2019–2020 summer period (North, 2020).

These observations allows the opportunity for model results to be compared against, to ensure that the model had been appropriately set up, and able to represent the field conditions by replicating the key features of the flow behaviour highlighted here. To be consistent with the field conditions, water was applied at the start of each day for 4 hours, in the model.

Duplex soil

For the Duplex soil, the model was run for 14 days and contours of matric potential at specific days are shown in Fig. 3(f – j). Figures 3(f, g, h, j) show contours at the end of selected days, or 20 hours after water is applied. These figures therefore show the matric potential at the end of the redistribution period, prior to the next watering event. Figure 3(i) shows contours directly after the end of water application on Day 13, before redistribution (t = 13.2 d). The dashed square (Fig. 3(j.)) shows the extent of approximately one-half (split along the vertical axis of symmetry) of the contour plots shown in Fig. 2(b.). The matric potentials at the end of 14 days' simulation represent the field data well. A wetter zone, confined mainly to a vertical region close to the emitter is evident, and the soil progressive becomes drier away from the centreline. This wetting behaviour is consistent with field observations by North (2021). In addition, the dry zone at the soil surface is also predicted well by the model. The matric potentials predicted by the model range from ~30 kPa close to the emitter location to ~170 kPa in the top corner dry zone, consistent with the field data (Fig 2 (b.)).

The contours plotted in Fig. 2(b) approach horizontal whereas the model predicts a more vertical distribution of the matric potential. The horizontal variation is likely due to a combination of a plotting artefact and a variable initial condition. Field data were obtained from 6 measurement points, three each along the two vertical axes passing through z = 0 cm and 50 cm, with no measurements along the bottom boundary. The gradation of matric potential along the lower boundary in Fig. 2(b.) is likely an artefact of plotting, since no measurements were made at the lower boundary. The matric potential at the bottom boundary predicted by the model varies from ~15 kPa to 30 kPa. Although the averaged measured values are within the same range, the difference appears to be smaller. This suggests a more uniform distribution of the matric potential at the lower boundary which can be attributed to wetter initial conditions at the deeper portion of the soil layer. This is likely to be site dependent and non-uniformity in starting conditions was not explored in the model. Given that the magnitude of the matric potential are well predicted, this affirms that the soil parameters determined from field experiments are generally representative for the given soil type. In addition, the model is able to replicate flow behaviour for the given soil conditions well, close to what was observed in the field.

Uniform clay

For the Uniform Clay soil, the model was run for 7 days and model contours of pore water pressures at specific days are shown in Fig. 4(f – j). Figures 4(f, g, h, j) show contours at the end of selected days (i.e., about 20 hours after water is applied). Figure 4(i) shows contours directly after the end of water application on Day 6 (t = 6.2 d), where the characteristic wetted area close to the emitter is evident. At the end of the redistribution period in Day 7 (Fig. 4(j.)), the contour lines approach horizontal and matric potentials are more uniform. By this time, the matric potential within the computation domain range between -210 cm (21 kPa) to -290 cm (29 kPa). The almost homogeneous wetting pattern that is observed in the Uniform Clay field data (Fig. 2(a.)) is well depicted by the model. The range of matric potential predicted by the model is in close agreement to the measurements made in the field (Fig. 2(a.)).

Further assessment with emitter at 5cm depth

The model was also run with the emitter placed at 5 cm below surface. This was done to further test the model and elucidate key differences in flow features between shallower and deeper placement of the emitter.

For the Duplex soil, with the emitter at 5 cm depth within the silty loam layer (Fig 3(a – e)), flow redistribution is more constrained after successive wetting cycles over the 14 days. It is observed that a zone of low matric potential persists (black region) throughout the entire 14 day simulation period. This is accompanied by an almost vertical front with a steep potential gradient emanating laterally through the upper soil layer travelling 50 cm after 14 water application cycles. Wetting of the lower soil layer is observed from this top layer, with the accompanying lateral redistribution just beneath the top layer proceeding at a faster rate evidenced by a potential gradient that is less steep than the silty loam layer and tilted almost horizontal at the interface of the two soil layers. In contrast to the deeper placement of the emitter, the potential gradient at the wetting front shows two distinct linear portions, with a characteristically steeper gradient extending vertically within the silty loam layer. The downward wetting behaviour with the 5 cm depth emitter placement is in contrast with the 20 cm depth placement, where wetting upwards is clearly evident even as flow in the bottom layer spreads laterally; this results is an almost continuously linear region of potential gradient tilted at a shallow angle (Fig. 2(f-i)). Lastly, a more distinct downward water movement along the emitter axis is observed for the emitter located at 20 cm.

Comparisons with the emitter placed at 20 cm depth for the Uniform Clay soil are unremarkable. Matric potential is almost uniform after 7 days, suggesting homogenous wetting, as was observed for the 20 cm emitter placement depth. A greater degree of surface wetting with the emitter placed at 5 cm is observed, which is to be expected.

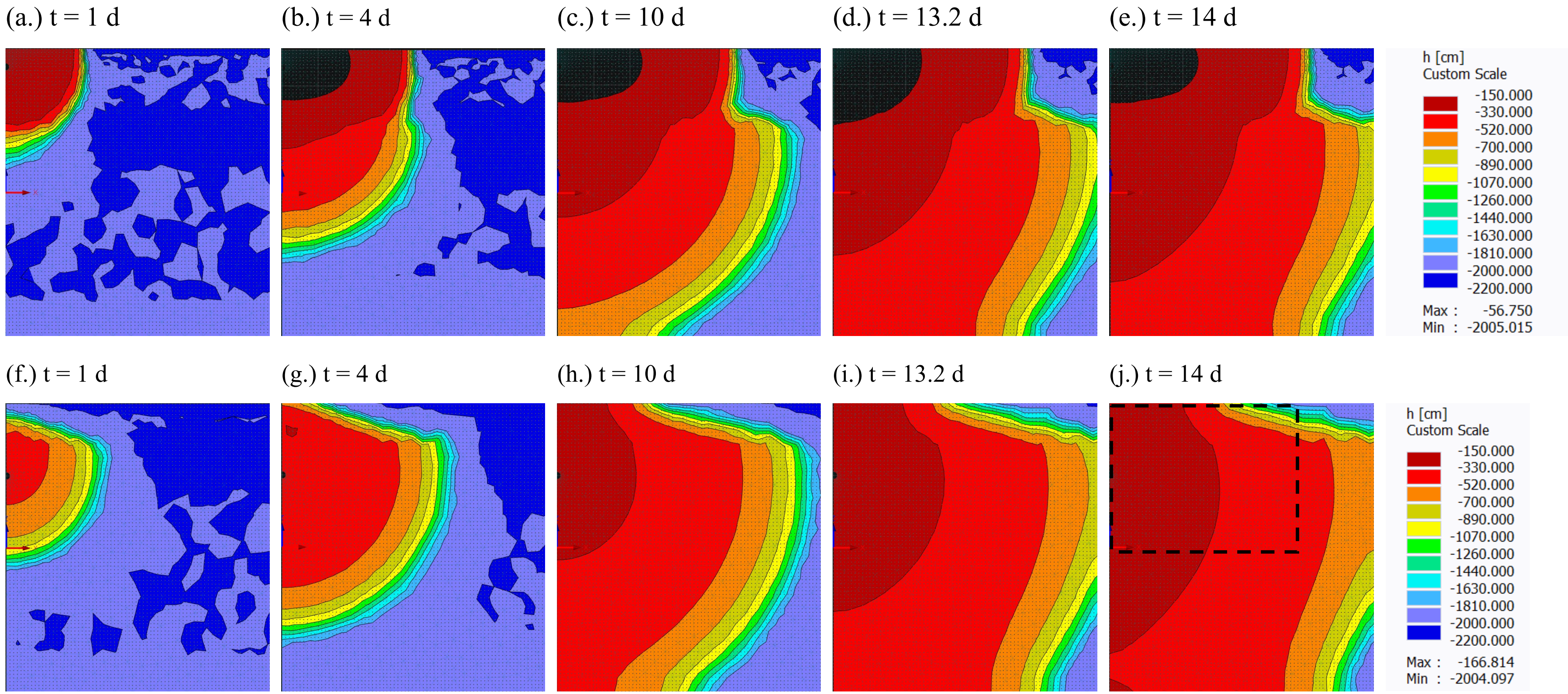


Figure 3. Contours of pore water pressures for Duplex soil with emitter placed at 5 cm (a. to e.) and 20 cm (f. to j.), below surface. Emitters are spaced 0.5 m apart, delivering 1.05 L/h.

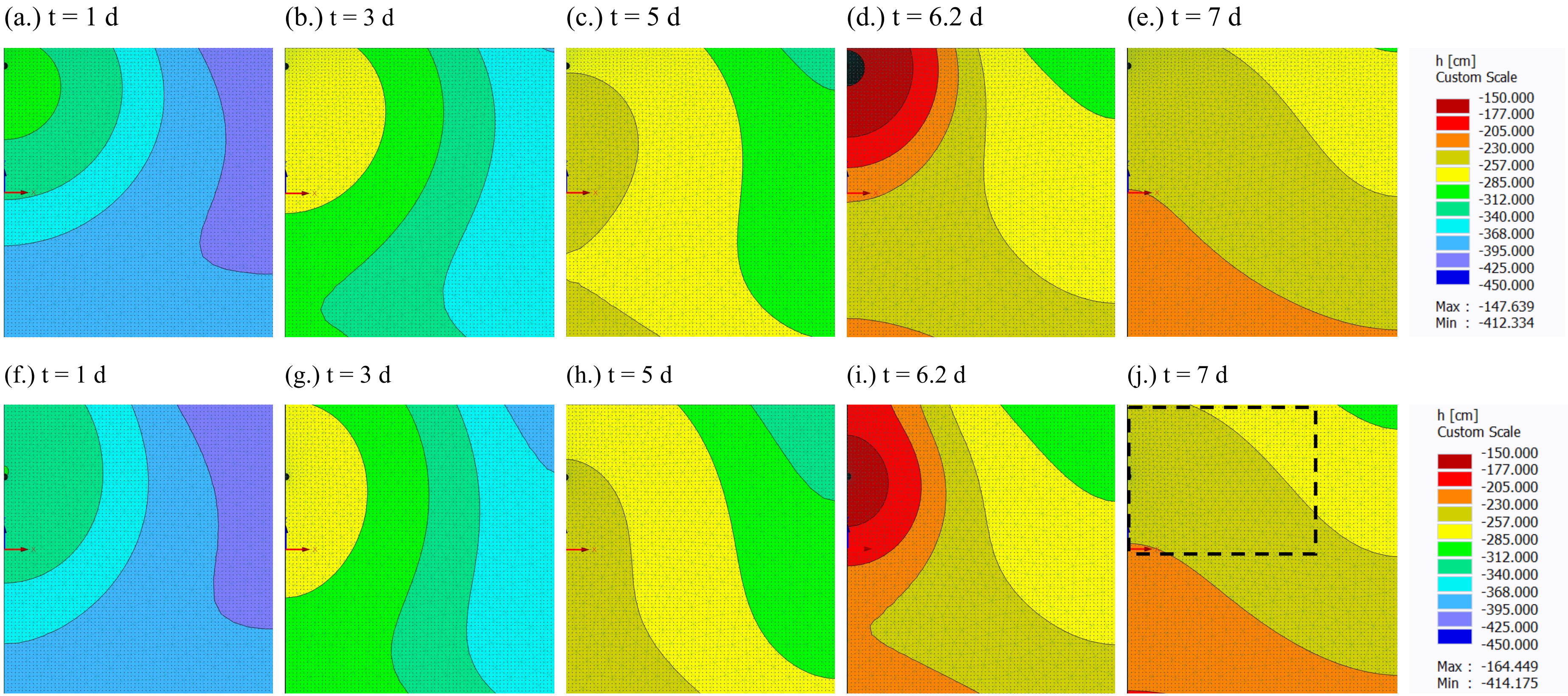


Figure 4. Contours of pore water pressures for Uniform Clay with emitter placed at 5 cm (a. to e.) and 20 cm (f. to j.), below surface. Emitters are spaced 0.5 m apart, delivering 1.05 L/h.

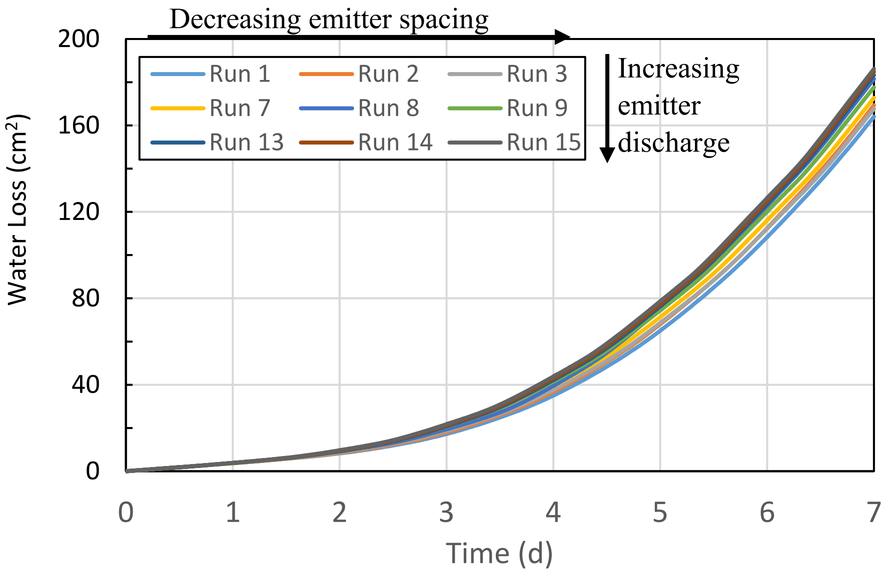
System Optimization

Uniform Clay

The time series of water loss to free drainage (water loss) for Uniform Clay is shown in Fig. 5 for emitters placed at 10 cm and 25 cm below surface. For each emitter depth, the results of a total of 9 runs with spacing ranging from 0.3 m to 0.5 m, and delivery rate ranging from 0.5 L/h to 1.5 L/h are shown. The model run was stopped after 7 days as it was shown earlier that this period of model runtime was sufficient for the soil to reach average wetting conditions. The water loss after 7 days, for emitter placed at 25 cm depth is about 7.0% higher than the emitter placed at 10 cm depth, and this increase is attributed to placement depth. For either of the emitter placement depths, the water loss varies over a narrow range, for the range of flow rates and emitter spacings tested. The coefficient of variation (standard variation/average) of water loss after 7 days is approximately 0.46% for both emitter placement depths. The variation (max – min) of water loss after 7 days is approximately 1.25% and 1.31% of the average water loss for emitter at 10 cm and 25 cm depths, respectively. This relatively smaller % variation between the maximum and minimum water loss values compared to the observed 7.0% difference for emitters placed at different depths suggest that placement depth has a relatively greater significance on water loss compared to emitter spacing and delivery rate.

The water loss to free drainage after seven days was extracted and are compared in Fig. 6. As observed earlier, data for the water losses for the emitter placed at 25 cm are greater than that at 10 cm depth. For either placement depth, the water loss increases monotonically with delivery rate. The water loss at 1.5 L/h is approximately 10.5% higher than at a delivery rate of 0.5 L/h. The variation of water loss with emitter spacing however is not as distinct without revealing any clear patterns. The variation of water loss with emitter spacing is likely to be small and not discernible by the model. For each emitter depth, it is observed that the separation between the data points become smaller as delivery rate increases. Thus it can be observed in Fig. 6 that at delivery rate of 0.5 L/h, the data points for water loss are separated but at delivery rate of 1.5 L/h, the water loss data almost overlap. This suggests that at high discharge rates, emitters spacing become even less important and delivery rate dominates. This phenomenon is observed for both emitter depth placements.

(a.)



(b.)

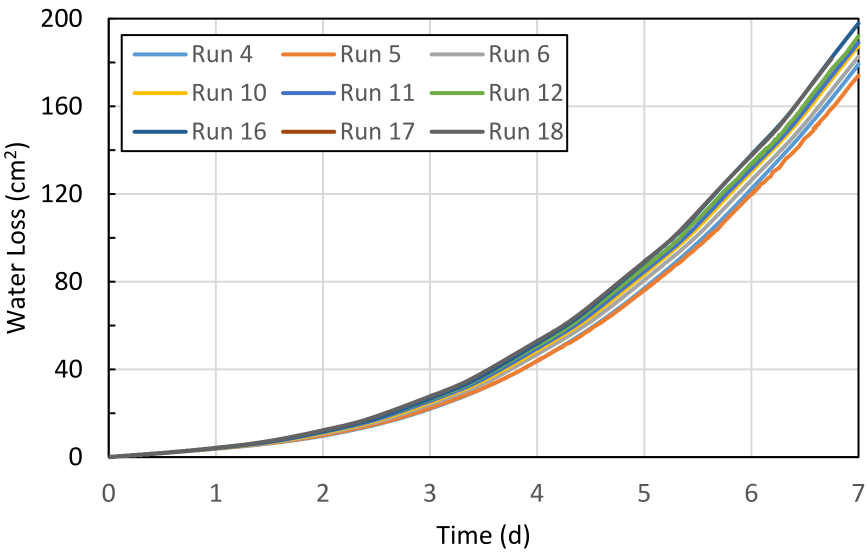


Figure 5. Water loss to free drainage for Uniform Clay with emitter depth at (a.) 5cm, (b.) 25 cm.

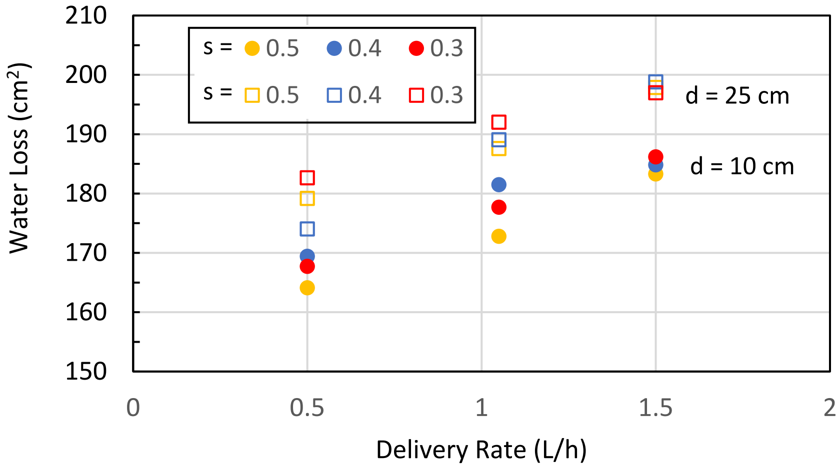


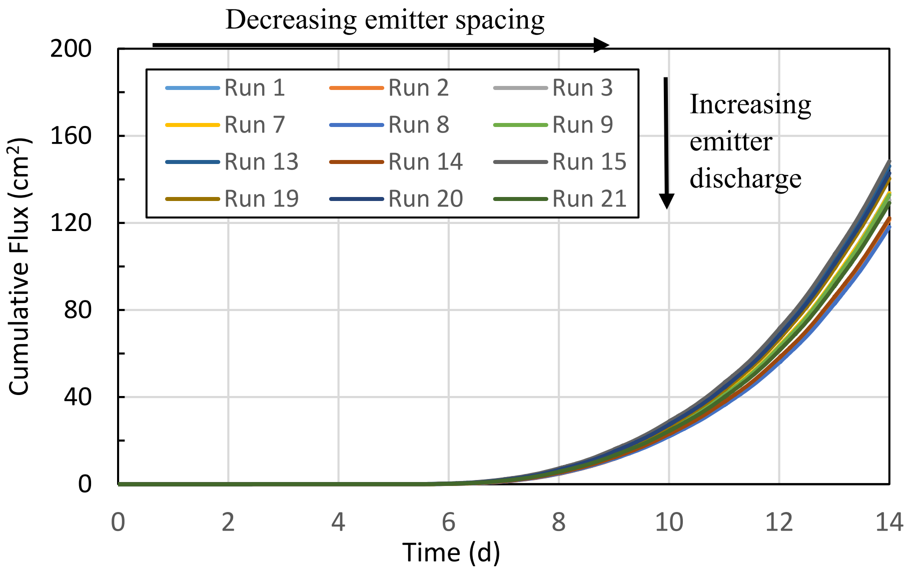
Figure 6. Water loss to free drainage for Uniform Clay.

Duplex soil

The time series of water loss for Duplex soil is shown in Fig. 7 for emitters placed at 10 cm and 25 cm below surface. For each emitter depth, the results of a total of 12 runs with spacing ranging from 0.3 m to 0.5 m, and delivery rate ranging from 0.5 L/h to 1.5 L/h are shown. The model run was stopped after 14 days as it was shown earlier that this period of model runtime was sufficient for the soil to reach average wetting conditions. The water loss after 14 days, for emitter placed at 25 cm depth is about 18.3% higher than the emitter placed at 10 cm depth, and this increase is attributed to placement depth and stratification. For either of the emitter placement depths, the water loss varies over a narrow range, for the range of flow rates and emitter spacings tested. The coefficient of variation (standard variation/average) of water loss after 14 days is approximately 0.45% and 0.34% for emitter at 10 cm and 25 cm depths, respectively. The variation between the maximum and minimum normalised by the average water loss rates [(max-min)/average)] is 1.74% and 0.97% for emitters placed at 5 cm and 25 cm, respectively. This relatively smaller % variation between the maximum and minimum water loss values compared to the observed 18.3% difference for emitters placed at different depths suggest that placement depth has a greater significance on water loss compared to emitter spacing and delivery rate.

The water losses of the water loss to free drainage after 14 days were extracted and are compared in Fig. 8. As observed earlier, data for the water losses for the emitter placed at 25 cm are greater than that at 5 cm depth. For either placement depth, there is a clear increase in the water loss for delivery rate from 1.0 L/h to 1.5 L/h. The trend of the data is however is not as distinct for delivery rates increasing from 0.5 L/h to 1.0 L/h and given the scatter in results. The uncertainly in the cumulative rates at smaller delivery rates is likely influenced by the proximity of the emitter to the interface between the soil layers, influencing water movement and redistribution. This influence is apparently less significant at higher delivery rates. The water loss at 1.5 L/h is approximately 12.0% higher than at a delivery rate of 0.5 L/h. This behaviour of the water loss in the Duplex soil is in contrast with the Uniform Clay where the increase in water loss with delivery rate is observed to be monotonic. This difference in behaviour supports the conjecture that the proximity of the emitter to the interface is playing a role on water redistribution at lower delivery rates. Similar to the Uniform Clay, the variation of water loss with emitter spacing is noticed to be small and not discernible by the model. Similarly, the separation between the data points become smaller as delivery rate increases indicating the significant role played by the delivery rate governing water loss.

(a.)



(b.)

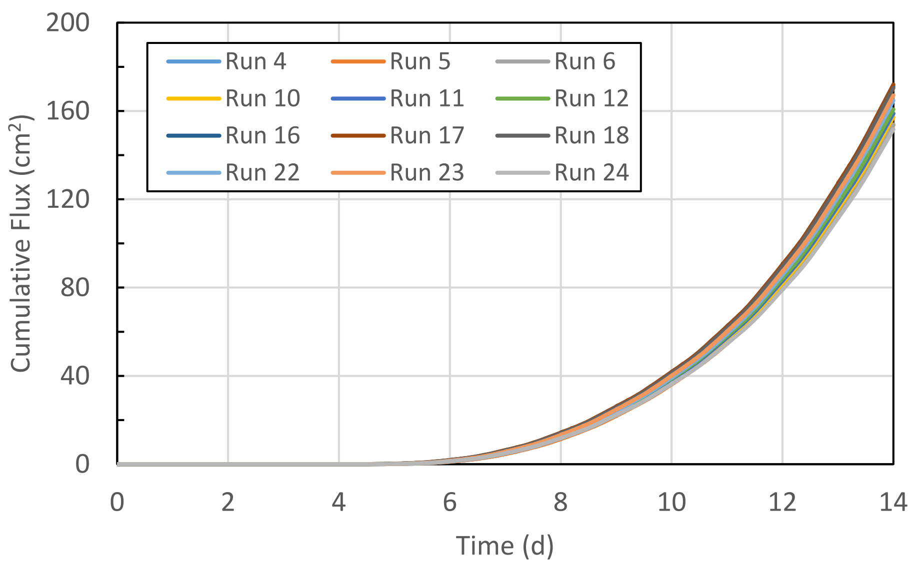


Figure 7. Water loss to free drainage for Duplex soil with emitter depth at (a.) 5cm, (b.) 25 cm.

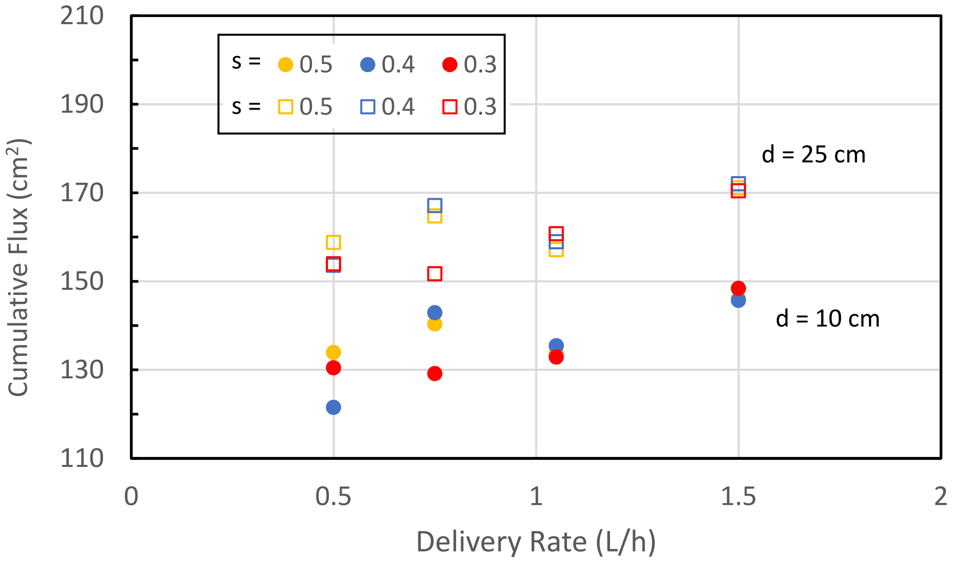


Figure 8. Water loss to free drainage for Duplex soil.

Qualitative Assessment of Soil Wetting Behaviour

Additional observations of wetting behaviour with variations in emitter placement depth, delivery rate and spacing can be inferred from an inspection of the matric potential plots. In each of these plots, contours of matric are compared, varying one parameter at a time. This understanding can provide awareness of wetting patterns within the soil matrix leading to informed decisions on irrigation design.

Emitter placement depth

Comparisons for different placement depths have been made for the emitters placed at 5 cm and 20 cm depths during model validation earlier. Further observations are made here for the emitters placed at 10 cm and 25 cm depths during the optimization runs. The comparisons are made for emitter spaced at 50 cm and delivering 1.05 L/h. Similar general observations can be made for other emitter spacings and delivery rates and are therefore not presented.

Figure 9 compares the distribution of matric potential for Duplex soil for 1.05 L/h delivery with emitters spaced at 0.5 m. The difference in wetting behaviour between the emitter placed in the top and bottom soil layers are again apparent. With a deeper emitter placement, the propagation of the wetting front in the bottom layer follows a classical bulb pattern, radiating from the source (Fig. 9 (f, g)). This radial wetting pattern is also observed with the shallower placement of the emitter (Fig. 9(a, b)). With the emitter at 10 cm, the progression of the wetting front is radial but due to the limited thickness of the top layer, the front appears vertical. Furthermore, the bottom portion of the front is also eroded due to wetting from the soil below, disappearing by the time t = 10 d (Fig. 9(c)). The most significant difference between the two placement depths is probably the persistence of a saturated zone (colored black) after flow redistribution, with the shallower emitter placement (Fig. 9(c, e)). The is evident from comparisons between Fig. 9(c) with Fig. 9(h) and Fig. 9(e.) with Fig. 9 (j), which show the matric potential contours at the end of the day, after redistribution. Figures 9(d) and 9(i) on the other hand compare the matric potential immediately after water application. Significant wetting to the soil surface is observed for the emitter placed at 5 cm, but not for the 25 cm.

Figure 10 compares the distribution of matric potential for Uniform Clay for 1.05 L/h delivery with emitters spaced at 0.5 m. The general wetting for a uniform material, following a radial spreading pattern from source and sinking under gravity are apparent (Figs. 10(a-d) and Figs. 10(f-i)). Significantly, by the end 6^{th} water application period (t = 6.35d), surface wetting can be observed for the emitter placed at 10 cm depth. Although full saturation is not observed for the emitter placed at 25 cm, significant increase in water content can be inferred from the figures. At the end of the redistribution period for t = 7 d (Fig. 10(e) and Fig. 10(j)) there is a greater uniformity of matric potential throughout the soil structure for the emitter placed at 25 cm.

Delivery rate

Comparisons for different delivery rates have been made for the emitters delivering 0.5 L/h and 1.5 L/h. These comparisons are made for emitters placed at 10 cm and 25 cm depth. The emitter spacing considered in these comparisons is 0.5 m. Similar general observations can be made for other emitter spacings, and are therefore not presented.

Contours of matric potential for Duplex soil with the emitter placed at 10 cm depth and spaced 50 cm apart are shown in Fig. 11. The significant difference is in the appearance of a saturated zone (shaded black) close to the emitter, even after flow redistribution, for the 0.5 L/h delivery (Fig. 11(a-e)). At this delivery rate, the application time is 18 hours, leaving only 6 hours for redistribution, before the next water cycle. Presunably, this time period is insufficient for the applied flow to be fully dissipated throughout the soil matrix, creating a non-uniform wetting pattern and surface wetting close to the emitter. That being said, some surface wetting can be seen for the 1.5 L/h delivery at the end of 14 days, although the size of the saturated zone is significantly smaller compared to 0.5 L/h delivery. Interestingly, the wetted zone at the end of water application is larger for the higher delivery (compare Fig. 11(i) with Fig. 11(d)). In spite of this, these simulations show that a longer redistribution period, associated with higher delivery rates is preferable to achieve uniformity in water redistribution and overall uniformity in soil wetting. Lastly, running a higher delivery results in a quicker propagation to the bottom boundary, resulting greater water loss to free drainage. This can be observed from a comparison of Fig. 11(b) and Fig. 11(g), where the wetting front for the 1.5 L/h delivery is observed to be closer to the bottom boundary. This is consistent with the increase in water loss with delivery shown in Fig. 8.

Contours of matric potential for Duplex Soil with the emitter placed at 25 cm depth and spaced 50 cm apart are shown in Fig. 12. With a deeper emitter placement, surficial wetting is absent. A quicker propagation of the wetting front, for the 1.5 L/h delivery, towards the bottom boundary is again evident (Fig. 12(g) and Fig. 12(b)). It can be concluded therefore from these observations that a shallower emitter placement results in lower water loss to free drainage, with greater likelihood for water retention within saturated zones close to the emitter at the soil surface.

Contours of matric potential for Uniform Clay with the emitter placed at 10 cm depth and spaced 50 cm apart are shown in Fig. 13. During initial wetting, soil within the vicinity of the emitter maintains a higher degree of wetness after redistribution with for 0.5 L/h delivery because of the longer application period (compare Fig. 13(a) and (b) and Fig. 13 (f) and (g)). Surface wetting appears to be more significant at lower delivery rates, as evidenced by the lower matric potential at the soil surface after 7 days for 0.5 L/h (Fig. 13(e)) compared to 1.5 L/h delivery (Fig. 13(j)). This would also imply that water loss to deep drainage will be higher at higher delivery rates, which is consistent with the results shown in Fig. 6. Contours of matric potential for Uniform Clay with the emitter placed at 25 cm depth and spaced 50 cm apart are shown in Fig. 14. With deeper emitter placement, surficial wetting is less significant. At higher delivery rates, the contour lines are flatter (Fig. 14(j)) and this is attributed to the longer redistribution time associated with higher delivery rates. Wetting towards the lower boundary is also noticeably more rapid at higher delivery rates (Fig. 14(f), (g) and (h)), consistent with higher water loss observed earlier.

Emitter spacing

Comparisons of soil wetting are made for delivery rate of 0.5 L/h since the water loss is less dependent on emitter spacing at higher delivery rates. Comparisons are made for the spacings at 0.3 m and 0.5 m. In order to achieve the 12 mm application target, the emitters spaced at 30 cm have to be operated for 10.5 hours and the 50 cm spaced emitters for 18 hours.

The comparisons for Duplex soil with the emitter placed at 10 cm and 25 cm depths are shown in Figs. 15 and Fig. 16, respectively. The general soil wetting features at the two spacings with the emitter placed in the shallower soil layer are basically similar. However it can be observed that there is a greater degree of surface wetting at the emitter location for the 50 cm spacing (Fig. 15(a, b, c, e)) presumably since water is applied over a longer period. There is a marked decrease in surface wetting when the emitters are placed closer together (Fig. 15(f, g, h, j)). Differences in wetting behaviour appear to be insignificant for the emitter placed at 25 cm with the matric potential contours appearing to be largely similar for both spacings considered (Fig. 16). This reduction in surface wetting is attributed to the deeper placement of the emitter, rather than emitter spacing.

The comparisons for Uniform Clay with the emitter placed at 10 cm and 25 cm depths are shown in Figs. 17 and Fig. 18, respectively. The wetting behaviour is mainly influenced by the placement depth; the contours are better distributed in the vertical direction with a deeper placement of the emitter, but shows a more rounded profile due to the surface boundary when placed at 10 cm. Comparing the profiles individually, differences in wetting behaviour with spacing can be attributed to the duration of application. For the same delivery rate, water application is shorter if the emitter are spaced closer, which allows a longer time for redistribution. This effect is clearly seen in the 7 d contours in Fig. 17 (e, j) and Fig. 18 (e, j), where the contours are observed to me more uniform laterally for the smaller emitter spacing (Fig. 17 (j) and Fig. 18 (j)).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Comparisons of the HYDRUS simulations (emitter placed at 20 cm depth) with field data show that the model predicts the wetting behaviour for the two soil types well:
   - For the Duplex soil, the main observations are that a wetter zone is confined mainly to a vertical region closer to the emitter exists, with the soil progressive becomes drier away from the centreline. The absolute values and distribution of matric potentials predicted by the model agree well with the field data.
   - For the Uniform Clay soil, wetting is mostly homogenous, with matric potentials varying over a narrow range, between -120 cm to -290 cm. This is close to the averaged conditions observed on site.
2. Comparison of results between emitter placed at 20 cm with emitter placed at a 5 cm depth show relatively lesser changes to soil wetting for the Uniform Clay soil. For the Duplex soil however, shallower emitter placement reveal significant differences in wetting behaviour, particularly a steeper gradient in matric potential extending vertically within the silty loam layer with significant downward wetting from the top layer.
3. There is good agreement of model results with measured data. Key differences in wetting behaviour with emitter placed at different depths are also highlighted. This validation allowed for a methodology for further analysis at optimising irrigation design to be proposed.
4. The water loss of water lost to free drainage is influenced significantly by emitter placement depth. Emitters located at 25 cm results in an increase in water lost to deep drainage by approximately 7.0% and 18.3% for Uniform Clay and Duplex soils, respectively.

5. For emitters located at the same depth, delivery rate has a greater influence on water loss compared to spacing. At the highest delivery rate tested (1.5 L/h), spacing was found to be insignificant effect on water loss, for both soil types.
6. For Uniform Clay, the water loss increases monotonically with delivery rate. An increase in water loss of 18.5 cm^2 for every 1 L/h increase in delivery rate is estimated. Water loss was found to be increased by 10.5% for 1.5 L/h compared to a delivery rate of 0.5 L/h.
7. For Duplex soil, behaviour of the water loss at lower delivery rates is less clear, apparently due to the proximity of the emitter to the interface, influencing water redistribution. At higher delivery rates, this influence becomes less of a significance and a clear increase in the water loss is again observed. An increase in water loss of 14.9 cm^2 for every 1 L/h increase in delivery rate is estimated. Water loss was found to be increased by 12% at 1.5 L/h compared to a delivery rate of 0.5 L/h.
8. The effect of spacing is limited to the lower delivery rates. There is greater surface wetting with emitters placed at 10 cm with emitter placed further apart, due to the longer delivery period.

Recommendations

Experimental model runs with the HYDRUS numerical modelling package on two soil types have revealed key findings on flow behaviour and water loss characteristics for a range of design parameters. These results can be used to provide guidance on the design of follow on field experimentation. The numerical model shows clear dependence on water loss on emitter depth and delivery rate, with spacing as a secondary influence. The following considerations are recommended when planning field trials at optimizing irrigation design:

Delivery rate: As one of the key parameters affecting loss to free drainage, a lower delivery rate should be adopted in irrigation design. Future field trials should focus on testing at the minimum and maximum delivery rates practicable, to quantify anticipated differences to free drainage.

Emitter depth: Water loss to free drainage increases with emitter depth and emitters should be placed as high as possible to reduce water losses. However, too shallow a placement may bring about unwanted surface wetting effects, particularly in Duplex soils.

Emitter spacing: Emitter spacing is likely to influence surface wetting particularly for shallower emitter placement. For Duplex soils especially, emitters should be spaced closer together if surface wetting is to be reduced. The effect of spacing on free drainage losses reduces as delivery rate increases. At higher delivery rates, spacing is not expected to strongly influence losses to free drainage.

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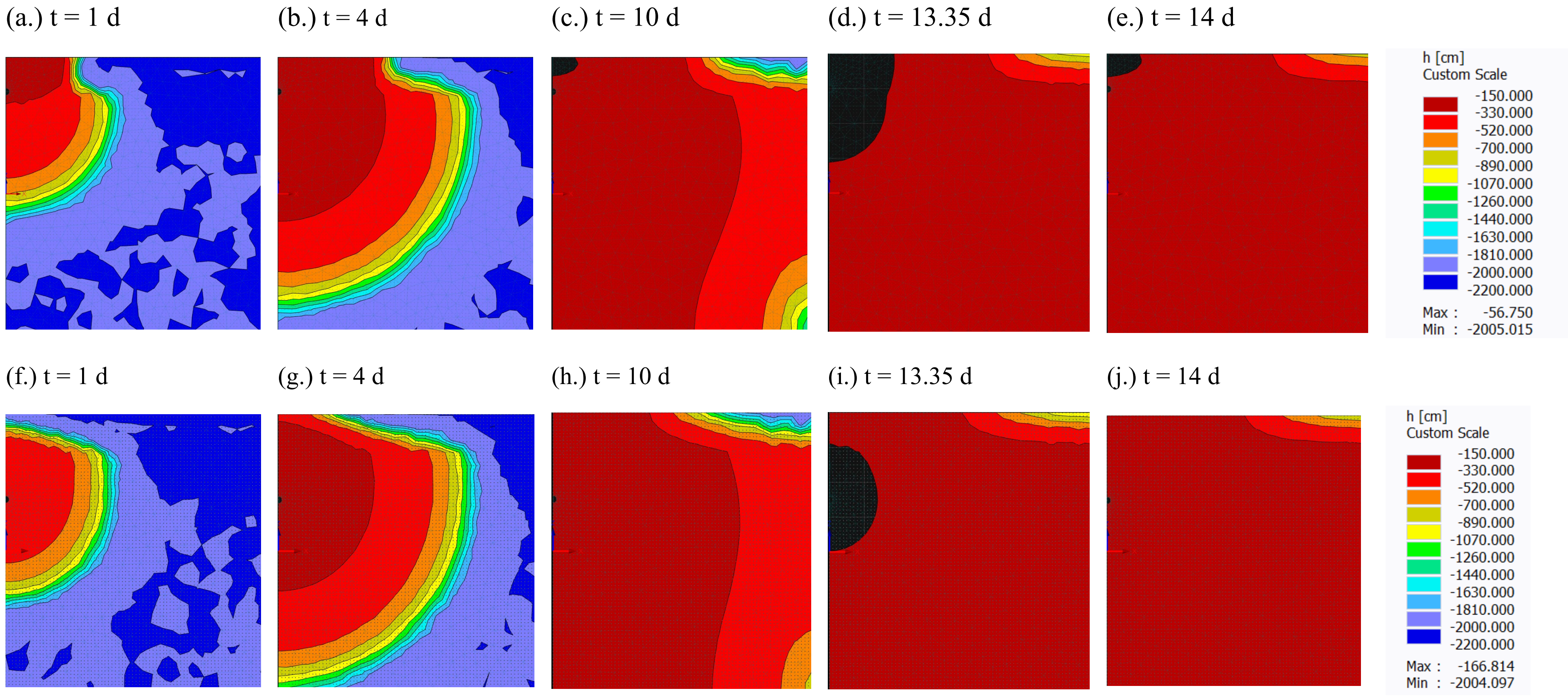

Figure 9. Contours of matric potential for Duplex soil. (a. to e.) Run 7: emitter placed at 10 cm depth, 50 cm spacing and discharging at 1.05 L/h. (f. to j.) Run10: emitter placed at 25 cm depth, 50 cm spacing and discharging at 1.05 L/h.

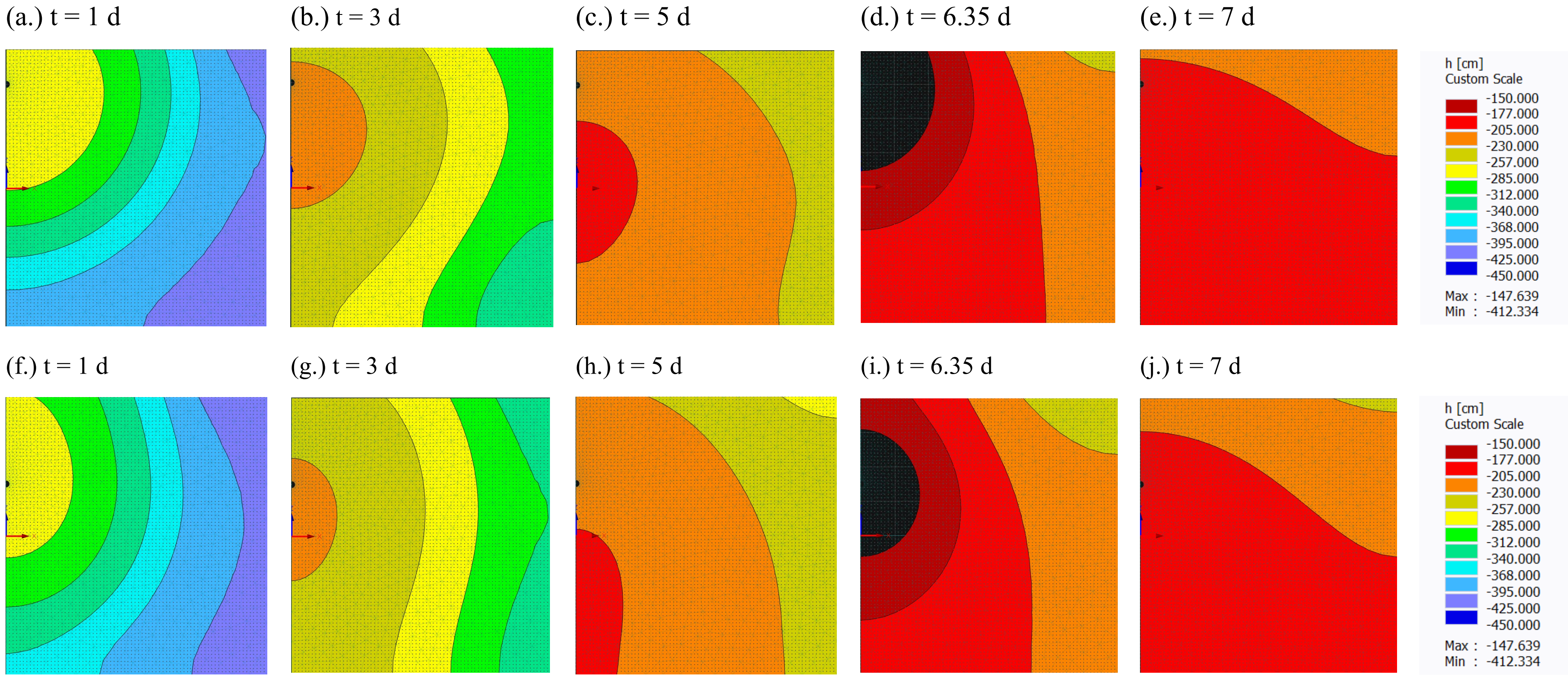

Figure 10. Contours of matric potential for Uniform Clay. (a. to e.) Run 7: emitter placed at 10 cm depth, 50 cm spacing and discharging at 1.05 L/h. (f. to j.) Run10: emitter placed at 25 cm depth, 50 cm spacing and discharging at 1.05 L/h.

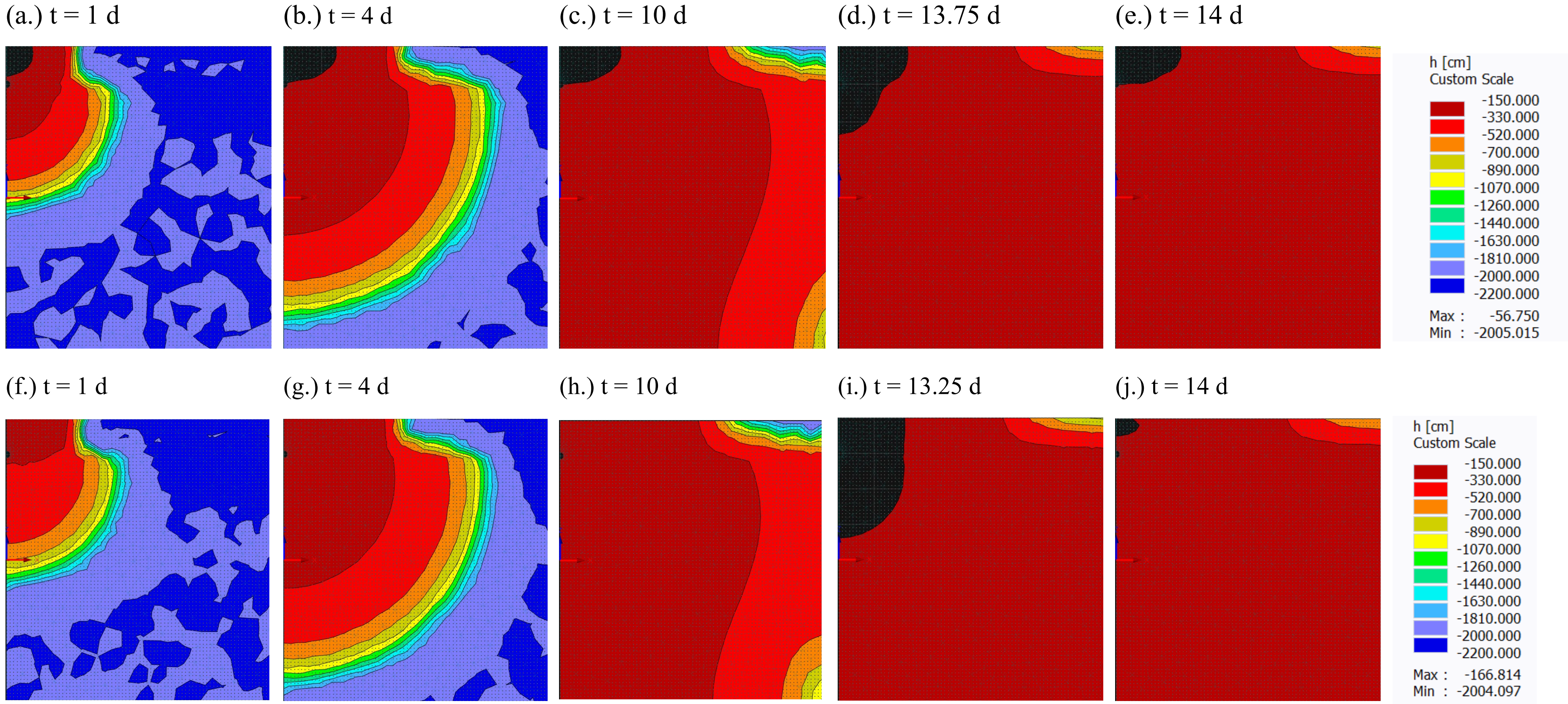

Figure 11. Contours of matric potential for Duplex soil. (a. to e.) Run1 1: emitter placed at 10 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run1 13: emitter placed at 10 cm depth, 50 cm spacing and discharging at 1.5 L/h.

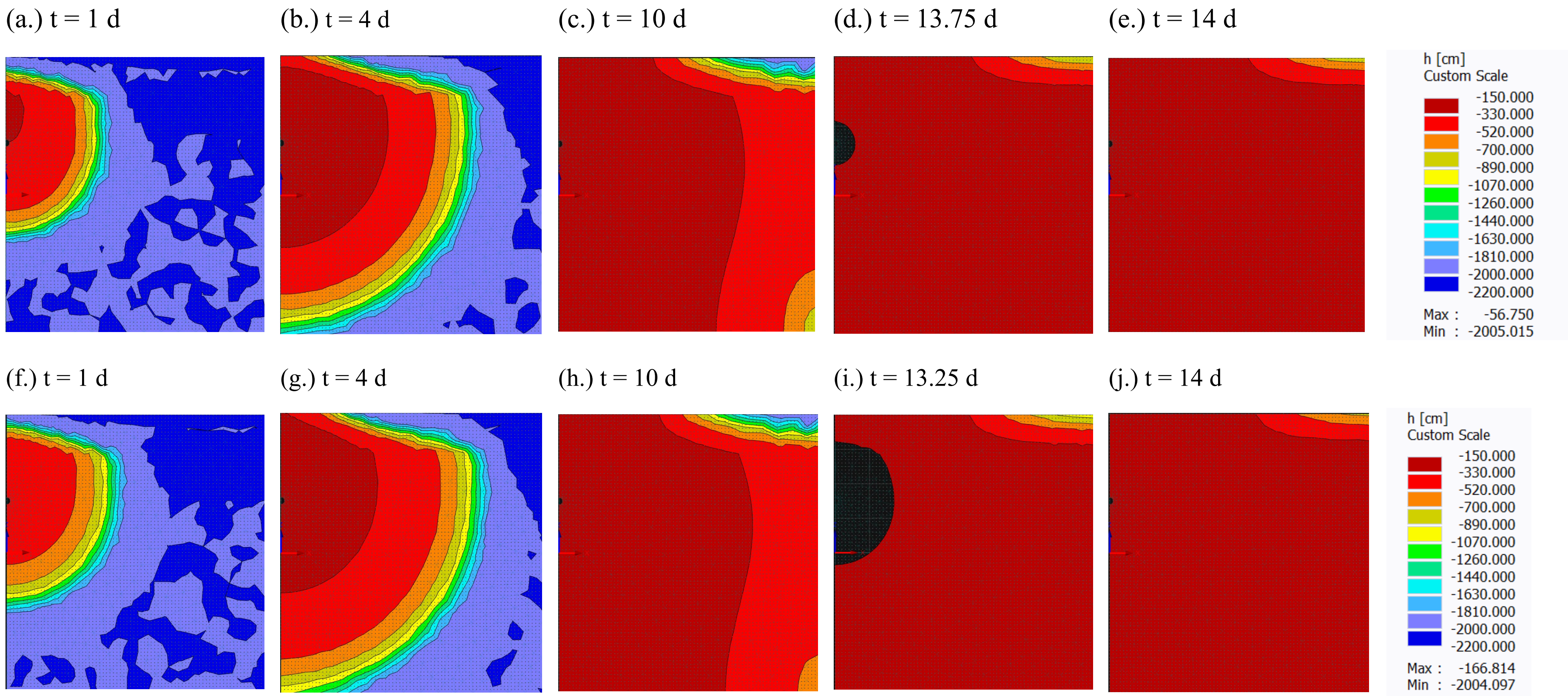

Figure 12. Contours of matric potential for Duplex soil. (a. to e.) Run 4: emitter placed at 25 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run 16: emitter placed at 25 cm depth, 50 cm spacing and discharging at 1.5 L/h.

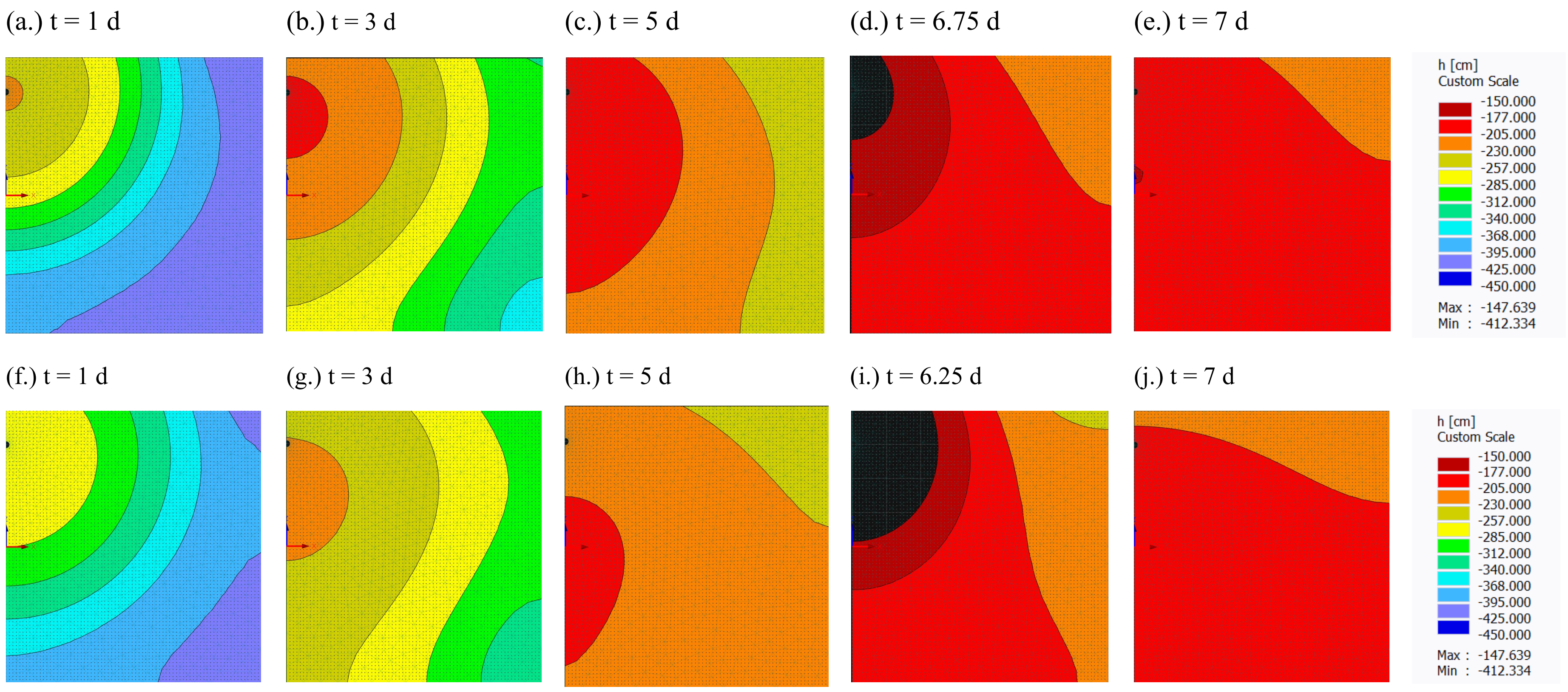

Figure 13. Contours of matric potential for Uniform Clay. (a. to e.) Run 1: emitter placed at 10 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run 13: emitter placed at 10 cm depth, 50 cm spacing and discharging at 1.5 L/h.

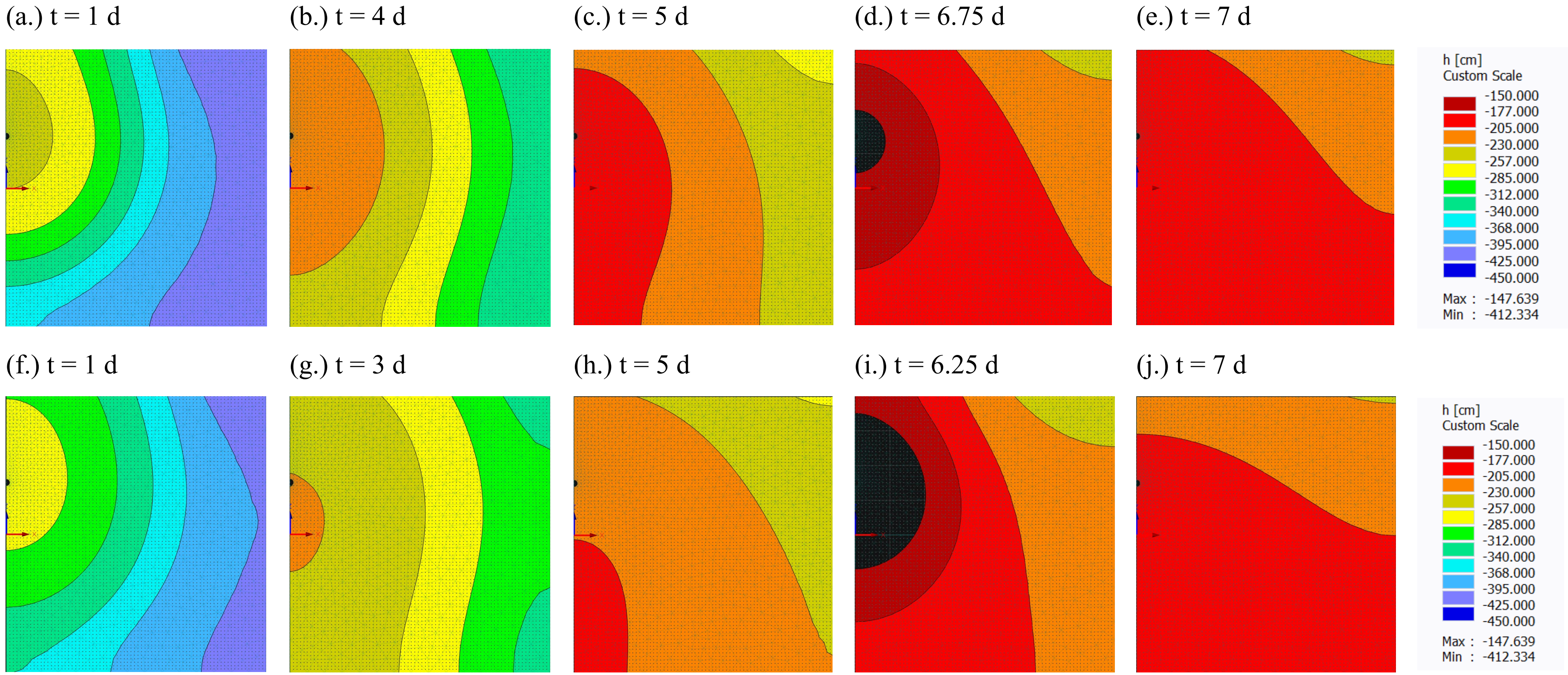

Figure 14. Contours of matric potential for Uniform Clay. (a. to e.) Run 4: emitter placed at 25 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run16: emitter placed at 25 cm depth, 50 cm spacing and discharging at 1.5 L/h.

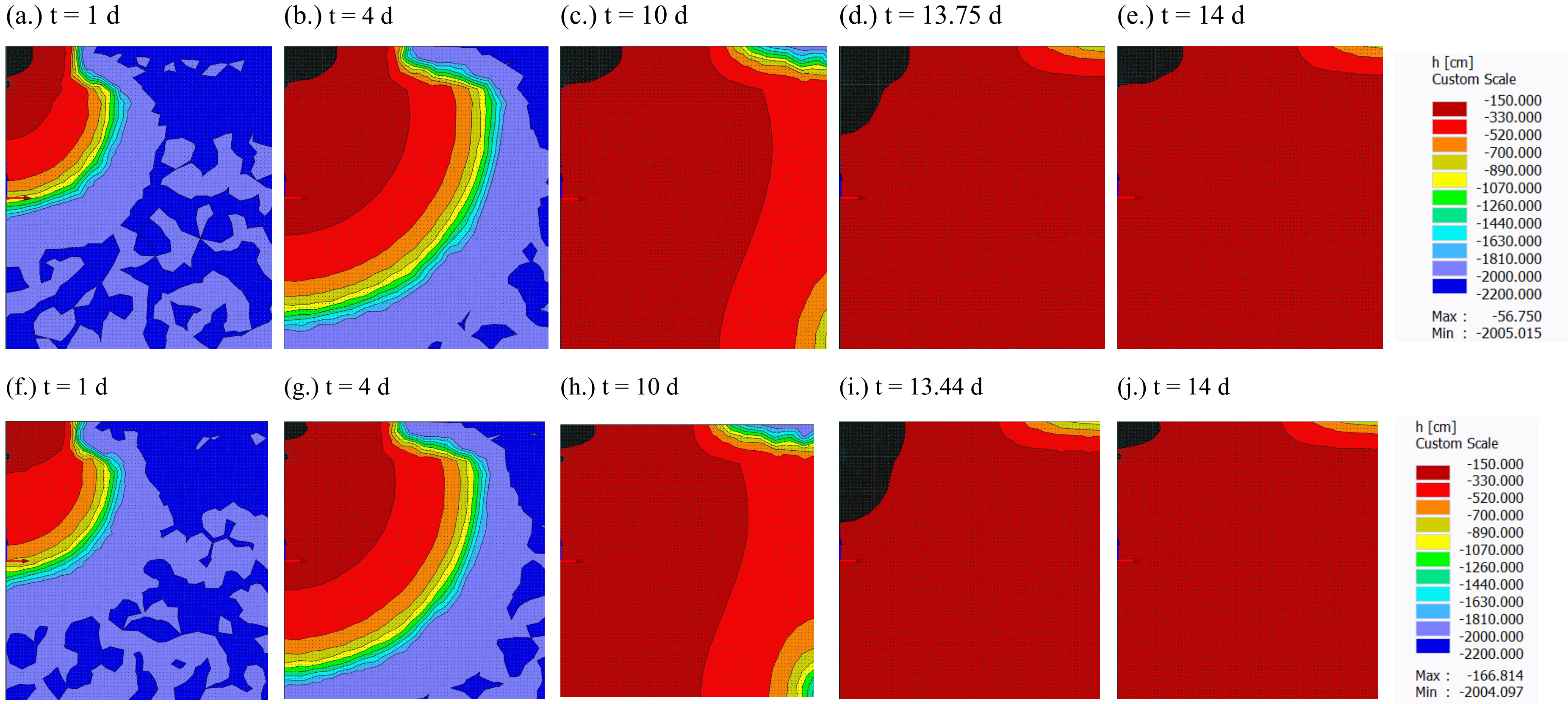

Figure 15. Contours of matric potential for Duplex soil. (a. to e.) Run1 1: emitter placed at 10 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run 3: emitter placed at 10 cm depth, 30 cm spacing and discharging at 0.5 L/h.

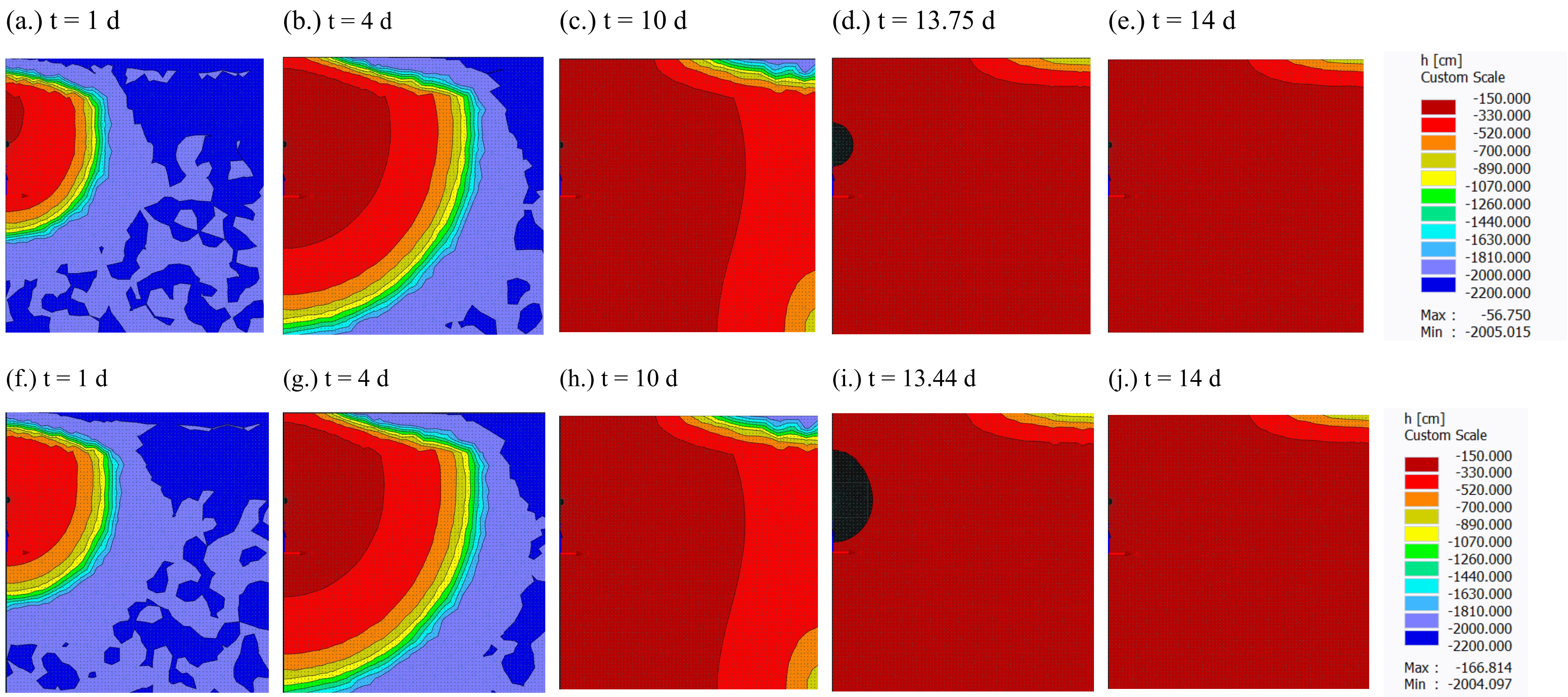

Figure 16. Contours of matric potential for Duplex soil. (a. to e.) Run 4: emitter placed at 25 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run 6: emitter placed at 25 cm depth, 30 cm spacing and discharging at 0.5 L/h.

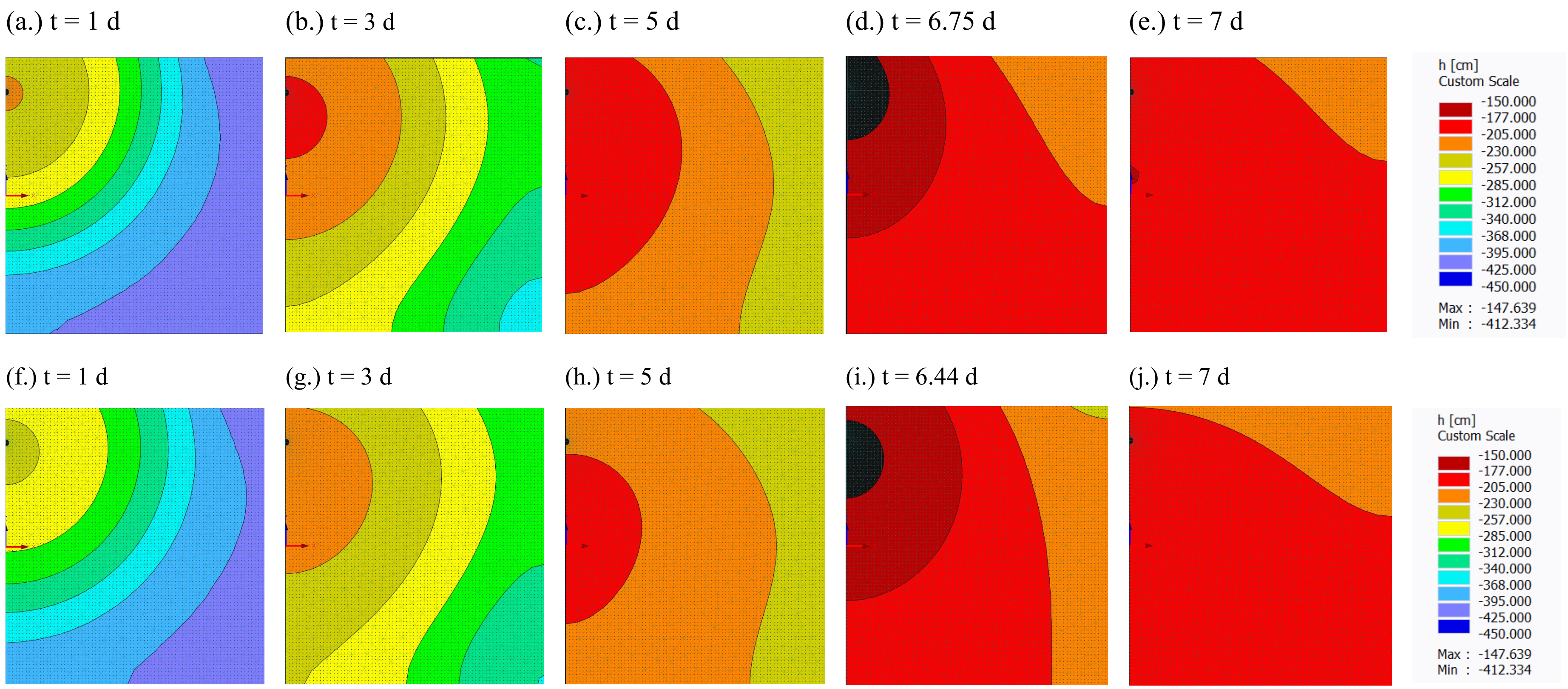

Figure 17. Contours of matric potential for Uniform Clay. (a. to e.) Run 1: emitter placed at 10 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run 3: emitter placed at 10 cm depth, 30 cm spacing and discharging at 0.5 L/h.

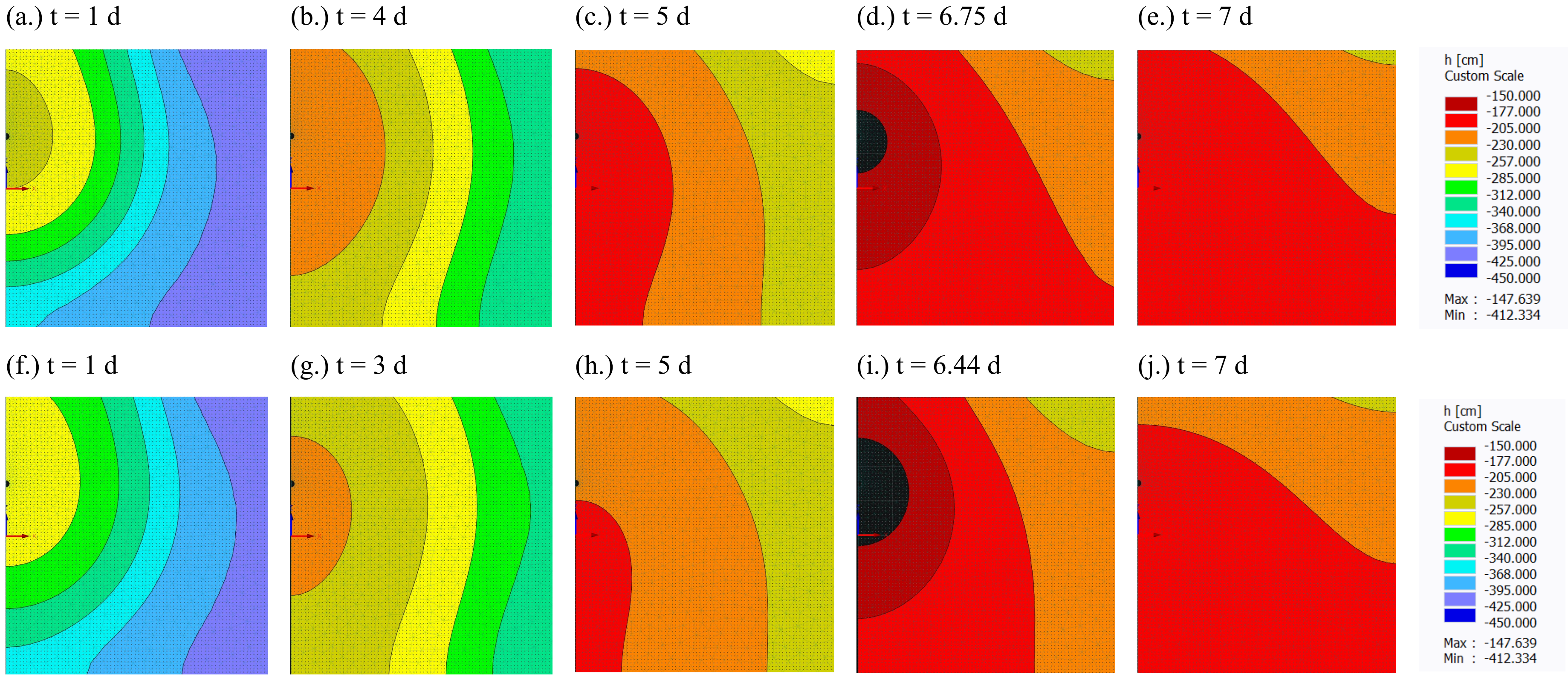

Figure 18. Contours of matric potential for Uniform Clay. (a. to e.) Run 4: emitter placed at 25 cm depth, 50 cm spacing and discharging at 0.5 L/h. (f. to j.) Run 6: emitter placed at 25 cm depth, 30 cm spacing and discharging at 0.5 L/h.