Gravel and Sidewall Flow Effects in On-Site System Trenches

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Introduction

Gravel in conventional on-site system trenches is thought to impede infiltration in several ways (Siegrist, 1987). Gravel particles may mask part of the soil surface at the bottom of a trench, preventing infiltration in these areas. Gravel particles may compact or become embedded in the soil or in the biomat that forms at the trench-soil interface and reduce the hydraulic conductivity of this layer. Fine particles that wash off coarse gravel particles may form a low-conductivity layer at the trench-soil interface. Chamber systems have been developed for on-site systems that, unlike standard systems, do not use gravel in the trench bottom. In Georgia, chamber systems have been approved by the State Department of Human Resources for installation using half the drain line length of gravel systems. The assumption is that infiltration rates are twice that of gravel systems since gravel particles block about half of the trench bottom. This assumption is based on an analysis using Darcy's Law for steady 1D flow:

$$Q = K\, i\, A \qquad (1)$$

where Q is the infiltration rate, i is the hydraulic gradient, and A is the cross-sectional area for infiltration. The argument is that if A is reduced by half in gravel systems, then the infiltration rate should be reduced by half.

Conclusions have varied among the studies that have looked at the effect of gravel. Beach (2001) conducted column infiltration studies and found that flow through columns without gravel was twice the rate of columns with gravel. On the other hand, Amerson et al. (1999) found no effect of gravel masking or compaction on wastewater infiltration rates in columns.

Objective

Our objective was to use HYDRUS-2D to determine the effect of gravel masking and embedded gravel in on-site system trenches. This work led us to investigations of the role that sidewall flow plays in infiltration from trenches.

Gravel Effects

We simulated an on-site system installation in a Cecil soil (fine, kaolinitic, thermic Typic Kanhapludult). The Cecil is a common soil in the southern Piedmont, occupying 15% of the soils mapped in the region (Radcliffe and West, 2000). The typical septic system installation in the Georgia Piedmont would be to place the bottom of the trench in the BC horizon below finer-textured Bt horizons, based on the assumption that the fine-textured horizons have the lowest K_s in the profile. This assumption is often erroneous for the Cecil soil. As shown by the data from Bruce et al. (1983), the upper Bt horizons have a relatively high K_s due to good structure; the BC horizon often has the lowest saturated hydraulic conductivity. Studies on the Cecil soil in North Carolina have also shown that the depth of minimum hydraulic conductivity does not coincide with the depth of maximum clay content (Schoeneberger and Amoozegar, 1990). An alternative would be to place the trench bottom in the Bt1 horizon above the depth of minimum K_s. We simulated water movement from the bottom of a trench into both the BC and Bt1 horizons, using the saturated hydraulic conductivity and water retention parameters for the Bt1 and BC horizons of the Cecil soil reported by Bruce et al. (1983).

The model space for the first simulations consisted of a block of soil at the bottom of a trench that was 30 cm wide and 60 cm deep. The field saturated hydraulic conductivity (K_s) for the Bt1 horizon was 128.76 cm day^{-1} and 0.42 cm day^{-1} for the BC horizon. We included a biomat with a K_s = 0.05 cm day^{-1} based on the research by Bouma (1975). The biomat was 2 cm in thickness. The biomat layer was superimposed on the soil at the trench-soil interface.

The boundary condition at the top of the block was used to differentiate between a chamber system and two configurations of a standard gravel system. For a chamber system (which would not have gravel in the trench), a constant pressure head of 5 cm, representing ponded water above the biomat, was imposed at all locations across the top of the block beginning at time zero. One configuration of a standard system was used to simulate the effect of gravel masking. This was simulated by imposing alternating no-flux boundary conditions (representing gravel particles above the biomat) and pressure heads of 5 cm (representing ponded water) across the top of the block so that 50% of the surface was designated a no-flux boundary. Each zone was 2.5 cm wide. Gravel particles were assumed to sit above the biomat and block the surface of the biomat directly below each gravel particle. The other configuration was designed to simulate the effect of gravel embedded in the biomat. In this case, gravel particles within the biomat layer were simulated by including zones 2.5 cm square with a K_s of 0.0001 cm day^{-1} (HYDRUS-2D does not allow a K_s of zero).

Table 1. Summary of steady infiltration rates and ratios for the chamber and gravel systems in the BC and Bt1 horizons.

Horizon	System	Steady Infiltration Rate cm day^{-1}	Infiltration Ratio to Chamber
BC	Chamber	0.31	
	Gravel Masking	0.27	1.15
	Embedded Gravel	0.21	1.50
	Chamber with Sidewall Flow	0.43	
	Embedded Gravel with Sidewall Flow	0.32	1.33
Bt1	Chamber	0.75	
	Gravel Masking	0.56	1.34
	Embedded Gravel	0.39	1.93
	Chamber with Sidewall Flow	1.04	
	Embedded Gravel with Sidewall Flow	0.61	1.70

We found that gravel masking had very little effect on the final steady infiltration rate into the Cecil BC horizon compared to the chamber system. The final infiltration rate in conventional system with gravel masking was 0.31 cm/day compared to 0.27 cm/day in the chamber system, a chamber-to-gravel ratio of 1.15 (Table 1). When we modeled flow into the Cecil Bt1 horizon, there was a slightly greater effect of gravel masking (chamber-to-gravel ratio of 1.34). but this was still substantially less than a two-fold difference that one would expect from an analysis using Equation (1). The error in this analysis is the assumption that the hydraulic gradient (*i*) is the same in the chamber and gravel systems. In the gravel system, the gradient is much larger because two-dimensional flow pulls water into the areas beneath the gravel particles masking the soil/biomat surface.

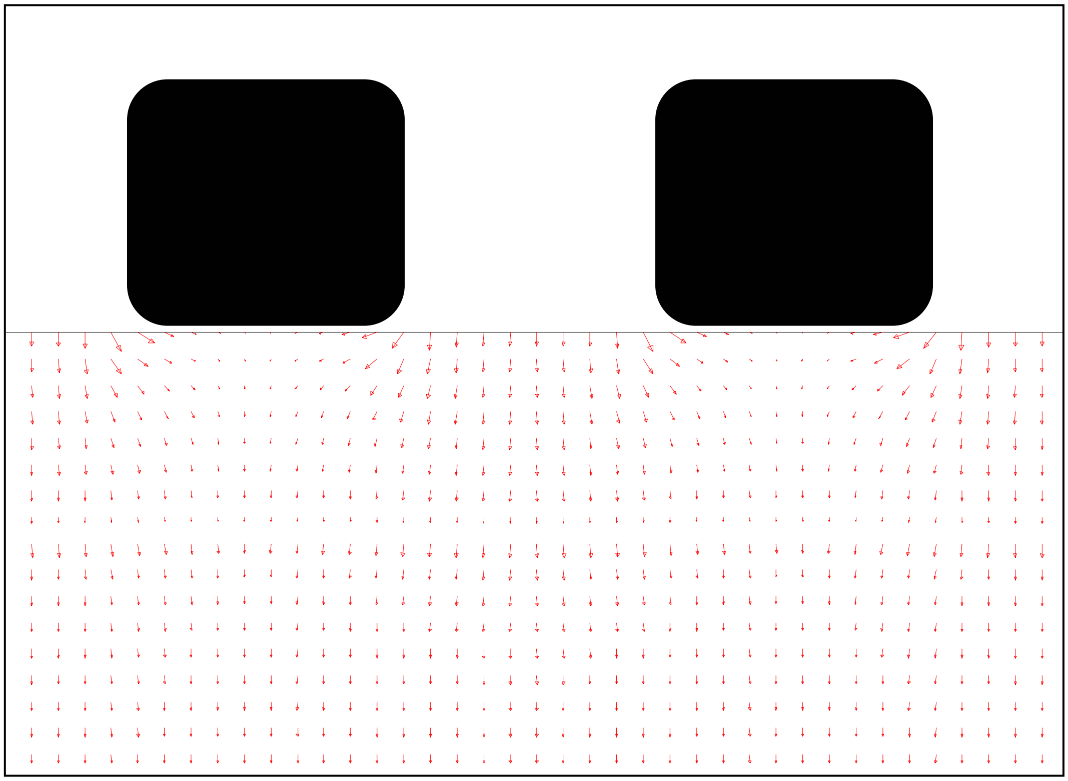

Figure 1. Velocity vectors of flow in the biomat in simulations showing the effect of gravel masking for infiltration into the Cecil BC horizon. The arrows show the direction and rate of flow (longer arrows indicate faster flow).

This can be seen in Fig. 1 where the direction and rate of flow near the surface in a gravel-masking system is shown. The arrows show the direction of flow and longer arrows indicate faster flow. Two gravel particles have been superimposed on the figure to show gravel particles that block infiltration at the surface. Water is flowing laterally from where it infiltrates between the gravel particles into the soil beneath the gravel particles. As such, there is both a vertical and lateral gradient pulling water into the soil. Lateral gradients pulling water into the areas beneath gravel particles compensate, in part, for the reduced cross-sectional area available for infiltration in the gravel systems.

When we simulated the effect of embedded gravel on infiltration into the Cecil BC horizon, there was a greater effect of gravel in reducing flow and the chamber-to-gravel ratio was 1.50 (Table 1). The direction and rate of flow near the surface in an embedded gravel system is shown in Fig. 3. The lateral gradient pulling water into areas beneath the embedded gravel in this system was not as effective because these areas are more distant from the surface compared to gravel masking (Fig. 2). As a result, the lateral gradient does not entirely compensate for the loss in infiltration surface due to embedded gravel particles.

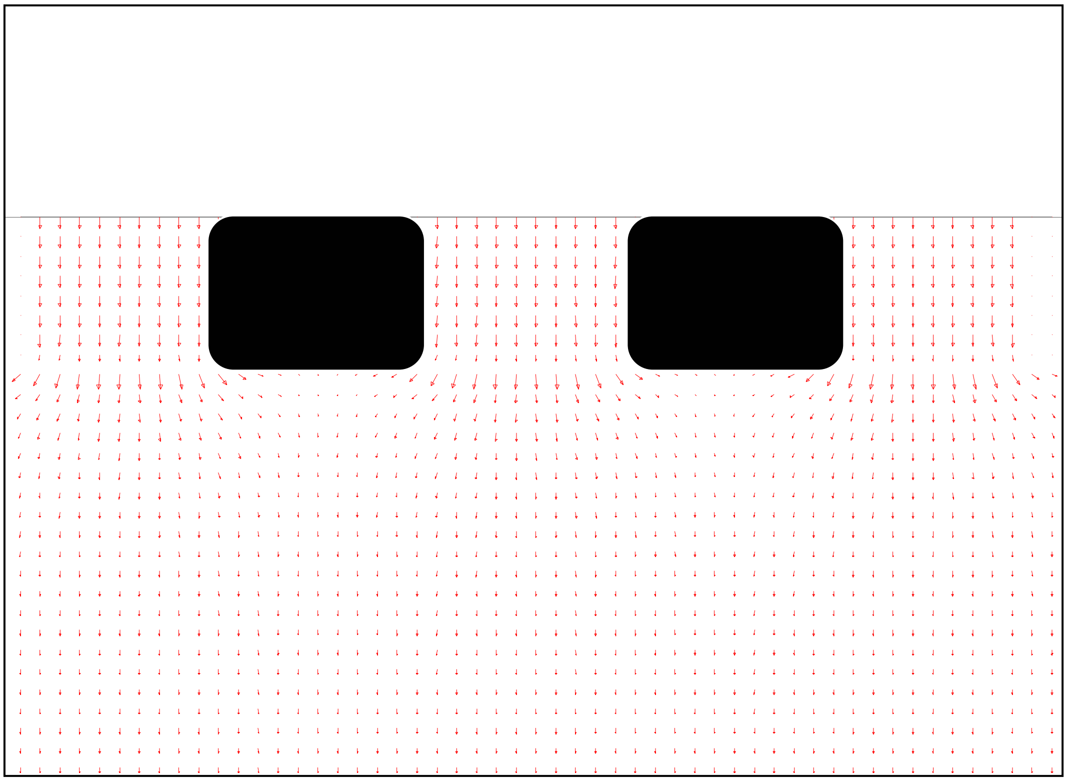

Figure 3. Velocity vectors of flow in the biomat in simulations showing the effect of embedded gravel for infiltration into the Cecil BC horizon. The arrows show the direction and rate of flow (longer arrows indicate faster flow).

Both gravel masking and embedded gravel had more of an effect on infiltration in the Cecil Bt1 horizon (Table 1). Chamber-to-gravel infiltration ratios were 1.34 and 1.93 for gravel masking and embedded gravel effects, respectively. The reason why the effect is greater in this horizon is because there is such a large difference between the biomat K_s (0.05 cm/day) and the Bt1 horizon K_s (128.76 cm/day). Infiltration rates are most sensitive to the conditions in the biomat (masking or embedded gravel) when there is a large difference between the biomat hydraulic conductivity and soil hydraulic conductivity. This is most likely to occur in highly permeable soils such as sands.

Sidewall Flow Effects

These results led us to the question of what effect gravel would have on sidewall flow, and in a more general sense, how important was sidewall flow in overall infiltration. In these simulations we modeled a half-trench profile, assuming that the middle of the trench would be an axis of symmetry for two-dimensional water flow. The trench bottom was placed at a depth of 150 cm below the surface on the left side of the block and the soil extended 60 cm below the trench (total depth of soil block was 210 cm). The width of the soil block from the center of the trench was 350 cm. This width was chosen to ensure that the right side of the block did not interfere with water flow. The width of the soil trench was 45 cm, half that of a full trench. At the trench bottom, the same boundary conditions used in the earlier simulations to distinguish between a chamber system and two configurations of a gravel system were used. We assumed water was ponded in the trench to a height of 5 cm. On the sidewall, a

2-cm thick biomat extended to a height 5 cm above the trench bottom. No masking or embedded gravel was simulated in the sidewall biomat.

Sidewall flow reduced the chamber-to-gravel ratios for the effect of embedded gravel to 1.33 in the BC horizon and 1.70 in the Bt1 horizon (Table 1). Sidewall flow allowed more water to infiltrate from the trench and diminished the effect of embedded gravel. We did not simulate the effect of sidewall flow with gravel masking, but since the effect was small in the trench bottom flow simulations, we expect that it would be even less important when sidewall flow is allowed.

We realized that there were serious limitations to the way we simulated sidewall flow in these systems. The ponding height of 5 cm was completely arbitrary, as was the assumed height of the sidewall biomat. Also, for a given dose of water, the ponding depth could be expected to be greater in gravel systems compared to chamber systems due to the volume occupied by gravel particles in the trench. This could increase infiltration in the gravel systems and further diminish differences between chamber and gravel systems due to a larger gradient. Also, it is unrealistic so assume that the ponding height (whatever the level) is constant in an on-site system. The level of water in the trench probably varies over time, especially in a system with a dosing device.

Recently, we have begun experimenting with a different way of simulating flow from the trench. Instead of treating the trench as an open void and fixing the height of the water in the trench, we have included the trench void and filled soil above the trench within our model space (Fig. 3). We have simulated three daily doses (at 8 am, 1 pm, and 6 pm) equivalent to a constant rate of 2 cm/day (0.5 gal/ft^2) in a gravel system. We assumed that the biomat extended 15 cm above the trench bottom and that the sidewall biomat K_s (0.1 cm/day) was twice that of the bottom biomat (0.05 cm/day). We simulated the void space as a "porous media" with an extremely high K_s (1,000 cm/day) and a porosity of 0.50 (half of the void space is occupied by gravel particles). We used a sandy clay loam soil from the HYDRUS-2D database for our simulations.

Our preliminary results show that water levels reach a "dynamic equilibrium" after about two days. In Fig. 4, the water pressure at the base of the trench is shown. Positive pressures indicate water is ponded in the trench and the depth of ponding is equal to the pressure. The water level rises to a little above 20 cm above the trench bottom during a dose but drops rapidly in between doses. At night, the water level drops to near zero indicating that most of the water has infiltrated.

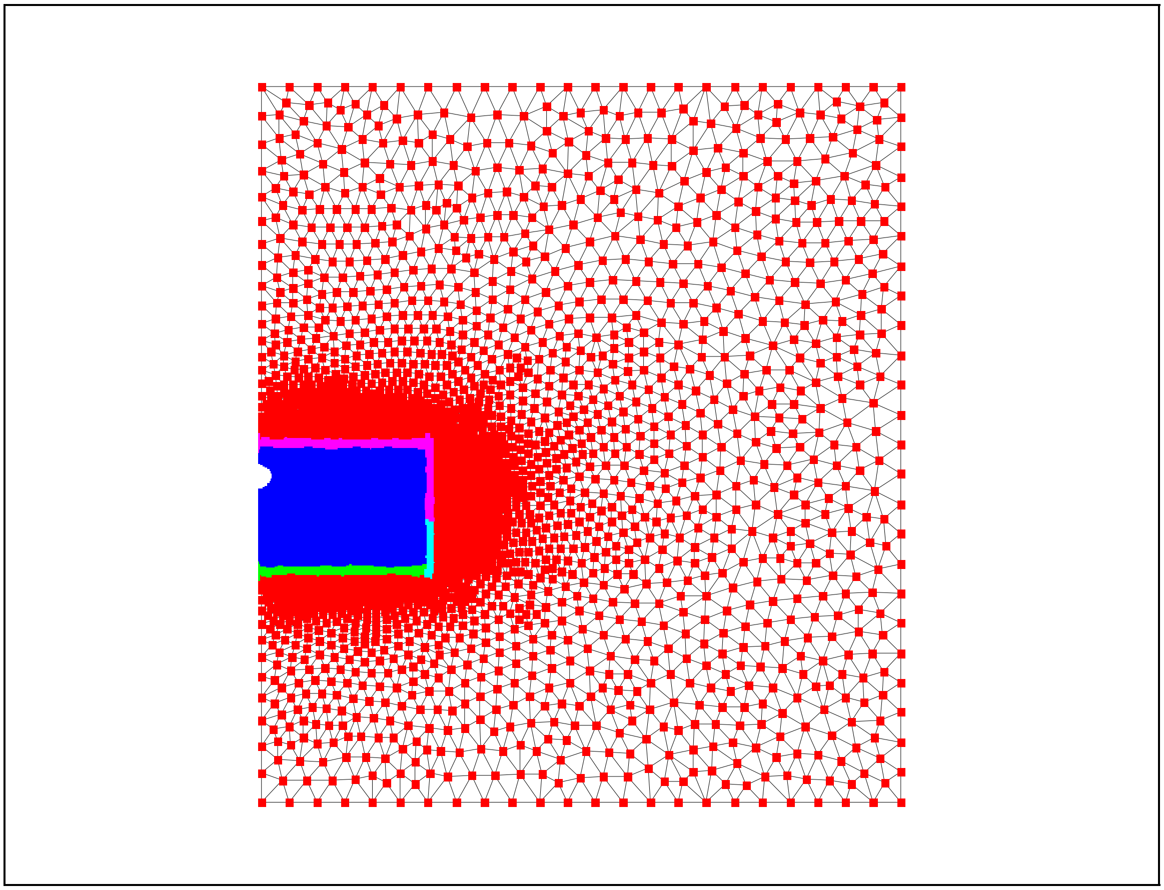

Figure 3. Model space for simulating fluctuating water levels within a trench in response to daily doses and flow from the trench through the trench bottom and sidewall. The blue area represents the trench void and the semi-circle on the boundary is the drain line opening.

In HYDRUS-2D, one can determine what the flux is across any given line at the boundary or within the model space. We have used this feature to calculate how much flow occurs across the sidewall and bottom during a typical daily cycle. We found that 92% of the total flow from the trench was through the sidewall in these simulations. This is because the water level rises above the height of the sidewall biomat and most of the flow is over the biomat "lip". This can be seen in Fig. 5 where the direction and velocity of water flow is shown in a close-up of the trench area. The longer the arrows the faster the flow and green-to-yellow colors indicate faster flow than red. The figure shows flow during a dose and it is clear that most of the flow is through the sidewall just above the biomat.

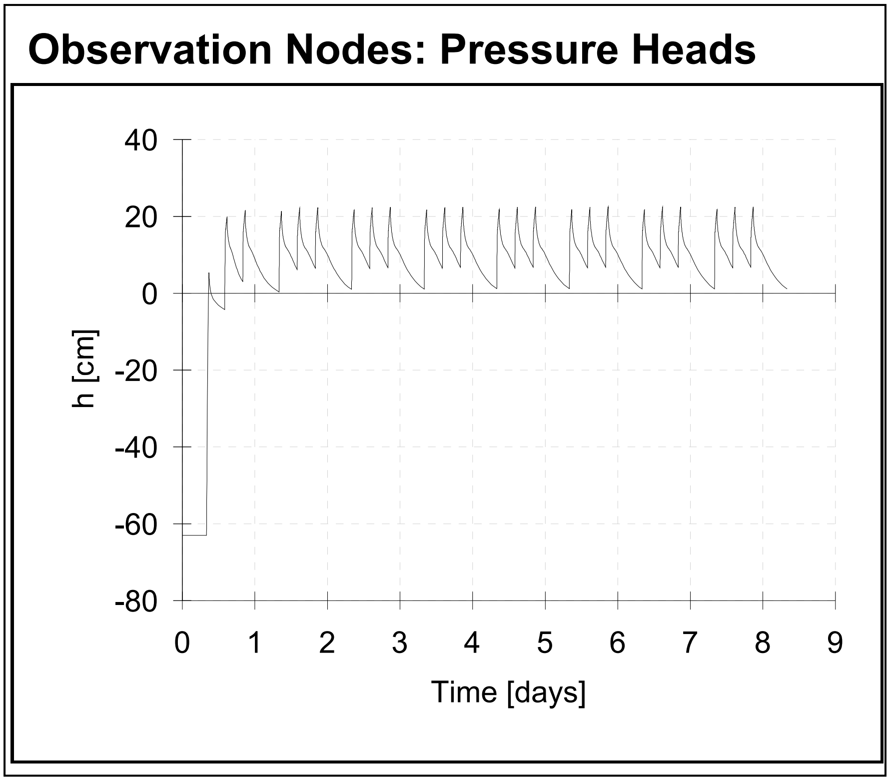

Figure 4. Pressure heads at the bottom of the trench in a sandy clay loam soil under a dosed system. Positive pressures indicate water is ponded in the trench and the height of ponding is equivalent to the positive pressure.

We stress that our results are preliminary in that there are several problems associated with trying to model a void space as a "porous media". Ideally, we would like to use a water retention curve relationship that would not allow water to enter the void until positive pressures occurred. We could not get HYDRUS-2D to use such a severe water retention curve. By putting a thin sand barrier around the void space above the biomat, we were able to prevent flow from the void if the pressure was more negative than about -10 cm. This still allowed some water to flow from the void at heights above the water level. Our results probably overestimate sideflow as a result, but we are going to run some simulations using constant levels of ponding using our new method and the earlier method where the ponding level was fixed at the boundary to see how much error is introduced.

We think that we can use this method to determine how much sideflow occurs in different systems and soils. If it is a significant amount, then it may be possible to investigate different trench geometries that would take better advantage of sidewall flow. For example, tall narrow trenches may be more effective than the conventional design.

Conclusions

Our results show that gravel masking has a negligible effect on infiltration. Embedded gravel had more of an effect, especially when the in the Cecil Bt1 horizon soil where the biomat K_s was four orders of magnitude less than that of the soil. Sidewall flow also reduces the effect of embedded gravel in that the biomat on the sidewall does not include embedded gravel (our assumption). The reason why gravel does not have as large an effect as one might expect from a simple analysis based on flow in one dimension is that lateral gradients compensate for the reduced cross-sectional area for infiltration in gravel systems. Our analysis is for two-dimensional flow. In true systems, where flow is in three dimensions, lateral gradients may be more important and there may be even less of an effect of gravel.

We have tested a new way to model infiltration from trenches that allows the level of water in the trench to fluctuate in response to dosing. Although this method has some problems, it indicates that much of the flow may be through the sidewall. If this is true, then it may be possible to design alternative systems that take better advantage of sidewall surfaces.

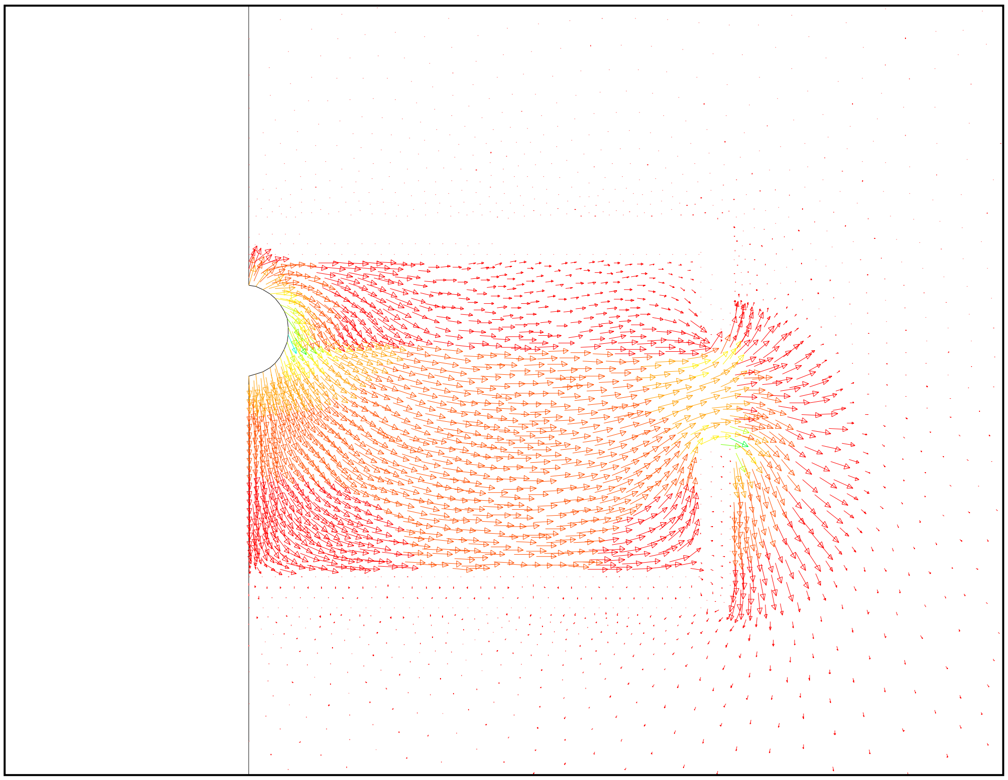

Figure 5. Flow velocity vectors in the trench and surrounding region during a dose. The direction of flow is indicated by the arrow and longer arrows indicate faster flow. The fastest flow occurs in the green and yellow areas.

Our results also show that there are a number of questions that can only be answered through field and laboratory experiments:

- Is gravel embedded (in the biomat or soil)? If gravel is not embedded, then our results show that it has little effect on infiltration.
- What is the saturated hydraulic conductivity and thickness of biomats in soils of different textures? How do these properties change over time?
- To what extent do fines occur and what is their effect on the hydraulic properties of a biomat or a separate fines layer?
- Do biomats form on sidewalls and if so how high do they extend and what are their properties?

References

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