In-Ground Dispersal of Wastewater Effluent: The Science of Getting Water into the Ground

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ABSTRACT: This paper describes the scientific principles of Darcy's law and hydraulic resistance as they relate to the in-ground dispersal of onsite wastewater effluent. A clear understanding of how water moves into the ground via dispersal trenches is needed to facilitate proper system design and effect some standardization of dispersal trench sizing and design. Hydraulic conductivity of the media, hydraulic head, media layer thickness, and area of infiltration are key in determining water movement into the soil. Restrictive media layers, such as fines or biomat, are shown to control infiltration rates and long-term soil acceptance rates of septic tank effluent because of low hydraulic conductivity characteristics.

In the U.S., a conventional onsite wastewater system consists of a septic tank and a subsurface soil absorption system (commonly called a dispersal field, a drainfield, or a leachfield). Typically, these effluent dispersal systems consist of several narrow trenches filled with a porous media such as gravel. The gravel media functions to maintain the structure of the trenches, to distribute the effluent to the soil infiltrative surfaces, to provide storage capacity during peak discharges, and may help provide a limited amount of effluent treatment (Kreissl, 1982).

Dispersal trenches are designed to allow the applied septic tank effluent to infiltrate into the soil below and around the trenches for treatment and transport it away from the drainfield area. However, the rate of infiltration into the subsurface may be greatly influenced by a number of factors, both naturally occurring and as a result of how the dispersal systems are designed and constructed. Currently, there is little regulatory standardization for how to accurately determine infiltration rates and size (or configuration) of dispersal systems. Standard effluent dispersal methods based upon scientific principles are needed to optimize infiltration and to better protect water quality and public health.

Soil structure and character obviously affect infiltration rates, but hydraulic and organic loading, as well as dispersal trench construction materials and configurations, also impact infiltration performance. As effluent is applied to the dispersal field, a biomat develops on the infiltrative surfaces of the trenches. Functionally, the biomat acts as a biological treatment unit and as a mechanical filter. It also reduces the size and amount of pores at the trench-soil interface, and thus, the rate of flow of effluent from the disposal field into the surrounding soil.

Orlob and Butler (1955) showed that the infiltration capacity of a soil absorption system is controlled primarily by the nature of the biomat and not by the permeability of the soil. It has been shown by Siegrist (1987) and others that the formation of a biomat is accelerated by increasing either the hydraulic or organic loading rate of the applied septic tank effluent.

Fine-grained materials (fines), often present in gravels used to construct conventional dispersal trenches, can accumulate along the trench bottom and also impede infiltration. These low hydraulic conductivity (K) layers (biomat and fines), individually or collectively, can greatly reduce the effective hydraulic conductivity (K_{EFF}) and infiltration rates independent of the in-situ soil material (Amoozegar and Niewoehner, 1998). Bouma (1975) also described the hydraulic resistance in specific soil layers and unsaturated flow characteristics as being key factors in effluent infiltration.

As the onsite industry continues to grow, there is increased interest in the development and use of alternative dispersal systems. Alternative subsurface drainfield technologies provide a convenient and economical alternative to conventional gravel systems, and use of alternative dispersal systems has grown dramatically over the last several years. In fact, in some areas, alternative drainfield technologies are the mechanism most often used for distributing septic tank effluent in trench disposal systems.

In seeking approval for alternative dispersal systems, manufacturers often compare the hydraulic performance of their system to that of conventional gravel systems. In many cases this comparison serves as the basis of developing sizing criteria. Standardization of sizing criteria based upon scientific principles is important to ensure the long-term effectiveness of these systems.

The infiltration of water into a soil media is described using Darcy's law, which is universally accepted as the soil physics principle describing saturated flow through a porous media. The use of Darcy's law to determine effluent flow from a dispersal trench is complex and sometimes misunderstood. An example is the concept of trench–media (gravel) shadowing, which is often misunderstood and not consistent with the Darcy description of flow through porous media.

This shadowing concept suggests that solid trench media (gravel) completely blocks the movement of water directly beneath the media itself. Saturated infiltration is a 3-dimensional phenomena, where water moves around soil (and trench media) particles and through pores into the soil matrix. Darcy described this flow rate (Q) through porous media (soil and/or trench media) as being influenced by several factors, including the hydraulic gradient, the soil characteristics, and cross-sectional area. The cross-sectional area term includes both the media and the openings between the media.

The purpose of this paper is to describe dispersal trench infiltration hydraulics using Darcy's law and known soil physics principles. More specifically, hydraulic resistance theory and components of Darcy's law, including hydraulic head, media length, and hydraulic conductivity will be illustrated. These illustrations will define key factors that should be incorporated into dispersal trench sizing criteria and the impacts of such factors on rate of wastewater infiltration into soils.

Additionally, the discussions herein will show that the factors described in Darcy's law are the mechanisms for determining saturated effluent flow (Q) into soils via dispersal trenches and that "trench media shadowing" of underlying soils is not consistent with Darcian flow concepts. A model dispersal trench will be described that illustrates zones of resistance to effluent infiltration based on hydraulic conductivity of soil characteristics. It is the cumulative resistance to flow from each of these resistance zones (soils or other solid media) that significantly determines the overall flow rate of water into soils.

SOILS

The soil at and below a dispersal trench normally consists of several layers or horizons. There may be significant differences from horizon to horizon in soil properties such as color, particle size distribution (texture), structure, and hydraulic properties. In addition to natural soil variation, additional layers such as fines (from gravel used in construction) and biomat (microbiological growth that occurs as a result of organic-laden effluent) accumulate in dispersal trench bottoms and sidewalls, and these layers have their own hydraulic properties that influence wastewater infiltration.

Each soil horizon has a specific capacity for water and air movement that is related to its pore size, continuity, and specific soil particle characteristics. The porosity of soils is defined as the percentage of void volume in a unit volume of soil. Due to differences in hydraulic conductivity, effluent (liquid) and oxygen (gas) move through different horizons at different rates. Therefore, onsite systems must be designed to account for the hydraulic capacity and gas exchange potential of the horizon(s), both natural and trench-construction induced, in which the system is installed. These factors determine the acceptable design hydraulic loading rate for the system.

DARCY'S LAW: FLOW THROUGH POROUS MEDIA

Water flow through porous media was first studied and defined by the French engineer Henry Darcy. Darcy's experiments were conducted through beds of sand used for water filtration. Darcy found through his experiments that the flow (Q) of water through a given cross-sectional area of porous media is related to head loss (hydraulic or piezometric head, H) and flow path length (L) through a proportionality constant known as hydraulic conductivity (K). Note that, by definition, the area term includes the entire cross-sectional area (A), comprised of both soil particles and the openings between particles.

Darcy's law is stated as follows:

$$Q = -KA\,(dH/dL)$$

Where

Q = the flow rate of effluent (gpd),

K = the hydraulic conductivity of the media (gpd/ft^2),

A = area for effluent transmission (ft^2), and

dH/dL = hydraulic gradient (unit less).

Hydraulic conductivity is an indication of a porous media's ability to transmit water and is based upon a variety of physical factors (Bedient and Huber, 2002). Hubbert (1956) showed that Darcy's proportionality constant (K) is a function of both the porous media properties and the properties of the fluid (viscosity, for example) passing through the media. However, because the viscosity of water and septic tank effluent are essentially the same, K will be considered only as a property of the media in the discussions that follow. The quantity dH represents the change in head (height of the water level in piezometers) between two points in the media, and dL is length of media through which flow occurs. The negative sign indicates that flow is in the direction of decreasing hydraulic head.

The total water potential in a saturated soil is a function of the gravitational (z) and hydrostatic pressure (p) components. The sum of these two components is known as the hydraulic head (H),

$$H = p + z$$

The definition of H always applies. H reduces to p only when the water elevation difference between two points is zero (horizontal flow) (Jury and others, 1991). H is constant on planes normal to parallel streamlines.

Darcy's law can be rearranged into a term J_w, called specific discharge (or flux), with dimensions of length/time, or velocity.

$$J_w = Q/A = -K\,(dH/dL)$$

It is sometimes called the Darcian velocity and represents an average discharge velocity through the entire cross-sectional area. Flow through a porous media is limited to pore channels, so that the seepage velocity (V_s) is equal to the Darcy velocity divided by porosity (Fetter, 2001). Key factors in determining flow (or velocity) from a given area must include hydraulic conductivity and the hydraulic gradient.

The rate of infiltration of effluent depends upon the saturated hydraulic conductivity (K_s) of all soil horizons surrounding and beneath the dispersal trench system. Although the K_s of the horizon in which the trench was installed may be great enough to adequately transport the effluent, an adjacent horizon with a low K_s may significantly reduce the flow. This could cause effluent to pond in the trench system and potentially cause system failure.

Unsaturated Flow

When soil is not saturated, water moves downward by gravity through interconnected pores filled with water, and to a lesser extent as a film flowing along particle surfaces in pores that also contain air. As the water content of the soil increases, more and larger pores become filled and the rate of downward water movement increases (Fetter, 2001). Darcy's law is valid for flow in the unsaturated zone, although the unsaturated hydraulic conductivity is not a constant, but is a function of volumetric water content.

Under unsaturated conditions, flow only occurs in small, water-filled pores and in thin films in larger, mostly air-filled pores. Thus, as the water content decreases, the pore pressure decreases because molecular attraction between the water and soil increases, increasing the resistance to flow. In addition, the water is constrained to smaller and more meandering channels (Jury and others, 1991). The net effect is that as the soil becomes drier, its hydraulic conductivity decreases.

Partially or completely counteracting the effect of reduced hydraulic conductivity in unsaturated soils is the effect of the soil matrix potential.

Fetter (1998) describes the hydraulic gradient for movement of water in unsaturated soil in terms of both a gravity potential and a soil matrix potential.

The matrix potential is a negative pressure (or suction) due to soil-water interactions. As the soil becomes drier, the soil-water molecular interaction increases resulting in increased matrix potential and a corresponding increase in the hydraulic gradient. It is the high matrix potential (high hydraulic gradient) that causes rapid infiltration of water into dry soil. As the soil becomes wet, the hydraulic conductivity increases, and the matrix potential component of the hydraulic gradient decreases. It is the relative magnitudes of these two components that will determine rates of water movement through unsaturated soils.

In reality, the infiltration of wastewater from a dispersal trench to the surrounding soil may be by both saturated and unsaturated flow, depending upon the saturated and unsaturated hydraulic conductivities of the different horizons, both natural and dispersal system induced, in and proximal to the soil-trench interface. If, for example, the biomat has a saturated hydraulic conductivity that is less than the saturated hydraulic conductivity of the underlying soil horizon, the quantity of water moving through the biomat will not be great enough to keep all pores in the soil filled and to maintain saturated conditions. When a steady state is reached, the water content of the soil horizon will be such that the resulting hydraulic conductivity and matrix potential will move water through the horizon at about the same rate as it moves through the biomat under saturated conditions. In contrast, if the saturated hydraulic conductivity of the biomat is greater than that of the underlying soil, both the soil and biomat will be saturated.

THE CONCEPT OF HYDRAULIC RESISTANCE

Each soil layer or zone (with its characteristic properties) provides a degree of resistance to effluent flow. Similar to a simple electric circuit, resistance in series is additive. Thus, the zones with the highest resistance determine and control flow rate. The additive effect of resistance is seen using Darcy's law,

where

$$Q = KA\frac{dH}{dL} \text{ and } J_w = \frac{Q}{A} = \text{hydraulic flux}$$

Then using Darcy's law,

$$dH = H_1 - H_0 = \frac{J_w L}{K_s}$$

and for each soil layer (or zone, z) we can define a hydraulic resistance term

$$R = dH/Jw = L/Ks$$

The effective hydraulic resistance for a number of soil layers is the sum of the individual resistances of each soil layer,

$$R_{EFF} = \sum_{Z=1}^{n} R_Z \text{ , where } R_Z = \frac{L_Z}{K_Z}$$

For example, if we use the hydraulic resistance (R) for each of five soil layers, soil 1 to soil 5, then

$$R_{EFF} = \sum_{Z=1}^{5} R_Z = \sum_{Z=1}^{5} \frac{L_Z}{K_Z}$$

Further substituting into Darcy's equation

$$K_{EFF} = \frac{\sum_{Z=1}^{5} R_Z}{\sum_{Z=1}^{5} \left[\frac{L_Z}{K_Z}\right]}$$

Thus, we can define an effective hydraulic conductivity that is a function of individual hydraulic conductivities of each of several soil layers.

This relationship suggests that in situations where several soil layers exist, each with its own characteristic hydraulic conductivity, the layer(s) with low hydraulic conductivity are significant in controlling water movement through the porous media (see Figure 1). Envision a dispersal trench with (from top to bottom) a layer of gravel, a layer of fines, and a bulk soil layer. If the layer of fines has a hydraulic conductivity that is appreciably less than the hydraulic conductivities of the gravel and soil, the layer of fines, although thin, may have the greatest impact on the overall hydraulic conductivity (K_{EFF}) of the three layers and, thus, have the greatest impact on the rate of wastewater infiltration into the soil.

COLUMN STUDIES SIMULATE TRENCH INFILTRATION

Column studies are an effective tool that can be used to test the various hydraulic parameters of soils or dispersal trenches (as described by Darcy's law), while reducing selected parameters to constants. For example, in column studies, the area through which flow occurs is constant (the column bottom). Similarly, the hydraulic head can be held constant in a column study. Thus, each of the key factors controlling flow through porous media can be evaluated independently.

Based on Darcy's law, laboratory experiments were conducted in order to determine the hydraulic conductivity of

- **sand**—representing soil (and aggregate free or open-bottom dispersal trenches),
- **sand and washed gravel**—representing a washed-gravel dispersal trench over soil (no fines),
- **sand and polystyrene aggregate**—representing an engineered aggregate (gravel-less) dispersal trench over soil (no fines), and
- **sand, fines, and gravel**—representing conventional gravel dispersal trenches over soil (fines present).

Plexiglass columns, 8 inches (20 cm) in diameter and 20 inches (51 cm) tall, were packed with combinations of the aforementioned media and then continuously loaded with water at a constant head (see Figure 2). A filter-fabric-covered aluminum screen kept media in the column. A constant head was established (H ~ 18 inches) and maintained throughout the experiments. Once a constant head was maintained, the water passing through the column was collected over a period of 60 seconds. The weight of water collected for the

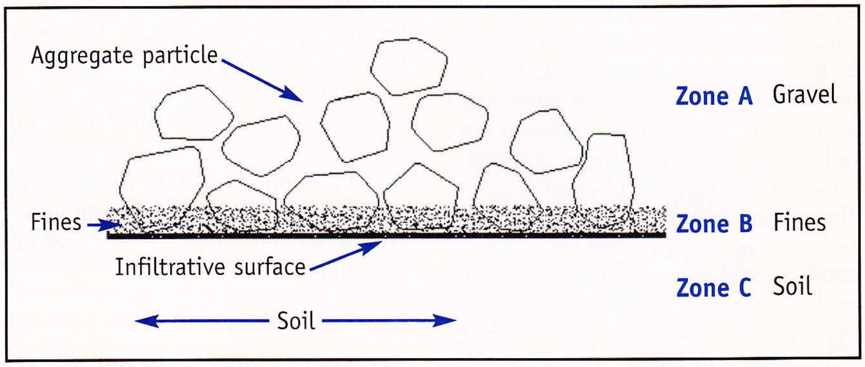

Figure 1 **Layering of Porous Medias, Each with Its Own Characteristic Hydraulic Conductivity**

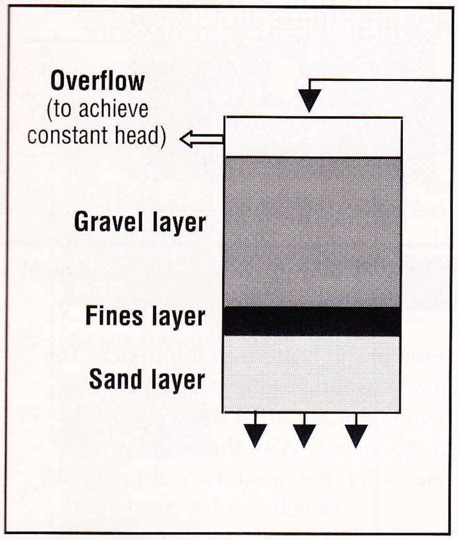

Figure 2 **Column Used for Study**

given period was then determined. From the amount of water that passed through the column in 60 seconds (Q) and knowing the cross-sectional area of the cylinder (A), the media thickness (L), and the hydraulic head (H), the hydraulic conductivity could then be calculated.

Influence of Hydraulic Conductivity (K) on Flow (Q)

By utilizing different media (sand alone, sand and washed-gravel, sand and polystyrene aggregate, and/or sand, fines, and gravel) in the column, the influence of hydraulic conductivity (K) on flow rate through the column was observed. A 2-inch layer of sand (effective size 0.008 inches, or 0.2 mm) representing a porous soil was used in all columns. Figure 3 shows the particle size distribution of the sand used.

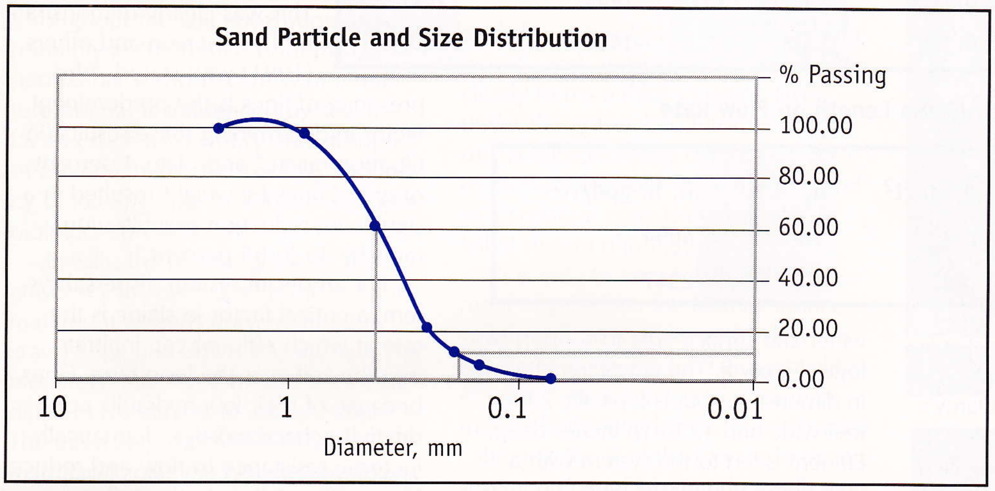

Figure 3 **Particle Size Distribution for Sand (d_{10} = 0.008 inches or 0.2 mm)**

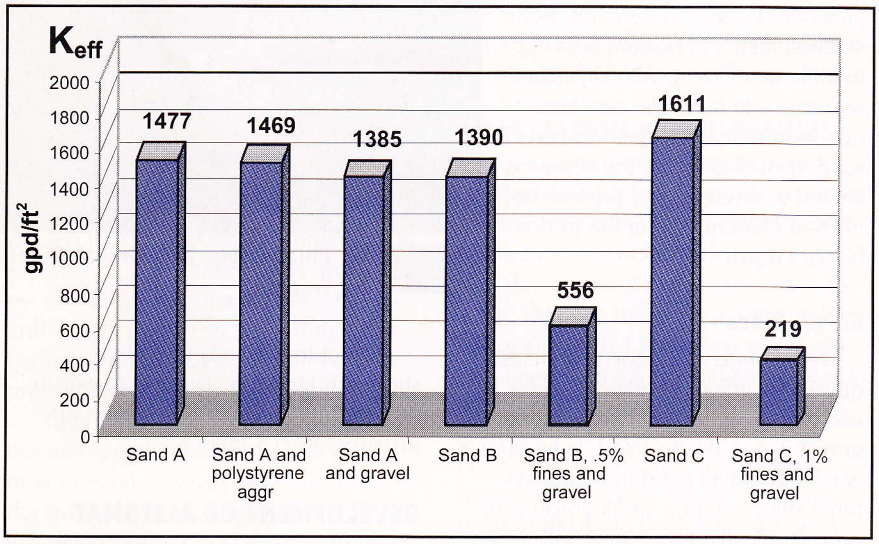

Figure 4 **Hydraulic Conductivity of Several Soil or Soil/Aggregate Media, as Determined by Column Experiments Utilizing Constant Head and Constant Area**

Determinations of hydraulic conductivity (K) from column studies (incorporating constant head and constant area) using media with no biomat formation are shown in Figure 4. Hydraulic conductivity values are effective values (K_{EFF}) reflecting the composite hydraulic conductivity as a result of all porous media through which flow is occurring.

Experimental determinations show that there is virtually no difference in the effective hydraulic conductivity of sand (1,477 gpd/ft^2) and sand overlain by 12 inches of aggregate (gravel or polystyrene with an effective size of 1 inch. This directly reflects the concept of hydraulic resistance, in that the soil layer with the lowest hydraulic conductivity (sand) controls the effective hydraulic conductivity. Thus, the incorporation of aggregate free from fines into a dispersal trench exhibits a K_{EFF} that is essentially the same as an open-bottom trench, and does not change the rate of movement of liquid into the soil horizon.

The hydraulic conductivity of the sand (soil) layer controls the rate of liquid movement into the soil environment, and the addition of aggregate has an insignificant effect, because of its much higher characteristic hydraulic conductivity. However, the presence of just 0.5 percent fines (effective size of 0.002 inches, or 0.05 mm), commonly associated with gravel, reduces the K_{EFF} to 556 gpd/ft^2 (a 60 percent-plus reduction in K_{EFF}). The presence of 1percent fines reduces the K_{EFF} to 219 gpd/ft^2 (an 84 percent reduction in K_{EFF}). Thus, without considering biomat effects, the fine material present (the material with the lowest hydraulic conductivity) controls the rate of movement of liquid into the soil, given constant head and area considerations.

Influence of Hydraulic Head (h) on Flow (Q)

Again, columns were utilized to evaluate the effects of hydraulic head on the rate of flow through porous media. Two equal-size columns were prepared, column A with a 2-inch layer of sand and column B with a similar 2-inch layer of sand overlain by 12 inches of aggregate (gravel). Column A (sand only) represents an open-bottom trench (no aggregate) and column B represents a conventional gravel trench. At time zero, exactly one gallon of water was added to each column, representing an equal volumetric dose to each system.

Because of the presence of aggregate in column B displacing water volume, the water level in column B at time zero is higher than the water level in column A by 6.25 inches. The time to completely drain the one gallon of water added was determined and following Darcy law principles, column B (with aggregate and an initially higher head) drained more quickly (see Table 1). This illustrates the effect of hydraulic head on flow rate through porous media, exactly as described by Darcy's law, given that all other factors are constant. It also shows that aggregate-filled trench dispersal systems in similar soil conditions (i.e. free of fines and/or biomat) perform as well, or better than systems without aggregate in terms of moving water through a given soil layer.

Table 1 **The Effect of Increased Hydraulic Head (H) on Flow (Q)**

Description	Hydraulic Head, H (ft)	Area (ft^2)	Media Length, L (ft)	Hydraulic Conductivity, K (gpd/ft^2)	Flow, Q (gpd)
Sand	0.40	0.349	0.16	~1400	1222
Gravel/Sand	0.92	0.349	0.16	~1400	2809

Table 2 **The Influence of Media Length on Flow Rate**

L, in ft	K, in gpd/ft^2	A, in ft^2	h, in ft	Q, in gpd/ft^2
0.167	1493	0.35	1.5	4694
0.334	1493	0.35	1.5	2347

Influence of Media Length (L) on Flow (Q)

Similarly, media length variation can be evaluated in the column. Knowing the hydraulic conductivity of the sand (1,493 gpd/ft^2, based on three trials), the area of the column cross-section (0.35 ft^2), the hydraulic head (1.5 ft), and the length of the media layer (2 inches, or 0.167 ft), flow rate (Q) can be determined. The column was operated with a sand layer length of 2 inches (0.167 ft) and with a sand layer length of 4 inches (0.334 ft). Table 2 shows that the flow rate is inversely proportional to the sand layer length, just as Darcy's law describes.

MODELING FLOW FROM ONSITE DISPERSAL TRENCHES

The Gravel Standard

Onsite gravity drainfields depend on their ability to deliver effluent to the soil for absorption. The traditional drainfield system is the gravel trench. Gravel provides many functions, but primarily serves to provide structural support and storage volume while serving as a vehicle for dispersal of effluent to the soil (see Figure 5).

Gravel trenches provide soil interface area for the application of wastewater and surface area to support biological growth. The gravel trench varies in dimensions, but is typically 2 to 3 feet wide and 12 to 18 inches deep. Effluent is fed to the system with a 4-inch perforated plastic pipe.

Keys and others (1998) showed examples of the importance of sidewall flow in the performance of gravity fed dispersal trenches. Both sidewall area and bottom area act to infiltrate effluent, with significant reductions in hydraulic conductivity due to biomat and fines. However, for purposes of focus, this review is limited to discussion of the mechanism of effluent flow at the trench bottom (QB).

Gravel Fines

Most state regulatory agencies require that gravel be washed prior to use, however, in practice, washed gravel is not always used. Even after washing, gravel used in onsite systems still contain a small amount of fines (typically 3 to 5 percent). Fines range in size from 2 mm to less than 20 µm. Over a short period of time, the fines wash from the gravel and settle at the bottom of the trench. The height of the fines layers varies but could typically be in the range of 0.1 to 0.5 inches. With the addition of a fines layer, the illustration of the gravel trench can be considered as having three zones: gravel, fines, and soil.

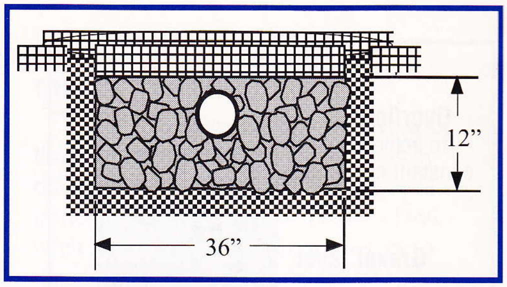

Figure 5 **Depiction of a Typical Gravel Trench**

Fines are a significant problem in gravity fed dispersal systems, as they significantly reduce flow rates. This was clearly demonstrated by Amerson and others (1991) who stated "the presence of fines is the predominant factor in determining these results (infiltration rates)," and "1 to 4 percent of gravel fines by weight resulted in a significant reduction of infiltration rates by 35 to 65 percent."

For an onsite system dispersal system, a critical factor in sizing is the rate at which effluent can infiltrate into the soil over the long term. Fines, because of their low hydraulic conductivity characteristics, dramatically increase resistance to flow and reduce Q, or effluent flow to the soil.

Figure 6 **Fines Layer in a Gravel Dispersal Trench**

A picture of fines in gravel is shown in Figure 6. The fines layer in this example is measured to be approximately 0.5 inches.

DEVELOPMENT OF A BIOMAT

As a gravel system matures, a biomat made up of microorganisms typically formed on the trench bottom. The biological growth is distributed

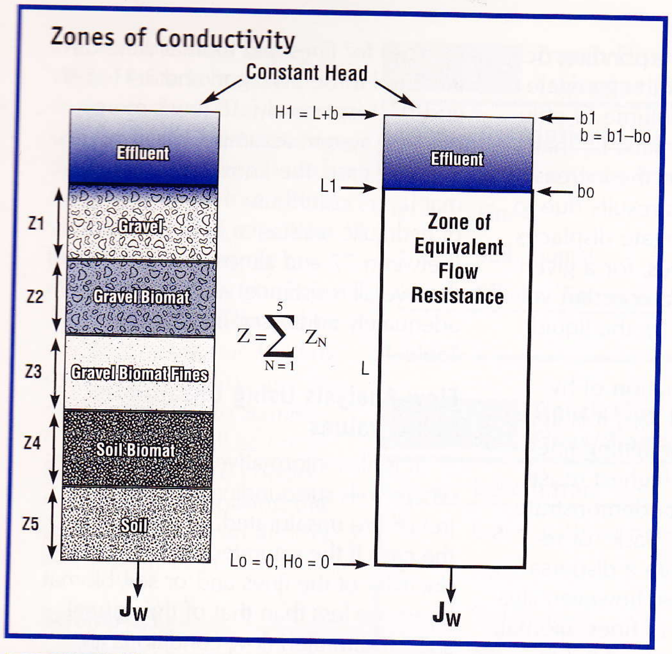

Figure 7 **Infiltration Trench Representation Showing Zones of Differing Hydraulic Conductivity**

throughout the soil absorption area, primarily at the trench bottom. The permeability and thickness of a mature biomat is influenced by several factors such as quantity and strength of effluent, hydraulic loading, frequency of loading and available oxygen for biological breakdown.

Initially, the biomat grows at the gravel soil interface, but as the biomat matures, it extends upward into the gravel zone and down into the soil. This biomat creates three biomat zones with different resistances to effluent flow. The three zones are defined as the biomat/gravel zone, the biomat/gravel/fines zone, and biomat/soil zone. The whole gravel trench bottom system can now be depicted as having five separate zones. Each zone will have its own unique properties and a different hydraulic conductivity (K) associated with it (see Figure 7).

ZONES OF CONDUCTIVITY

Because of the hydraulic characteristics of the biomat and fines, it is expected that zones 3 and 4 provide the smallest K or, in other words, the greatest resistance to effluent flow. Keys and others (1998) suggested that the hydraulic conductivity of a trench bottom biomat is about 0.005 gpd/ft^2.

Total flow (Q Bottom) through the five layers is dependent on the thickness of each zone, its hydraulic conductivity and the hydraulic head above. In solving Darcy's equation for Q, the area is determined to be the entire surface area of the trench bottom that is covered by the permeable media and for which K is determined.

When comparing the performance of an alternative dispersal system one must consider comparison of performance to all five zones. Alternative dispersal systems without fines will have a higher flow rate Q than a standard gravel system with fines because of the low hydraulic conductivity of the biomat/fines layer.

Effluent flow through saturated biomat zones offer the greatest resistance to flow or the lowest K. Figure 8 also shows a sidewall biomat without gravel, and, as Figure 9 shows, biomat clearly forms a thick clogging layer under the gravel. The thickness of the mat is approximately 0.25 to 0.5 inches. Separation from the soil and gravel as a separate zone is evident in this failed system photograph.

It is easy to envision that the placement of gravel on the biomat surface will do little to further restrict flow. In other words the resistance of gravel to effluent flow is significantly less than that of the biomat layers. In mathematical terms, the K of the biomat layers are several orders of magnitude smaller than the K of gravel.

From this illustration it is clear that the biomat permeates the fines and the soil layer. It is also illustrated in Figure 10 that the biomat forms within the gravel layer as well.

INFILTRATION MODEL RESULTS

The concept of hydraulic resistance and Darcy's law can be used to predict (or model) both the effective hydraulic conductivity (K_{EFF}) and the flux (J_w) from a given trench area. Assume that the trench is a 1-foot-wide, 1-foot-long and 1-foot-deep gravel system (assuming full ponding, dH/dL = 1). Hydraulic conductivity values (high and low estimates) and infiltration layer depths are estimated below, based on literature values, and are used to illustrate both flow (Q) and flux (J_w) from a dispersal trench system. Values for biomat/fines hydraulic conductivity were estimated using the work of Keys and others (1998).

Flow Model Using Low Hydraulic Conductivity Values

Using the equation

$$K_{EFF} = \frac{\sum_{Z=1}^{4} L_Z}{\sum_{Z=1}^{4} \frac{L_Z}{K_Z}}$$

where

$$R_Z = \frac{L_Z}{K_Z},$$

both K_{EFF} and the overall flux from this hypothetical trench can be determined. The hydraulic resistance of each layer is

$$R_{ZONE\_1} = \frac{.3}{1000} = .0003$$

(gravel layer, 0.3 feet in length, K=1,000 gpd/ft^2)

$$R_{ZONE\_2} = \frac{.03}{.01} = 3 \quad \text{(fines layer,}$$

Figure 8 **Sidewall Biomat in an Actual Trench**

Figure 9 **Biomat Present at Trench Bottom**

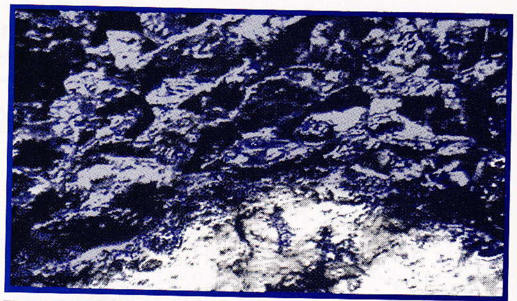

Figure 10 **Biomat Growth within the Gravel Layer**

0.03 feet in length, K=0.01 gpd/ft^2)

$$R_{ZONE\_3} = \frac{.04}{.01} = 4$$ (soil/biomat layer, 0.04 feet in length, K=0.01 gpd/ft^2)

$$R_{ZONE\_4} = \frac{.25}{6} = .04$$ (soil layer, 0.25 feet in length, K=6 gpd/ft^2)

K effective can be determined as follows:

$$K_{EFF} = \frac{.3+.03+.04+.25}{.003+3+4+.04} = \frac{0.62}{7.04} = .088 \text{ gpd/ft}^2$$

Now, if K effective is substituted into Darcy's equation, where

$K_{EFF} = .088$ gpd/ft^2
$I = 1$
$A = 1$ ft^2

$$Q = K_{EFF} IA = (.088 \text{ gpd/ft}^2)(1)(1 \text{ ft}^2) = .088\_\text{gpd and } J_w = \frac{.088\text{gpd}}{\text{ft}^2}$$

As is illustrated, the fines and biomat layers, with their characteristically low hydraulic conductivity values, define the hydraulic resistance and the K_{EFF}. The hydraulic conductivity for fines or fines/biomat is much less than the hydraulic conductivity for soils, except for highly restrictive soils, such as clay (see Table 3).

Experimental column studies verify this concept of K_{EFF} and show that the effective hydraulic conductivity of systems with aggregate (and no fines or biomat) are not significantly different from open systems with no aggregate (assuming constant head). Thus, the importance of eliminating fines, by either thoroughly washing gravel media or utilizing engineered (nongravel) dispersal trench technologies, is shown. However, even with the elimination of fines, the biomat layer, with a low hydraulic conductivity value, will significantly determine K_{EFF}, and thus reduce flow from a dispersal trench.

For situations where ponding occurs, trench systems with aggregate dosed with an exact volume of effluent will have a greater flux, J_w, than an open system due to the increased hydraulic head, h. This results due to the fact that the aggregate displaces liquid volume, and, thus, for a given volume of effluent in a constant volume column (or trench), the liquid level is higher.

From the determination of hydraulic resistance and K_{EFF}, it is apparent that the zones containing fines and biomat offer the highest resistance to flow. This data demonstrate that gravel does not "mask" or reduce effluent flow from a dispersal trench bottom; it does, however, illustrate the significance of fines, biomat, hydraulic conductivity, and the hydraulic head in affecting flow from a dispersal trench.

Flow Model Using High Hydraulic Conductivity Values

Hydraulic conductivity (K) for the fines and biomat zones can vary depending on a number of factors including fines present and size, oxygen availability, organic loading, age of the system, etc. Various values for K of the biomat layer have been measured and reported in the literature. As K changes, the relative resistance or impact of the gravel fines layers also change. For example, as a system ages, the biomat layer will grow, and K will decrease significantly.

To explore the entire range of possible K values assigned to fines and biomat, the K of the fines and soil/biomat layers was increased from 0.01 gpd/ft^2 to 0.5 gpd/ft^2, a 50 fold increase, as suggested by the range of values reported by Keys et al. (1998). This change causes the percent of the total resistance for the fines layer to decrease from 43 to 33 percent. The total resistance for the soil/biomat layer decreases from 57 to 44 percent. Flow and flux from this system using higher K values for fines and biomat were determined to be 3.41 gpd and 3.41 gpd/ft^2, respectively, 38 times more than the system assuming low K values. In either case, the fines layers and biomat layers contribute the vast majority of hydraulic resistance in a soil column (between 77 and almost 100 percent of the overall resistance) and should be adequately addressed in design (see Table 4).

Flow Analysis Using Unsaturated Soil K Values

It is also informative to look at cases where soils surrounding a dispersal trench are unsaturated, which may be the case if the saturated hydraulic conductivity of the fines and/or soil/biomat layers are less than that of the natural soil. Unsaturated flow conditions are also useful in effluent treatment, a key goal of dispersal system design.

The calculation of the K_{EFF} for this system must include the soil's unsaturated hydraulic conductivity, which, by definition, is a function of the volumetric water content. At relatively high soil moisture contents, a sandy soil may have an unsaturated hydraulic conductivity of between 0.1 gpd/ft^2 and 100 gpd/ft^2, or more. Using a hydraulic conductivity of 0.6 (an order of magnitude less than our saturated soil K used previously), and a hydraulic gradient of 1.0, K_{EFF} can be determined (as before) and flows and fluxes from the dispersal trench can be estimated.

This illustrates that unsaturated flow from dispersal trenches is similar to saturated flow from trenches under conditions of highly restrictive fines and biomat layers (see Table 5).

EVALUATION OF ALTERNATIVE DISPERSAL SYSTEMS

When comparing the performance of alternative dispersal systems to gravel-based systems for sizing considerations, one should consider the key factors that address the rate of flow across the trench-soil interface and into the soil (i.e., hydraulic conductivity, infiltration area, media layer depth, and hydraulic head). Clearly, systems without fines have less hydraulic resistance and will perform more effectively than systems with fines. However, it is essential to understand that the hydraulic conductivity associated with biomat layers

Table 3 **Trench Flow Model Using Low Hydraulic Conductivity Estimates for Fines/Biomat Layers**

Zone	Description	K (gpd/ft^2)	L (ft)	Q (gpd)	J_w (gpd/ft^2)
1	Gravel with no fines	1000	0.3	—	—
2	Fines	0.01	0.03	—	—
3	Soil/Biomat	0.01	0.04	—	—
4	Effluent Saturated Soil	6	0.25	—	—
		K_{EFF} = 0.088		Q = 0.088	J_w = 0.088

are variable until some steady state layer depth and K are reached after months of operation. Hydraulic conductivity of a biomat and the resulting rate of effluent infiltration into the soil can change as a result of numerous factors, including effluent application rate or frequency, organic loading, oxygen availability, and soil characteristics, to name a few. Each and all of these factors should be considered when comparing the performance of an alternative system to gravel.

Table 4 **Trench Flow Model Using High Hydraulic Conductivity Estimates for Fines/Biomat Layers**

Zone	Description	K (gpd/ft^2)	L (ft)	R	Q (gpd)	J_w (gpd/ft^2)
1	Gravel with no fines	1000	0.3	.0003	—-	—-
2	Fines	0.5	0.03	.06	—-	—-
3	Soil/Biomat	0.5	0.04	.08	—-	—-
4	Effluent Saturated Soil	6	0.25	.0417	—-	—-
		K_{EFF} = 3.41			Q = 3.41	J_w = 3.41

Table 5 **Trench Flow Model Using Low Hydraulic Conductivity Values for Fines/Biomat, and Unsaturated Soils**

Zone	Description	K (gpd/ft^2)	L (ft)	R	Q (gpd)	J_w(gpd/ft^8)
1	Gravel with no fines	1000	0.3	.0003	—-	—-
2	Fines	0.01	0.03	3	—-	—-
3	Soil/Biomat	0.01	0.04	4	—-	—-
4	Effluent Unsaturated Soil	0.6	0.25	1.25	—-	—-
		K_{EFF} = 0.075			Q = 0.115	J_w = 0.115

SUMMARY

The key to understanding the infiltration of effluent into soils is to understand the elements of Darcy's law—hydraulic conductivity, hydraulic head, flow path length, and area of flux. Each of these elements must be understood and accurately characterized to effectively predict infiltration adequately and, thus, appropriately design an infiltration mechanism. The characteristic hydraulic conductivity of restrictive soil (media) layers, such as fines or biomat, typically controls infiltration from traditional dispersal trenches. Hydraulic head, the length of the media layer through which flow is occurring, and the area utilized for infiltration are also important.

It should be noted that in designing infiltration systems, the area of infiltration is determined by trench/bed configuration and is constant. This area for infiltration is determined based upon key factors, such as hydraulic conductivity of the most restrictive media layers (typically fines and /or biomat). Without fines (associated with gravels), systems of equal size and loading, with and without gravel, have characteristically similar effective hydraulic conductivity (K_{EFF}).

A key issue in designing soil infiltration systems is how to incorporate trench sidewall area into the sizing determinations, while still maintaining factors of safety. As further research more accurately describes the hydraulic conductivity (and overall influence) of biomat, effluent dispersal system sizing will become more accurate and more standardized, no matter the delivery system. SF

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