*Soil Oxygen Delivery to Wastewater Infiltration Surfaces[i]

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ABSTRACT

The life, loading rate, and therefore the wastewater infiltration system design are controlled by the presence of an organic clogging mat. Clogging mats develop when organic matter loading is higher than the oxygen supply for aerobic bacteria. If the oxygen supply meets the demand of the soil organisms, then the organic clogging mat will not form. In the absence of a mat, the soil could accept wastewater at rates two to three orders of magnitude higher than the current design loading rates. The biochemical oxygen demand (BOD) for wastewater systems ranges from 10-500 mg L^{-1}, however the rate of oxygen supply has not been determined for wastewater infiltration systems. This work reports techniques for estimating oxygen supply utilizing models. The models are applied to existing system design and examples are given of how soil oxygen estimations can be used to establish wastewater loading rates so that added BOD does not exceed the soil oxygen supply. The design of wastewater infiltration surfaces should be estimated using both oxygen demand and hydraulics. For high BOD wastewater, the design is based on BOD loading and oxygen supply and for low BOD wastewater the design is based on volume and design soil acceptance rates. Based on the model, the soil component of the wastewater infiltration system should be large, shallow, narrow, and have separated infiltration areas to maximize oxygen supply. Future designs should incorporate knowledge of wastewater BOD and soil oxygen availability.

INTRODUCTION

An efficient onsite wastewater system has a balance between the amount of oxygen entering the system with the amount of oxygen needed to decompose the organic matter and meet the demand from other reactions. If the amount of oxygen entering the system cannot meet the demand, a clogging mat will form. Clogging mats form between the gravel and soil at the infiltration surface. If the system design can be manipulated to supply oxygen into the soil exceeding the rate needed, the life and loading rate of the onsite wastewater system can be greatly increased.

Aerobic bacteria use oxygen as their terminal electron acceptor to convert organic molecules to carbon dioxide and ammonia to nitrate. Oxygen is the most effective oxidizing agent, therefore decomposition in an aerobic setting is far more efficient than in an anaerobic environment. If the oxygen supply runs out, the bacteria are forced to use alternative means that are less efficient in order to decompose the wastewater. Under large bed onsite wastewater infiltration systems the environment is likely anaerobic and methane accumulation may occur under the center of the infiltration surface. In this anaerobic environment, methane could be used as a reducing agent, but decomposition with methane is much less efficient than with oxygen. In this situation decomposition of the wastewater is much slower.

The total oxygen demand is measured as the biochemical oxygen demand (BOD) and the organic matter loading rate. The BOD is the amount of oxygen needed by the aerobic bacteria to decompose a volume of the wastewater and supply other reactions. The wastewater loading rate is the volume of wastewater released into the soil in a unit of time. The mass flux is the amount of oxygen per unit area moving into the soil in a unit of time. Oxygen is supplied to the infiltration surface by diffusion in the soil atmosphere, and it can be calculated using a form of Fick's law (Yanful, 1993).

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DESCRIPTION OF MODELS

In order to understand the ramifications of Fick's Law, two applications will be studied. In each example the goal is to estimate the movement of oxygen from the ground surface to the infiltrative surface. The amount of oxygen dissolved in soil water is low and the movement of the oxygen in the water is slow. Therefore, most oxygen supplied to wastewater infiltration systems will be as a gas. Since the pressure of the soil atmosphere is nearly uniform in the soil, mass flow contributes very little to oxygen movement. Diffusion of oxygen is the major mechanism of transport. Soil factors affecting oxygen diffusion in the gaseous phase will control the supply of oxygen to infiltrative surfaces.

Theoretical Background

The transport of oxygen from the atmosphere through the soil and eventually to the onsite system is by molecular diffusion. Diffusion is a response to the concentration gradient formed between the oxygen rich atmosphere and the oxygen poor wastewater infiltration site. The mass flux can be calculated using a form of Fick's first law of diffusion (Yanful, 1993) by:

$$F = -\theta_a D_e \left(\frac{\Delta C_a}{\Delta h} \right)$$

Where: F is the mass flux of oxygen into the system (lb ft^{-2} day^{-1}), D_e is the effective diffusion coefficient (ft^2 day^{-1}), ($\Delta C_a/\Delta h$) is the change of oxygen concentration in the soil (lb ft^{-3}) as a function of depth (ft) and θ_a is the air filled porosity (ft^3 ft^{-3}). θ_a is related to the degree of saturation of the soil (Yanful, 1993) by:

$$\theta_a = \theta_t (1 - S_r)$$

Where θ_t is the total porosity and S_r is the degree of saturation.

A typical soil might be comprised of 50% solid space and 50% void space. Both the individual soil particles and the organic material are considered solid space. The other half of the soil volume is filled with either liquid or gas. Porosity is the void space between the soil particles, and once these voids are connected they form pores or passages for the air or water to travel through.

The water content or degree of saturation (S_r) of the soil greatly affects the oxygen flux (F) through the system. As the degree of water saturation increases, the mass flux of oxygen decreases. Moisture in the soil is held with matric potential in the smaller pores, and the gases are transported through the larger pores in the system (θ_a). As the moisture content increases, the next largest pores fill with water, which in turn traps or pushes the gas out of the soil and reduces the volume of pores for gas transport. As the water content of the soil increases, the gas filled pore space continuity decreases. Figure 1 depicts three degrees of saturation. In a typical wastewater infiltration system the moisture content is high, therefore the gas filled volume is low. In this type of system much of the oxygen needed for the decomposition of the wastewater cannot reach the site of infiltration.

The mass flux of oxygen into the system is based on the oxygen diffusion coefficient (D_e), which is a function of many parameters of the soil and the environment. One factor that influences the D_e is the amount of large pores in the soil. As the amount of these large pores increase, the D_e also increases. The amount of large pores in the soil is a reflection of the size and shape of the soil particles. However, generally as the particle size increases the total porosity decreases, and the number of large pores increases. Based on that reasoning, sand sized particles (0.05-2mm) would have a greater D_e than clay sized particles (<2μm), but clay would have a higher total porosity. The large void space between the sand particles allows the oxygen to diffuse through the soil much faster than through the clay-sized particles. At the same water potential the water content of clay is higher than sand. The shape of the individual grains also influences the oxygen diffusion coefficient. Irregular shapes do not form tight connections between the individual particles. The extra voids between the particles form pores that the oxygen can diffuse through easily. On the other hand, in compacted soils the pores have been crushed, therefore oxygen cannot be effectively transported.

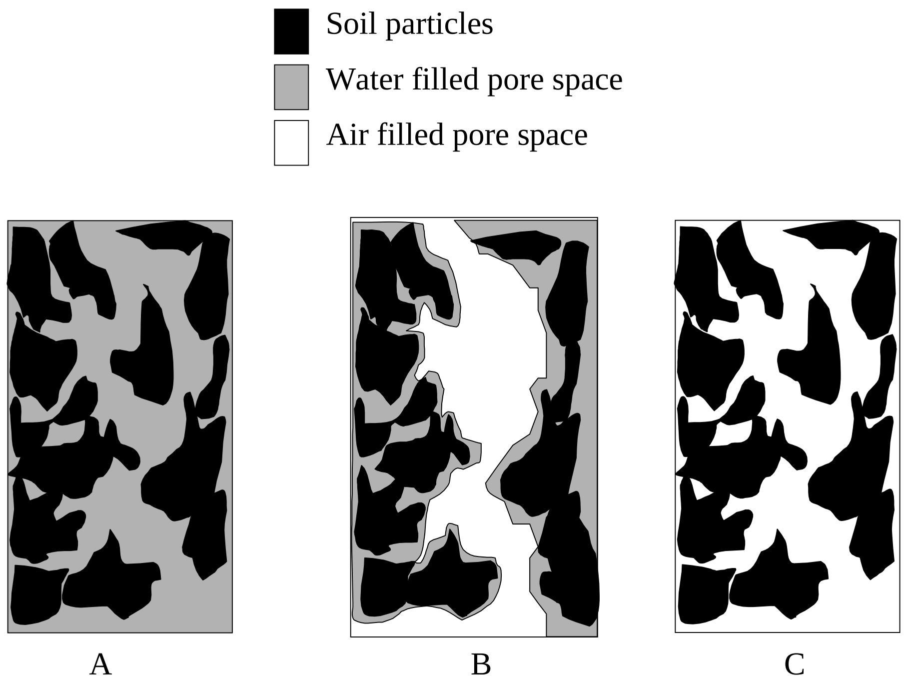

Figure 1. Image A is a soil saturated with water. In example B, the smaller pores are filled with water and the larger pores transport gases via diffusion. Image C is a completely dry soil.

The oxygen concentration gradient and the distance between the ground surface and the onsite wastewater infiltration site of the system affect flux of oxygen into the system. A gradient is created when the oxygen concentration at the ground surface is equivalent to the atmospheric concentration (C_a) 0.0187lb/ft^3 assuming that the concentration (C_0) at the infiltration site is 0lb/ft^3. This gradient is a function of the distance to the infiltration site. As the distance between the ground and the infiltration site of the system increases the concentration gradient decreases. The greater the distance the infiltration bed is from the ground the longer the path the oxygen must travel causing a decrease in the mass flux of oxygen. Since the gradient is the force behind diffusion, a steep concentration gradient is preferred.

Model One

For the simplest case, assume a large bed wastewater infiltration area that is both long and wide. Also, assume that the void volume in the aggregate of the bed is completely wastewater ponded. The problem is in determining the oxygen supply from the ground surface through the soil to the top surface of the bed, therefore this model accounts for only part of the entire system. Figure 2 is a cross-section of the system revealing the ground surface at the top and the infiltration surface at the bottom. In this case, assume the oxygen flow paths are straight through the soil and parallel to each other as depicted by the parallel flow lines in fig 2. This is known as laminar flow. Applying Fick's Law to this simple system, it is known that the oxygen flux is affected by the moisture content of the soil, the effective diffusion coefficient, and the change in concentration of oxygen with depth.

In order to test the model, Fick's law of diffusion was applied to the simplified system in fig 2. The oxygen diffusion coefficient (0.011ft^2/day) accounted for the high moisture content found in most infiltration systems so the air filled porosity was dropped from the equation (Jaynes and Rogowski, 1983). The atmospheric oxygen concentration, 0.0187lb/ft^3, was based on normal atmospheric conditions, and the depth of the system was 1.6 ft. The system was loaded at 0.5 gal/day/ft^2, and the BOD was 0.00125lb/gal. The total oxygen demand was .000625lb/ft^2/day, while the oxygen flux to the infiltration bed was .000128 lb/ft^2/day. The demand for oxygen is much greater than the supply to the infiltrative surface, therefore a clogging mat will likely occur. In order for the supply to meet the demand the loading rate would have to be decreased to 0.10gal/day/ft^2. Therefore, application of the wastewater is five times greater than oxygen supply. This suggests that for domestic wastewater, the loading rate should be one fifth of the current rate or the area for infiltration should be increased five times. To improve the oxygen balance the designer could make the system shallower, reduce the loading rate, or pretreat the wastewater.

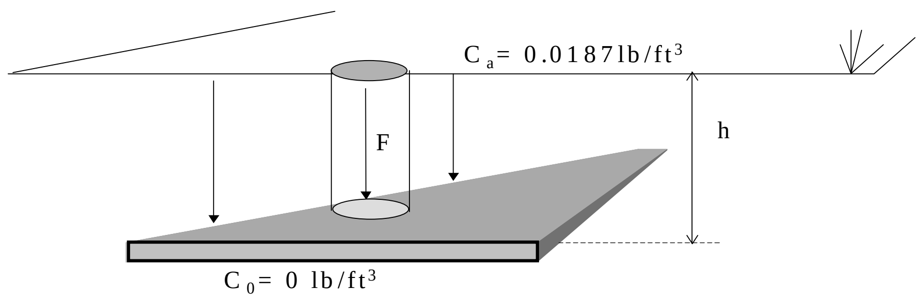

Figure 2. A schematic representation of a saturated bed. F is the laminar flux into the system, C_a is the oxygen concentration in the atmosphere, and h is the depth of the system.

Model Two

The same principles from the first model can be applied to the second model, a drip line distribution system. The oxygen diffusion coefficient, the concentration gradient, and the water content affect the system in a similar manner. In this system a drip line is buried under the ground and since the drip line is much longer than it is wide, it can be assumed to be two-dimensional. The two-dimensional aspect of this model also assumes that oxygen diffuses to the drip line in a flow net pattern. A flow net pattern is one in which the gas diffuses through the soil from all sides of the drip tube. Figure 3 represents a theoretical pattern of oxygen diffusion to a drip line. For the second model, a new form of Fick's law is utilized in order to account for the outer radius of the drip line and the flow net pattern of diffusion. This model is based on the assumption that the depth of the drip line (h) is much greater than the radius (r) of the line.

$$F = \frac{2\pi D_e C_a}{\ln\left(\frac{h}{r}\right)}$$

Where: F (lb/ft/day) is the mass flux of oxygen per unit length of drip line per unit time, and D_e is the oxygen diffusion coefficient (ft^2/day) in the soil. Where: C_a (lb/ft^3) is the concentration of oxygen in the atmosphere, h (ft) is the depth, and r (ft) is the radius of the drip line (Carslaw and Jaeger, 1978).

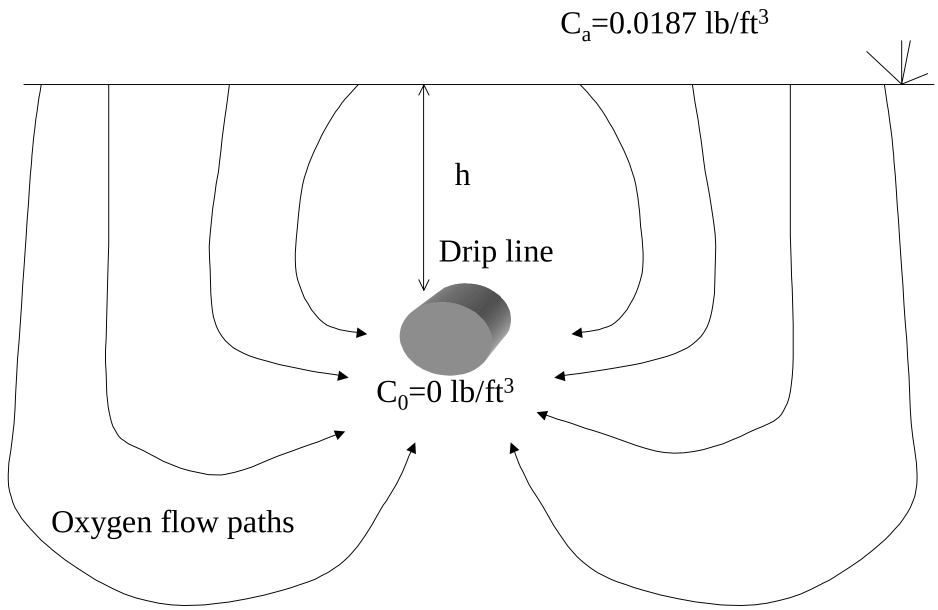

Figure 3. A schematic representation of a single drip line emphasizing the flow paths of oxygen diffusion. C_a is the concentration of oxygen in the atmosphere and h is the depth of the drip line in the soil.

In order to test the second model, Fick's law of diffusion was applied to a drip line and a trench. In both cases the oxygen diffusion coefficient, 0.0112ft^2/day, was assumed to be very low due to the high moisture content found in most infiltration systems (Jaynes and Rogowski, 1983). The atmospheric oxygen concentration, 0.0187lb/ft^3, was based on normal atmospheric conditions. In the first example, it was assumed that the drip tube had an outer diameter of 0.082ft, and it was buried 0.33ft under the ground. This system was loaded at 0.24gal/day/ft, and the BOD was 0.00125lb/gal. Applying Fick's law to the model, the oxygen flux to the system was 0.0006lb/ft/day, and the total oxygen demand was .0003lb/ft/day. The oxygen supply exceeds the demand therefore a clogging mat will not form under the drip line. Field experience verifies this conclusion. The loading rate could be doubled to 0.5gal/day/ft before the demand equaled the flux of oxygen to the system.

The same equation was applied to a trench loaded with 1.20 gal/day/ft and the BOD was 0.00125lb/gal. Assume the trench was a cylinder, and it was buried 3ft under the ground with a diameter of 1ft. The oxygen flux into the system was 0.0007ft/day while the total oxygen demand for this system is 0.0015lb/ft/day. In this case the supply of oxygen into the system will not be enough to meet the demand therefore a clogging mat will likely form under the bed. Field experience verifies this conclusion. In order for the flux to meet the demand the loading rate would have to be decreased by half the current loading rate.

The models presented here are based on several assumptions and have not been field confirmed. Confirmation of the input variables from laboratory physical models and field systems is needed.

CONCLUSIONS

Both the model and the mathematics suggest that in order for an onsite infiltration system to work efficiently, many variables must be in the right proportions. In order to increase the oxygen flux to the infiltration surface, the system design must be long, thin, and located close to the ground surface. A dry, porous soil loaded with a low BOD wastewater will also increase the efficiency of the system. If the oxygen supply calculated is correct, it is consistent with field observations of clogging mats.

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