MAR Clogging Monograph Part I - Clogging Phenomena Related to Surface Water Recharge Facilities

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Section 1.0 Introduction

Dr. Herman Bouwer once wrote:

> "Clogging of the infiltration surface and resulting reductions in infiltration rates are the *bane* of all artificial recharge systems." (added emphasis) (Bouwer, 2002).

In many cases, clogging is what limits the capacity of managed aquifer recharge (MAR) facilities, whether they be injection wells, subsurface recharge galleries or surface spreading facilities. Needless to say, in order to maximize the capacity of MAR facilities, understanding clogging and developing successful mitigation strategies are critical. This section of the clogging monograph focuses on clogging of surface spreading facilities and is divided into two parts. Part I presents a summary of literature reviewed on this topic Part II presents surface spreading performance data for Orange County Water District (OCWD or District), located in southern California, USA. The purpose of Part I of the Clogging Monograph is to present a literature review of the mechanisms that control clogging.

Section 2.0 Clogging of Surface Spreading Facilities

Over time, all surface water spreading facilities will clog (Baveye et al. 2001; Bouwer et al. 2001; Bouwer& Rice 2001; Schubert 2004). Surface waters used for recharge often contain significant quantities of suspended sediments and microorganisms, which lead to clogging (Bouwer & Rice 1989; Behnke 1969). It must be noted that the clogging seen in spreading basins is different than in rivers and stream channels due to the self-cleaning potential of rivers and stream channels (e.g., bed sediment transport), which can reduce clogging depending on the timing and magnitude of runoff events (Rehg, 2005; Schubert 2004, Lacher, 1996).

Clogging can be caused by physical, biological and chemical processes. Each of these processes can work individually or collectively to reduce infiltration rates. Factors that influence the development and extent of a clogging layer include the effluent water quality, basin soil texture, ponding depth, hydraulic loading rate and cycle, and vegetation. Moreover, due to changes in water quality, water depth, and basin bottom conditions, these processes can be active at different times and in different locations (Becker et al. 2012; Racz et al. 2012). Thus obtaining a detailed understanding of how clogging affects infiltration rates is challenging because it involves multiple processes that are changing in importance in time and space.

Clogging of the infiltration surface has multiple effects, including:

1. Reducing infiltration rates (Duryea 1996, Bouwer & Rice 1989; Behnke 1969; Allison

1947);
2. Diminishing the effectiveness of soil aquifer treatment (Siegrist 1987);
3. Necessitating regular maintenance (e.g., draining and scraping basin floors); and,
4. Potentially leading to site abandonment in extreme cases (Grischek 2006).

The clogging layer is often thin (millimeters to 4 centimeters) and may consist of suspended solids, algae, microbes, dust, and salts. As defined by Houston et al. (1999), the clogging layer is the zone of material over which a sharp drop in hydraulic head occurs as water infiltrates into a sedimentary profile. That is, the clogging layer reduces the hydraulic conductivity of the sediment such that the underlying material below the basin bottom will eventually become unsaturated. Hydraulic conductivity is a quantitative measure of sediment's ability to transmit water when subjected to a given hydraulic gradient. The effective hydraulic conductivity (K_e) is the overall hydraulic conductivity of an infiltrative zone that includes the clogging layer and the sediment below (Beach 2005). K_e will be used in this paper to discuss the hydraulic conductivity of sediments except if specified otherwise.

Two distinct types of clogging layers typically exist:

1. Upper Layer - is an accumulation of particulate matter, algae, and/ or microbes above the original sediment surface (outer blockage); and,
2. Lower Layer - the native sediment with organic and inorganic solids trapped in the pore space (inner blockage).

Consolidation from overburden pressure caused by the depth of ponding typically controls the conductivity of the upper layer (outer blockage). Loss of high conductivity pore space in the native soil controls the conductivity of the lower layer (inner blockage).

The water quality components that primarily influence the formation of a clogging layer are physical (accumulation of suspended solids) and biological (blockage by microorganisms and their byproducts). In addition, extended ponding periods enhance soil clogging, whereas wetting and drying cycles tend to destroy the clogging layer; under long-term ponding conditions, the hydraulics of an infiltration basin is often controlled by the clogging layer, regardless of the native soil media (Beach 2005; Houston 1999; Duryea 1996).

Section 2.1 Physical Clogging

Physical clogging is caused by the deposition and accumulation of organic and inorganic solids (such as clay and silt particles, algae cells, and microorganisms) at the water-sediment interface, leading to the formation of a filter cake (outer blockage). The rate of clogging is determined by the rate of suspended solids deposition, the size distribution of the suspended solids and the size distribution of the receiving sediments. Larger suspended solids will tend to accumulate on the sediment surface, but smaller suspended solids can potentially migrate into the pore space of the receiving sediment and cause inner blockage (Bouwer 2002; McDowell-Boyer et al. 1986). If deep penetration of particles occurs, it can reduce the effectiveness of surface cleaning, thus potentially leading to irrecoverable losses in infiltration capacities (Rehg 2005).

Additional suspended solids can be introduced to a spreading facility by erosion, wave action, and windborne dust. When suspended solids in the influent water are relatively high, the clogging caused by these additional factors is secondary to the clogging caused by the accumulation of solids in the influent water; When recharging water with low suspended solids, these factors dominate physical clogging processes. To address this, it is recommended to design recharge facilities to minimize the impact of erosion or wave action (Bouwer 2002).

Section 2.2 Biological Clogging

Microbial cells and their metabolic byproducts (gas entrapped in pores or exopolymers that clog pores) can alter a number of sediment properties such as pore size, pore volume, and flow path interconnectedness, which in turn affect the hydraulic conductivity of the media (Baveye et al. 1998). Water quality, in particular the nutrient load, is the most important factor that influences the development of the microbial component of the clogging layer (Winter & Goetz 2003). Elevated concentrations of carbon and macro-nutrients (i.e. nitrogen and phosphorus), commonly found in treated sewage effluent, stimulate microbial growth such that biological clogging rates correlate to the biological oxygen demand. Clogging from algal blooms may also occur even in relatively low nutrient waters and may need to be actively managed via herbicides or algal feeders (fish). Nonetheless, biological clogging can be reversed, typically by allowing the facility to dry, which causes the extracellular polysaccharides and microbes that cause clogging to biodegrade (Houston et al. 1999; Magesan et al. 1999; Duryea 1996).

Section 2.3 Other Clogging Factors

Other factors that play a minor role in clogging include chemical precipitation and deposition in the pores (Bouwer 2002; Platzer and Mauch 1997), growth of plant-rhizomes and roots (Vymazal et al. 1998; Brix 1994,1997; McIntyre & Riha 1991), formation and accumulation of humic substances (Siegrist et al. 1991), generation of gas (Langergraber et al. 2003), and compaction of the clogging layer (Houston et al. 1999; McDowell-Boyer et al. 1986). Chemical properties of soil particles and the infiltrating water, such as electrolyte concentration, pH, redox potential, and mineralogical composition of the sediment may influence the geometry of the pore space and may affect the shape and stability of the pores, which in turn determines the hydraulic conductivity of the media (Baveye et al. 1998).

Section 3.0 Parameters that Influence Clogging

Achievable infiltration rates in surface spreading operations, or the bulk Ke, is controlled by four main factors (Beach, 2005):

1) Hydraulic conductivity of the infiltrative surface, including the clogging layer;
2) Height of ponding above the infiltrative surface;
3) Thickness of the clogging layer; and,
4) Moisture pressure potential (tension) of the subsurface sediments.

Nonetheless, many studies show that the bulk K_e, is generally controlled by the characteristics of the clogging layer (Phipps et al. 2007; Beach 2005; Houston 1999; Duryea 1996). Moreover, total suspended solids and the nutrient load, typically characterized by Biological Oxygen Demand (BOD), appear to be the most important components that influence the formation of a clogging layer.

Physical clogging has been observed to depend on the total mass of suspended solids and particle size distribution of the porous media with reduction in basin recharge rates well described by an exponential decay function (Phipps et al. 2007). Microbial clogging has been observed to reduce hydraulic conductivity and eventually stabilize to a constant value (Taylor and Jaffe 1990; Frankenberger et al. 1979). Clogging usually occurs on or near the surface except in two instances: when a soil has hydraulic properties similar to those of the clogging material or when fines migrate and accumulate in a soil at a depth significantly below the surface, thereby resulting in a deeper restricting zone (Duryea 1996).

The following parameters influence the extent of clogging:

Water quality. The reduction and/ or prevention of clogging, is largely dependent on the quality of the infiltrated water (e.g. Hollander et al. 2005; Bouwer 2002). Bouwer (2002) and EWRI/ASCE (2001) recommend treating recharge water to "drinking water quality" to reduce or eliminate clogging. Attempts to develop guidelines on the quality of water suitable for aquifer recharge are often based on sparse data, and have not been reliably validated (Alvarez 2008; Pavelic 2007). To date, models to predict theoretical clogging time due to physical clogging have been limited in real-world application (e.g. Langergraber et al. 2003; Aaltomaa & Joy 2002), or not fully tested at the field scale (e.g. Phipps et al. 2007). The extent of soil clogging is closely correlated to total suspended solids (TSS), biological oxygen demand (BOD), and carbon to nitrogen (C:N) ratio. Following are more detailed descriptions of water quality impacts on clogging.

Total suspended solids (TSS). Clogging resulting from the deposition of TSS is typically the key determinant in recharge performance (Hutchinson 2007; Winter & Goetz 2003; Siegrist & Boyle 1987; Vecchioli 1972; Harpaz 1971; Hauser & Lotspeich 1967). The direct relationship between TSS load and recharge performance, however, is typically site specific. TSS consisting of primarily fine-grained (clay) particles may result in greater recharge reduction than a coarser particle load. Recharge facilities in the Netherlands and Great Britain do not allow recharge water with turbidity of more than 2 to 5 NTU (Hollander 2005); most recharge facilities appear to develop their own turbidity criteria. Although turbidity measures approximately the same water quality property as TSS, direct conversion between turbidity and TSS is typically not possible. Turbidity is caused by suspended matter or impurities that interfere with the clarity of the water; whereas larger light weight particles (e.g. algae) can cause greater turbidity than smaller, heavier inorganic particles.

BOD and C:N ratio. Soil irrigated with water that has a high C:N ratio (i.e. 50:1) and/or high BOD exhibits significant increases in soil microbial biomass and extracellular carbon deposition, with a subsequent decrease in hydraulic conductivity (Aaltomaa & Joy 2002; Jnad 2001, Magesan et al. 1999; Vandeviere & Baveye 1992a).

Other water quality parameters. Soil clogging layer development is loosely associated with total nitrogen and total phosphorous content, which also contribute to biological growth (Magesan et al. 1999). Bouwer (1988) also proposed the Sodium Adsorption Ratio (SAR) as a parameter for water quality assessment, due to the influence of sodium on the hydraulic property of clays.

Particle-size of sediment media. The importance of particle size on the extent of clogging varies. In the short term, clogging layer formation is accelerated in fine-grained sediments and reduction of infiltration rates occurs faster in these sediments than in coarse-grained sediments (Aaltomaa & Joy 2002). However, there is potentially a greater relative reduction in K_e in coarse-grained sediments than in fine-grained soils. Where the K_e may be similar to that of the clogging material, the clogging layer may not govern the K_e of the soil profile, whereas, sandier sediments may experience reductions of 0.5 to 5 orders of magnitude in hydraulic conductivity (i.e. from 10^{-2} cm/sec up to 10^{-7} cm/sec, Duryea 1996; Rinck-Pfeiffer 2000; Beach 2005; Taylor & Jaffe 1990; Magesan 2000; Jnad et al. 2001; Rodgers et al. 2004). Soil particle-size can impact the depth of the clogging layer with sandy sediments having shallower (up to a few cm) clogging layers, and gravels clogging deeper (more than 100 cm) (Blazejewski & Murat-Blazejewski 1997).

Ponding depth. Depending on clogging conditions, ponding depth may increase, decrease, or not affect the infiltration rate and K_e (Houston et al. 1999; Duryea 1996). Two opposing factors result from ponding water depth: an increased hydraulic gradient versus increased compaction of the clogging layer. Increasing the water ponding depth increases the infiltration rate if all other factors remain the same. However, increasing the water ponding depth causes the loose clogging layer to compact which can then cause a reduction in the infiltration rate (Bouwer & Rice 1989). In general, field studies have found that infiltration rates decrease as clogging layer thickness and ponding depth increases (Houston et al. 1999).

Hydraulic loading rate. Loading rate, the rate at which water is applied to the soil surface, also affects the extent of clogging. Lower loading rates may reduce the formation of a clogging layer (Siegrist 1987). However, in the long-term, for a given media and application method, the clogging layer may reach a maximum reduction in hydraulic conductivity independent of loading rate (Beach 2005). In practice, a lower hydraulic loading rate is best achieved through loading cycles (see below).

Loading cycles. Techniques such as cycles of flooding and drying can restore hydraulic conductivity to higher levels by disturbing the clogging layer (Houston et al. 1999; Duryea 1996). Many managed aquifer recharge operations use 1:1 on-off cycle ratios where basins are allowed to dry for 50 percent of the time.

Vegetation. Vegetation may contribute to a decrease in soil hydraulic conductivity in wetland environments (Winter & Goetz 2003; Dahab & Surampalli 2001; Blazejewski 1997; Jiang 1995; Brix 1994; McIntyre & Riha 1991). Production of root exudates by plants may cause soil clogging, resulting in a decrease in hydraulic conductivity (McIntyre & Riha 1991). Leaf litter may also contribute to surface clogging (Batchelor & Loots 1997) whereas certain plants (i.e. *Phragmites australis*) may reduce soil clogging via penetration by plant roots and rhizomes which loosens the soil and increases the hydraulic conductivity (Cooper et al. 2005). Dead roots and rhizomes may create large pores or channels for water movement (Brix 1997).

Tables 1 and 2 present an overview of published data showing the influence of various parameters on extent of clogging. Table 1 gives actual K_e values with particular soil types and water quality. For studies where the actual K_e was not published, Table 2 shows the relative reductions in K_e due to clogging parameters. Table 3 provides water quality data from research where clogging was limited or absent.

Section 4.0 Conclusions

The hydraulic properties of infiltration basins used to recharge surface water and wastewater effluent typically become dominated by a low conductivity clogging layer which forms at the water-soil interface. The clogging layer is often thin (millimeters to 4 centimeters) and may consist of suspended solids, algae, microbes, dust, and salts. Clogging layer formation has been observed to reduce the hydraulic conductivity of soil materials by as much as five orders of magnitude.

There are physical, chemical, and biological causes of clogging. Factors that influence the development and extent of a clogging layer include water quality, basin soil texture, ponding depth, hydraulic loading rate and cycle, and vegetation. Research has found that biological oxygen demand and total suspended solids are the most important components of water quality that influence the formation of a clogging layer. In addition, extended ponding periods enhance soil clogging, whereas wetting and drying cycles tend to destroy the clogging layer.

Table 1. Effects of Soil Clogging on Effective Hydraulic Conductivity (K_e) with Various Soil Types and Influent Quality

Author	Study Conditions	Method	Soil Type, USCS/USDA Classification	Influent Quality* (mg/l)	Initial/ potential K_e (cm/sec, (ft/day))	Final Effective Hydraulic Conductivity K_e (cm/sec)	Reduction in K_e of surface soil (cm/sec)
Duryea (1996)	Column Study Using Soils and Wastewater from Tucson and Phoenix, Arizona	Falling head permeability test Final conductivity measurements were taken 18 months after first wetting Columns were subject to a series of wetting and drying cycles during the 18 months	Agua Fria Soil SP (sand)	DSE N: 2-9; P: 3-6; TSS: 3-7 TOC: 8-10	8.4×10^{-2} (23.8)	0-2 cm: 1.31×10^{-2} 2-4 cm: 3.16×10^{-2} 4-6 cm: 2.38×10^{-2} 6-8 cm: 2.16×10^{-2}	< 0.5 order of magnitude reduction
			North Pond Soil SM (fine or loamy sand)	SE N:15-27; P: 2-5; TSS: 20-30 TOC: 15-25	1.8×10^{-4} (0.5)	0-2 cm: 6.67×10^{-5} 2-4 cm: 6.97×10^{-4} 4-6 cm: 1.40×10^{-3} 6-8 cm: 4.51×10^{-4}	≈ 0.5 order of magnitude reduction
				DSE No ponding		0-2 cm: 1.73×10^{-4} 2-4 cm: 2.30×10^{-4} 4-6 cm: 8.14×10^{-4} 6-8 cm: 3.51×10^{-4}	negligible change
				DSE Water ponded to 7.5 ft – 17 ft. deep		0-2 cm: 6.03×10^{-5} 2-4 cm: 6.96×10^{-4} 4-6 cm: 2.23×10^{-4} 6-8 cm: 5.75×10^{-4}	≈ 0.5 order of magnitude reduction
			Sweetwater Soil SP-SM (fine sand)	SE N:15-27; P: 2-5; SS: 20-30	1.9×10^{-2} (53.8)	0-2 cm: 2.48×10^{-3} 2-4 cm: 6.57×10^{-3}	≈ 1 order of magnitude reduction
				TE N:15-27 TSS: 5-10 TOC: 10-15		0-2 cm: 4.64×10^{-3} 2-4 cm: 1.63×10^{-2} 4-6 cm: 2.09×10^{-2} 6-8 cm: 4.40×10^{-2}	≈ 1.5 order of magnitude reduction
			Agricultural Field CL (low plasticity clay)	DSE N: 2-9; P: 3-6; TSS: 3-7	3.5×10^{-6} (1×10^{-2})	0-2 cm: 1.20×10^{-6} 2-4 cm: 4.86×10^{-7} 4-6 cm: 2.95×10^{-7} 6-8 cm: 3.80×10^{-7}	negligible change

Author	**Study Conditions**	**Method**	**Soil Type, USCS/USDA Classification**	**Influent Quality* (mg/l)**	**Initial/ potential K_e (cm/sec, (ft/day))**	**Final Effective Hydraulic Conductivity K_e (cm/sec)**	**Reduction in K_e of surface soil (cm/sec)**
Rinck-Pfeiffer (2000)	Column Study	Continuous injection of recycled water through columns	Soil from sandy limestone aquifer	SE All units mg/L N: 2.5-3.5 BOD: 2.0-3.0 COD: 165-170 TOC: 18-20 TSS: 3-4	9.03 x 10^{-4} (2.6)	Week 1: 7.18 x 10^{-5} Week 2: Stable Week 3: 3.12 x 10^{-4}	Initially ≈1 order of magnitude reduction, Reversed due to calcite dissolution at the inlet end of columns. Final ≈ 0.5 order of magnitude reduction
Beach (2005)	Column Study	Falling Head Test	Sand	STE Load rate: 200 cm/day	9.57 x 10^{-3} (27.1)	Week 2: 4.85 x 10^{-4} Week 6: 6.32 x 10^{-5} Week 20: 2.49 x 10^{-5}	≈ 1.5 order of magnitude reduction
				STE Load rate: 100 cm/day	9.86 x 10^{-3} (27.9)	Week 6: 7.70 x 10^{-5} Week 20: 3.53 x 10^{-5}	≈ 1.5 order of magnitude reduction
Taylor & Jaffe (1990)	Column Study	Not Reported	Sand 0.59 – 0.84mm diameter	Diluted primary and activated sludge	2.5 x 10^{-1} (709)	Max reduction after 40 weeks: 1.27 x 10^{-4}	≈ 3 order of magnitude reduction
Magesan (2000)	Column Study	Conductivity after 14 weeks	Sandy loam	C:N ratio 2.5:1	Not Reported	2.44 x 10^{-3}	≈ 1+ order of magnitude reduction
				C:N ratio 27:1		1.33 x 10^{-3}	
				C:N ratio 66:1		5.00 x 10^{-4}	
Rodgers et al. (2004)	Column Study, Synthetic wastewater	Constant-head method	Sand	N: 175.7 P: 23.0 SS: 352.9 BOD: 2208	1.9 x 10^{-1} (586) ± 1.7 x 10^{-4} (0.5)	3.5 x 10^{-5} ± 7.5 x 10^{-6}	≈ 5 order of magnitude reduction
Jnad et al. (2001)	Field Study, Treated wastewater	Darcy's Law	Silty clay loam	N: 37 P: 0.9 TSS: 5 BOD: 15	4.6 x 10^{-4} (1.3)	After 1.5 yrs: 1.97 x 10^{-7}	≈ 3 order of magnitude reduction
			Fine sandy loam	N: 29 P: 0.7 TSS: 5 BOD: 23	4.6 x 10^{-4} (1.3)	After 3 yrs: 3.70 x 10^{-7}	≈ 3 order of magnitude reduction

N: Total Nitrogen; P: Orthophosphate; TSS: Total Suspended Solids; TOC: total organic carbon; DSE: Denitrified Secondary Effluent; SE: Secondary Effluent; STE: Septic Tank Effluent; TE: Tertiary Effluent

Table 2. Effects of Soil Clogging due to Bacteria, Ponding Depth, and Vegetation

Author	Study Conditions	Soil Type, USCS/USDA Classification	Notes	Parameter investigated	Treatment	Magnitude Reduction in K_e of surface soil
Gupta & Swartzendruber (1962)	Column Study	Sand	Cultural techniques used to obtain counts, so underestimated bacterial density	Bacterial density	Density < 0.4 x 10^6 CFU/g	No change
					Density < 1.3 x 10^6 CFU/g	≈ 2 orders of magnitude
Vandevivere & Baveye (1992a)	Column Study	Sand	Sand columns inoculated with *Arthrobacter spp.*	Bacterial density	< 4 mg (wet weight)/ cm^3	No change
					10 mg (wet weight)/ cm^3	≈ 1 order of magnitude
					20 mg (wet weight)/ cm^3	≈ 2 orders of magnitude
					35 mg (wet weight)/ cm^3	≈ 3 orders of magnitude
Vandevivere & Baveye (1992b)	Column Study	Sand	Demonstrates the impact of microbial component	Effect of environmental conditions on microbial community	No treatment	Up to 4 orders of magnitude
					Oxygen-limited conditions	≈ 1-2 orders of magnitude
					Glucose-limiting conditions	≈ 1-2 orders of magnitude
Vandevivere & Baveye (1992c)	Column Study	Sand		Bacterial density	3.8 – 6.3% pore space occupied by bacteria	≈ 1-2 orders of magnitude
Duryea (1996)	Field Study	Sand		Ponding depth	Ponding depth 16 ft vs 7 ft	Up to 1.4 orders of magnitude
		Fine or loamy sand			Ponding depth 17.5 ft vs 7 ft	<1 order of magnitude
McIntyre & Riha (1991)	Control and Vegetated Boxes	Sand		Vegetation	Unvegetated vs. Vegetated simulated artificial wetlands	≈ 50% reduction in vegetated boxes

CFU: Colony Forming Units

Table 3. Research Showing Conditions with Limited or No Clogging

Author	Study Information	Influent Quality	Notes
Pavelic (2007)	Aquifer storage and recovery wells in Southern Australia Total amount of reclaimed water: 483×10^3 m^3 Mean injection rates: 8–15 L/s Sandy limestone aquifer	Turbidity < 3NTU N_{TOT} < 10mg/L pH < 7.2	Short-term cause of clogging: turbidity/TSS Long-term: biomass production
Masunaga (2007)	Lab-scale multi-soil layering (MSL) system MSL: soil mixture and zeolite layers Soil mixture: volcanic ash soil rich in OM, sawdust, and granular iron metal at a volume ratio of 75%, 12.5% and 12.5%, respectively	Domestic wastewater pH: 7.4 ± 0.25 TSS: 78.3 ± 75.3 mg/L BOD: 69.5 ± 52.7 mg/L COD: 121.6 ±96.7 mg/L TN: 9.6 ± 2.7 mg/L	No clogging at loading rate < 5.6×10^{-4} cm/s (1.6 ft/day) Higher loading rates caused clogging
Fischer (2005)	Riverbank filtration in Dresden, Germany along Elbe River Aquifer 15 m thick overlain by 2-4 m of meadow loam Range flow of river: 100-4500 m^3/s Mean flow of river: 300 m^3/s Range of $K_e \approx 2 \times 10^{-1}$ to 60 cm/s (280 to 170,000 ft/day)	DOC: 5.6 mg/L – 6.9 mg/ L Clogging occurs but functioning of Riverbank Filtration system is not compromised	Severe clogging occurred in the 80's due to river water pollution of organics from pulp and paper mills. Mean DOC was 24.2 mg/L
Hollander (2005)	Reports on Dillon, P. (2002) and Dillon P. & Pavelic, P. (1996)	TSS loads in the infiltrated water of not more than 150 mg/L do not cause considerable clogging	
Winter (2003)	Comparison of clogging of vertical flow constructed wetlands in Germany. All beds were made of coarse sand or gravel filter with $d_{60}/d_{10} \leq 5$ and $K_e \approx 10^{-2}$ to 10^{-1} cm/s (28 to 280 ft/day)	Recommend: TSS < 100 mg/L, esp. particles > 50µm TSS load: < 5 $g/m^2/day$ COD load: < 20 $g/m^2/day$	
Magesan (2000)	Sandy loam soil cores treated with secondary wastewater with different C:N ratios (2.5:1, 27:1, 66:1) for 28 weeks. Soil cores received weekly irrigation of 23 mm at a rate of 7 mm/h	Secondary treated wastewater pH: 8.6 TOC: 75 mg/L TN: 30 mg/L NH_4-N: 13 mg/L NO_3-N: <0.1 mg/L	Final K_e of soil treated with different C:N ratios 2.5:1 $K_h = 2.4 \times 10^{-3}$ cm/s (6.9 ft/day) 27:1 $K_e = 1.3 \times 10^{-3}$ cm/s (3.8 ft/day) 66:1 $K_e = 5.0 \times 10^{-4}$ cm/s (1.4 ft/day)
Okubo (1983)	Column experiment 10 cm gravel and 40 cm sand Bulk density: 1.4 to 1.5 g/ cm^3 K_e: 5.0×10^{-2} cm/s (142 ft/day)	Synthetic wastewater C:N: 1.44 TSS ranging from 1.4 – 14.6 mg/L TOC ranging from 7.2 – 21.6 mg/L	TSS < 2 mg/L and TOC < 10 mg/L for no clogging

NTU: Nepholemetric Turbidity Units; N_{TOT}: Total Nitrogen; TSS: Total Suspended Solids; BOD: Biological Oxygen Demand; COD: Chemical Oxygen Demand; DOC: Dissolved Organic Carbon; TOC: Total Organic Carbon; C:N: Carbon to Nitrogen Ratio; NO3-N: Nitrate as N; NH4-N: Ammonia as N

Section 5.0 References

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