NATURAL RESOURCES CONSERVATION SERVICE - ILLINOIS

CONSERVATION PRACTICE GUIDANCE

605 – Denitrifying Bioreactor

I. SCOPE

This guidance provides information and recommendations for planning and design of denitrifying bioreactors (referred to as bioreactors in this document). A bioreactor is a structure containing a carbon source, installed to reduce the concentration of nitrate nitrogen in subsurface agricultural drainage flow via enhanced denitrification. Typical implementation utilizes a chamber that is lined with plastic and filled with wood chips. The plastic is installed to keep the soil from migrating into the wood chips, and to make sure that the tile water stays in the wood chip chamber long enough to do the job. Most of the water from the drainage tile is diverted into the bioreactor chamber for treatment by the denitrifying bacteria.

II. SITING RECOMMENDATIONS

Select a location for the bioreactor that will protect the bioreactor chamber from surface flows that could result in flushing out of the established biofilm. If the location is adjacent to a stream or ditch that is subject to out of bank flooding, it might be advisable to select a different location, or cover the bioreactor chamber with a vegetated soil cap. It would also be possible to use spoil from the excavation of the bioreactor chamber to elevate the top of the bioreactor above the expected flood zone – however, this may create regulatory issues with fill in a floodplain, so caution is advised.

Locate the bioreactor where the inlet water level setting will not negatively affect adjacent properties, crops, upstream drainage, or other conservation structures.

Site bioreactors only on subsurface systems that are in good working condition, with minimal potential for debris and sediment to enter the reactor via surface inlets, tile suck holes, or other means.

III. DESIGN AND EVALUATION

A properly designed bioreactor must meet three primary design objectives:

- A capacity large enough to treat one of the flow requirements in the standard.
- A hydraulic retention time (HRT) within the bioreactor of at least 3 hours at the design flow capacity.
- At least 30% annual reduction in the nitrate-nitrogen load of the water flowing through the reactor.

The flow rate and HRT are governed by the difference in water level elevations set by the water control structure(s) at the inlet and outlet ends.

Conservation Practice Standard (CPS) 605 allows for several alternative methods for designing the bioreactor to meet the required flow capacity. The criteria typically used for bioreactor design in Illinois is treating 15% of the peak flow from the drainage system. This document provides several alternatives for determining the peak flow of the system, in order of increasing complexity.

Determining System Capacity

Option 1: Mainline Configuration

This alternative may be used in cases where there is very limited information about the drainage system; if more information is available, use a different method.

With the reactor sited near the tile outlet, use Manning's equation to estimate the maximum capacity of the outlet main using an appropriate value of Manning's n. Use the minimum predominant slope along the mainline between the last lateral inlet and the mainline outlet.

$$Q = \frac{1.486}{n} A\, R^{\frac{2}{3}} S^{\frac{1}{2}}$$

Where Q = Flow, ft^3/second (cfs)

n = Manning's roughness coefficient

A = Cross sectional area of flow, ft^2 ($A = \pi \frac{d^2}{4}$ for round pipe)

R = Hydraulic radius, ft ($R = \frac{d}{4}$ for round pipe)

d = diameter of pipe, ft

S = Slope of pipe, ft/ft

Example: 6" diameter mainline made of corrugated PE. Minimum mainline slope is 0.2% and *n* = 0.015.

d = 0.5 ft

$A = \pi \frac{0.5^2}{4}$ = 0.196 ft^2

$R = \frac{0.5}{4}$ = 0.125 ft

S = 0.2/100 = 0.002 ft/ft

Resulting system capacity for this example is 0.217 cfs. Design flow for the bioreactor would be 15% or 0.033 cfs.

Option 2: Drainage Coefficient

This alternative may be used if a tile map and information on the existing drainage system is available. The definition of the drained area is taken from the lateral spacing recommendations of the soil, as specified in the Illinois Drainage Guide. The outer boundary of the drained area is delineated by a line around the tiled area, at a distance of one-half of the tile lateral spacing recommended in the Drainage Guide.

$$Q = \left(\frac{DC}{24\ x\ 3600\ x\ 12}\right)(DA\ x\ 43{,}560)$$

$$Q = \frac{(DC)\ (DA)}{23.8}$$

Where DC = Drainage coefficient, inches/day

DA = Acres drained

Example: DC = 3/8 inch per day; 6 acres drained by system.

System capacity for this example is 0.095 cfs. The design flow for the bioreactor would be 15% or 0.014 cfs.

If a complete drainage tile map does not exist, it is possible to estimate the contributing acres of tile drainage (DA), especially if the landscape is characterized by a predominance of tile drainage. This estimation process assumes that all of the watershed acres with soil drainage group A (poorly drained) are either already drained or will be in the near future, plus half of the watershed acres in soil drainage group B (somewhat poorly drained). To use this estimation method:

- Delineate the surface drainage area of the point where the bioreactor is proposed.
- Create a list of the soils in the delineated area, along with the acres of each soil type and their drainage group.
- Estimated *DA* = sum of the acres of poorly drained soils plus half of the acres of somewhat poorly drained soils.

Option 3: Modeling Techniques

Drainage models such as DRAINMOD may be used to estimate flow into and through the drainage system, up to the inlet of the bioreactor. If a model of the system is created, drain flows by day, month and year may be obtained. The system capacity can be taken to be the maximum flow experienced during the simulation period, or the value with 10% probability of exceedance. A minimum simulation period of 15 years is recommended.

In addition, the University of Illinois has developed an interactive design routine for the bioreactor which may be used. The routine is available online at: wq.illinois.edu/DG/DrainageGuide.html. This routine utilizes predetermined DRAINMOD models for most tile drained soils in Illinois.

Determining Bioreactor Flow

The bioreactor does its work by directing at least 15% of the system flow capacity to the distribution pipe. The difference in water surface elevation between the inlet and outlet water control structures creates a hydraulic pressure differential that drives water along the length of the reactor. The flow through the bioreactor is governed by Darcy's Law:

$$Q_b = kiA_b$$

Where: Q_b = bioreactor flow (cfs)

k = hydraulic conductivity (ft/s)

A_b = average cross-sectional area of bioreactor flow path (sq. ft.)

i = hydraulic gradient; $i = \frac{\Delta h}{L}$

Δh = water surface elevation difference between inlet and outlet (ft)

L = length of bioreactor (ft)

For woodchip media, a value of 0.0964 ft/s is typically used for the hydraulic conductivity. This is based on an average of the values found by van Driel et al (2006) for wood media reactors.

Checking Hydraulic Retention Time

The hydraulic retention time (HRT) is the amount of time it takes for flow to travel from the inlet end of the reactor to the outlet end, and can be found by dividing the effective bioreactor flow volume by the flow rate through the bioreactor.

$$HRT = (\frac{p\ A\ L}{Q}) * 3600$$

Where p = porosity of the media (decimal %)

Because the flow is passing through porous media, the effective flow volume must be decreased from the full volume of the bioreactor chamber to reflect the fact that the flow can only pass through the voids between the media particles.

The porosity of the wood chips varies according to the type of woodchips and the weight of any soil cap that is placed on top of the bioreactor chamber. The data presented below are taken from the University of Illinois bioreactor design routine.

Wood Chip Porosity (decimal %)			
Type of woodchip	**No soil on top**	**1 ft of soil**	**2 ft of soil**
Hardwood	0.59	0.55	0.54
Shredded	0.64	0.60	0.59
Mixed	0.53	0.47	0.47

CPS 605 requires a minimum HRT of 3 hours. However, because byproducts such as methyl mercury can be produced when flow remains in the bioreactor long enough that all of the available nitrate is reduced, the bioreactor should be able to drain completely within 48 hours if there is no flow into the reactor.

Determining Load Reduction

An empirical relationship has been developed by Cooke et al (University of Illinois bioreactor routine) to relate the nitrate load reduction in a bioreactor to the reactor's loading density. The loading density is determined as:

$$L_D = \frac{DA}{A_r/_{100}}$$

Where: L_D = loading density

(acres per 100 sq.ft. of bioreactor)

A_r = surface area of bioreactor (sq. ft.)

The load reduction (L_r, in %) is then calculated using the following relationship:

$$L_r = \frac{95.42}{L_D^{0.435}}$$

CPS 605 requires a minimum load reduction of 30%. However, research has shown that if all of the nitrates in the bioreactor chamber are denitrified, sulfate reducing bacteria take over, and sulfate reducing conditions are associated with methylation of mercury (Hudson and Cooke, 2015). Design the bioreactor for a load reduction not to exceed 85%; this will help ensure that a small amount of nitrate remains in the bioreactor chamber to feed the denitrifying bacteria

In addition to the design load reduction, it is important to provide a means of draining the bioreactor chamber during periods of low flow, to prevent stagnant conditions and the associated methylation of mercury. This can be achieved through observation and management, or by providing a small, low flow orifice in the downstream water control structure.

Spreadsheet Design Tool

A spreadsheet tool has been developed to help automate some of the computations described in this section. The most recent version of the spreadsheet tool may be obtained on the Illinois NRCS engineering website at https://www.nrcs.usda.gov/wps/portal/nrcs/main/il/technical/engineering/.

REFERENCES

Cooke, R.A. and N.L. Bell. 2013. Protocol and Interactive Routine for the Design of Subsurface Bioreactors. Applied Engineering in Agriculture 30(5): 761-771.

Chun, J.A., R.A. Cooke, J.W. Eheart, M.S. Kang. 2009. Estimation of flow and transport paramters for woodchip-based bioreactors: I. Laboratory-scale bioreactor. Biosystems Engineering. 104(3): 384-395.

Christianson, Laura, Alok Bhandari, and Matthew J. Helmers. 2011. Pilot-Scale Evaluation of Dentrification Drainage Bioreactors: Reactor Geometry and Performance. Journal of Environmental Engineering 137(4): 213-220.

Christianson, Laura, A. Castello, R. Christianson, M. Helmers, A. Bhandari. 2010. Hydraulic Property Determination of Denitrifying Bioreactor Fill Media. Applied Engineering in Agriculture 26(5): 849-854.

Christianson, Laura, A. Castello, R. Christianson, M. Helmers, A. Bhandari. 2010. Hydraulic Property Determination of Denitrifying Bioreactor Fill Media. Applied Engineering in Agriculture 26(5): 849-854.

Hudson, Robert J.M. and Richard A. Cooke. 2015. Methylmercury Production in Denitrifying Woodchip Bioreactors. Illinois sustainable Technology Center, Prairie Research Institute RR-130. http://hdl.handle.net/2142/88352.

Roberston, W.D., D. W. Blowes, C. J. Ptacek, and J. A. Cherry. 2000. Long-term performance of in situ reactive barriers for nitrate remediation. Ground Water 38(5): 689-695.

USDA-NRCS. 2001. Water Management (Drainage). National Engineering Handbook, Part 650, Chapter 4, Table 14-7.

Van Driel, P. W., Robertson, W. D., and Merkley, L. C. 2006. Denitrification of agricultural drainage using wood-based reactors. Transactions of the ASABE 49(2): 565-573.