DETERMINING HYDRAULIC CONDUCTIVITIES IN A VERTICAL FLOW SYSTEM[1]

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Abstract: Vertical flow systems (VFS) are a type of passive treatment unit process in which acid mine drainage (AMD) flows vertically through layers of organic matter and limestone. Located in the coal belt of eastern Oklahoma, the Red Oak VFS was constructed to address AMD exiting an abandoned underground coal mine. The passive treatment system consists of five cells, alternating between surface flow (cells 1, 3, and 5) and vertical flow (cells 2 and 4) designs. The VFS included an approximately 0.6-m limestone drainage layer containing a network of pipe overlain by approximately 1-m of composted horse manure mixed with limestone. Design surface water elevations were approximately 1-m above the organic matter surface. In spring 2004, cell 4 appeared to be experiencing hydraulic conductivity problems as outflow discharge rates decreased and water levels increased, based on measured flows and staff-gauge readings, respectively. It was hypothesized that accumulated solids (either sulfides or degraded organic material) were causing clogging in the substrate. This investigation was conducted to evaluate these possible hydraulic conductivity problems. A well point screened throughout the substrate layer and water column and containing a pressure transducer was installed. A series of field dropping head permeameter tests was conducted to determine hydraulic conductivity. Although vertical flow cells have been shown to result in substantial water quality improvement, concerns about the long-term physical viability of these systems warrants further investigation.

Additional Key Words: Acid Mine Drainage, Vertical Flow Wetlands, Hydraulic Conductivity, Passive System Treatment, Metal Removal, Groundwater Flow

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Introduction

Over the past two decades passive treatment of acid mine drainage (AMD) has become increasingly common. Water quality improvements were first noticed in *Sphagnum* bogs over 20 years ago (e.g., Gusek, 2002), and since then scientists and engineers have worked to build systems that mimic and improve upon natural remediation traits. Currently most experts agree that there is not one “cookie cutter” solution for every system, but that several “puzzle pieces” exist that need to be fit together to achieve desired outcomes. These pieces include vertical flow systems (VFS) and aerobic wetlands. Each piece of the puzzle plays a specific role and they must be pieced together in an appropriate manner in order to achieve desired outcomes. Hedin et al. (1994) developed a simplified flow chart to help in the selection of AMD systems that would work best under specific conditions. It has been noted in many papers that the technology works well and when systems fail it may not be due to the technology but due to human errors in design or system size (e.g., Gusek and Wildeman, 2002; Watzlaf et al., 2002; Rose and Dietz, 2002). Ideally, a passive treatment system could work for many decades with only minimal maintenance; however long-term data do not exist on these systems as most systems were only constructed within the last few decades.

One of the major potential problems in VFS is a decrease in hydraulic conductivity, perhaps due to metal precipitation, eventually causing the ponds to overflow (e.g., Kepler and McCleary, 1997, Rose and Dietz, 2002). Rose and Dietz (2002) also note that many systems have failed due to preferential flow of water though the substrate. The goal of this study was to determine the hydraulic properties of these VFS that may have caused initial problems.

Red Oak Passive Treatment System

Constructed in late 1999, the Red Oak Passive Treatment System was built to address AMD that was seeping out of an abandoned coal mine in Latimer County in Eastern Oklahoma. The Red Oak system consists of five cells connected by PVC piping; these cells alternate between aerobic ponds (cells 1, 3 and 5) and VFS (cells 2 and 4). Water entering the system from the mine workings had been previously treated with a large coal combustion product injection in order to neutralize much of the discharge in situ and as a result water entering the system has a near neutral pH. This study focused on hydraulic properties occurring within cell 4. Cell 4 was designed to consist of a 0.6-m limestone drainage system which contained a network of outflow piping; this layer is overlain by 1-m of composted horse manure intermixed with limestone, and approximately 1-m of standing water (Fig. 1). In spring 2004 it was observed that water levels were slowly increasing in this cell and by early summer the eastern bank was overflowing. It was hypothesized that there was a hydraulic conductivity problem in the cell and that something was decreasing throughput of water though the substrate. As mentioned earlier, previous studies have found that clogging may be a problem over time in these cells and may cause ponds to overflow.

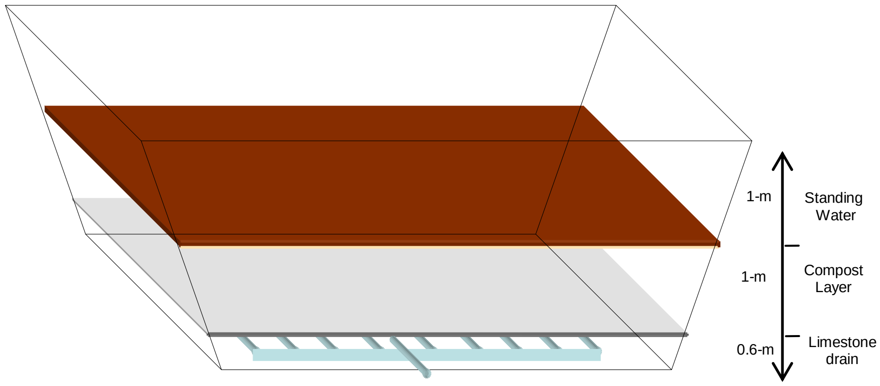

Figure 1. Conceptual design schematic of Cell 4 vertical flow system unit at the Red Oak passive treatment system.

Methods

In order to determine the hydraulic properties of the substrate in Cell 4, a number of different approaches were taken: lab-scale and field-scale falling head tests in order to give a estimate of hydraulic conductivity, analysis of substrate cores with the goal of determining what metals concentrations, installation of piezometers to gain an idea about hydrologic flow paths, and a tracer study to get an estimate of residence time in the cell. The results can then be compared with the engineering goal for the cell in terms of: residence time, flow paths, substrate composition, and hydraulic conductivity. Only hydraulic conductivity results will be presented.

Falling Head Test

A falling head test is designed to determine the hydraulic conductivity of a saturated material. This goal is achieved usually using columns in a laboratory. In a laboratory set up, a gradient is set up across a core of the substrate and over time the decrease in gradient, or head, is measured. Using the gradient and the known area of the core, the hydraulic conductivity can be determined using Darcy's equation:

$$Q = KIA \qquad (1)$$

where Q = volumetric flow rate of discharge, K = hydraulic conductivity, I = hydraulic head and A = cross-sectional area.

The premise behind a falling head test is that if the water is allowed to free flow out of the system the discharge rate will be determined by how fast the water is able to flow through the substrate in question. When conducting a lab scale test the known variables are substrate length and surface area of substrate. During the experiment heights are measures over a range of times. In this case, the depth and the substrate surface area of cell 4 is known, and a modification of this test to the field scale was conducted. Cell 4 is equipped with a flushing system so that the water can be drained quickly and can free flow out of the drainage pipes without affecting gradient. By recording the change in head in cell 4 over time it was hypothesized that hydraulic conductivity could be calculated in much the same way that is done in a laboratory.

Two separate falling head tests were conducted at this site. In the first test the flush valve was opened and staff gauge readings were taken. These reading were taken every fifteen minutes and continued until the water was no longer visible above the substrate surface. The test was repeated again after a 2-inch (7.6 cm) groundwater monitoring well equipment with a pressure transducer was installed into the cell. This pressure transducer allowed for data to be collected after the water was below the level of the substrate. The pressure transducer also allowed for more frequent and more accurate readings taken every minute.

Results and Discussion

Field Scale Falling Head Test

The hydraulic conductivity was calculated using the lab scale falling head test equation:

$$K = \frac{A_1 L}{A_2 t} * \ln(\frac{h_0}{h}) \qquad (2)$$

Where K=Hydraulic Conductivity, A= area of column and area of falling head tube, L=length of substrate, t=time from beginning of experiment, h_0=initial height of water in tube, and h= height of water after time t.

In this experiment the area of the substrate and the area of the water are identical, so the two areas cancel out leaving a simplified equation of:

$$K = \frac{L}{t} * \ln(\frac{h_0}{h}) \qquad (3)$$

The length of substrate (L) calculated in this experiment was 0.88-m which is very close to the assumed 1-m of substrate. The data from the data-logger are presented in Fig. 2.

Cell 4 was initially allowed to sit overnight before any draining began. Once the flush was opened the cell drained for approximately 12 hours. During that time the drawdown data show inflection points; these points are thought to coincide with changes in the substrate through which the water was flowing. The initial line shows the water draining as the standing water was draining out of the cell. The next line indicates the water flowing out of the substrate and the last line shows the water draining out of the limestone bed at the bottom of the cell. Using this information the depth of the sediment was estimated to be 0.88-m. Once the cell had completely drained it was again allowed to refill and that information was recorded and shown in Figure 2 as increasing depths. The groundwater monitoring well allowed for some preferential flow of water directly from the surface to the logger, however, it is not believed that this would significantly affect the draining of the pond and any conductivities that were recorded. Based on the lab scale set up for a falling head test, the data that would give us hydraulic conductivity for the organic substrate are the depth vs. time data of the standing water. Fig. 3 is a finer scale representation of Fig. 2, highlighting the area in which the standing water was draining. The relationship is linear which would indicate that the conductivity measurements would be fairly constant across the substrate.

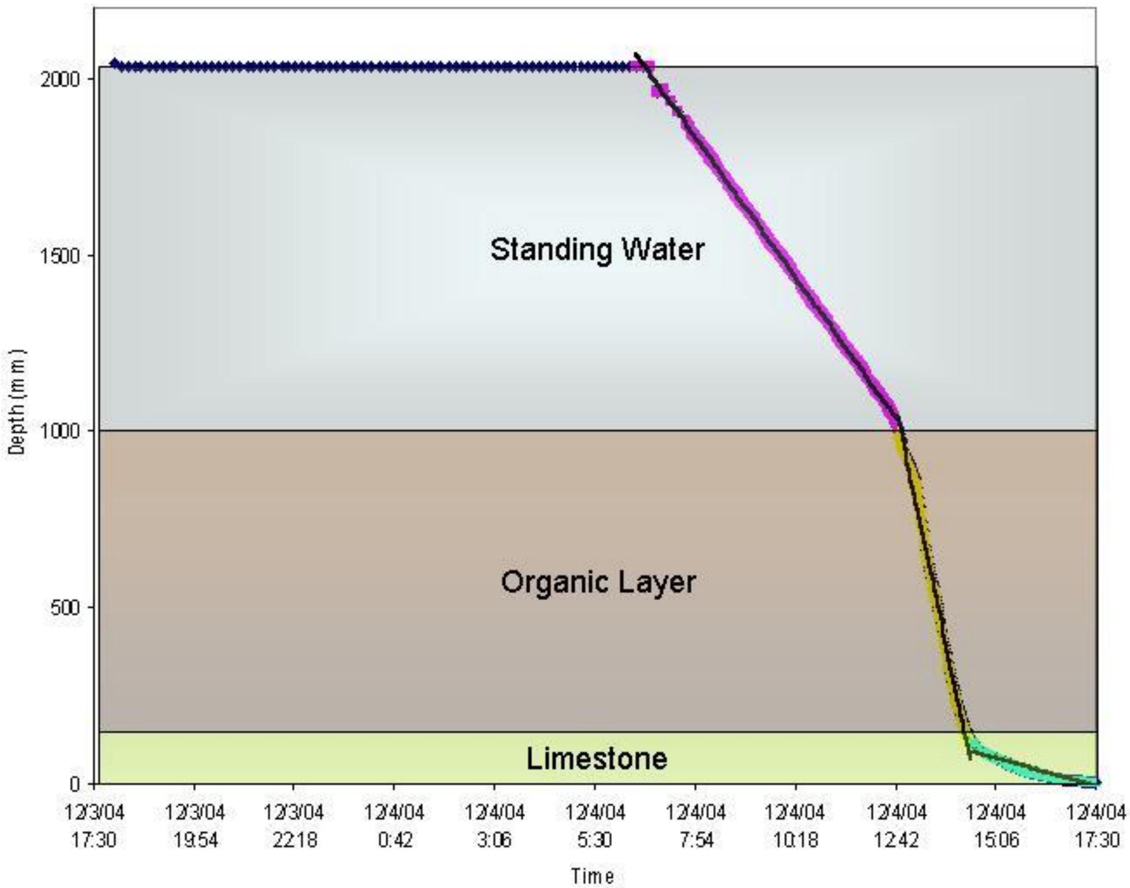

Figure 2. Field data collected from falling head test conducted 12/4/04. Bold line indicates depth of water above the logger.

Utilizing these data and equation 3, an estimate of hydraulic conductivity values was calculated. An example of these calculations is shown below:

$$K = \frac{L}{t} * \ln(\frac{h_0}{h})$$
$$K = \frac{0.88m}{50\min} * \ln(\frac{1.96m}{1.8m}) = 0.00149m/\min \qquad (4)$$
$$K = 2.158m/day$$

Fig. 4 shows hydraulic conductivity values vs. time. The estimated conductivity of the substrate is fairly constant across the time frame. The mean conductivity was calculated to be 2.11 m/day.

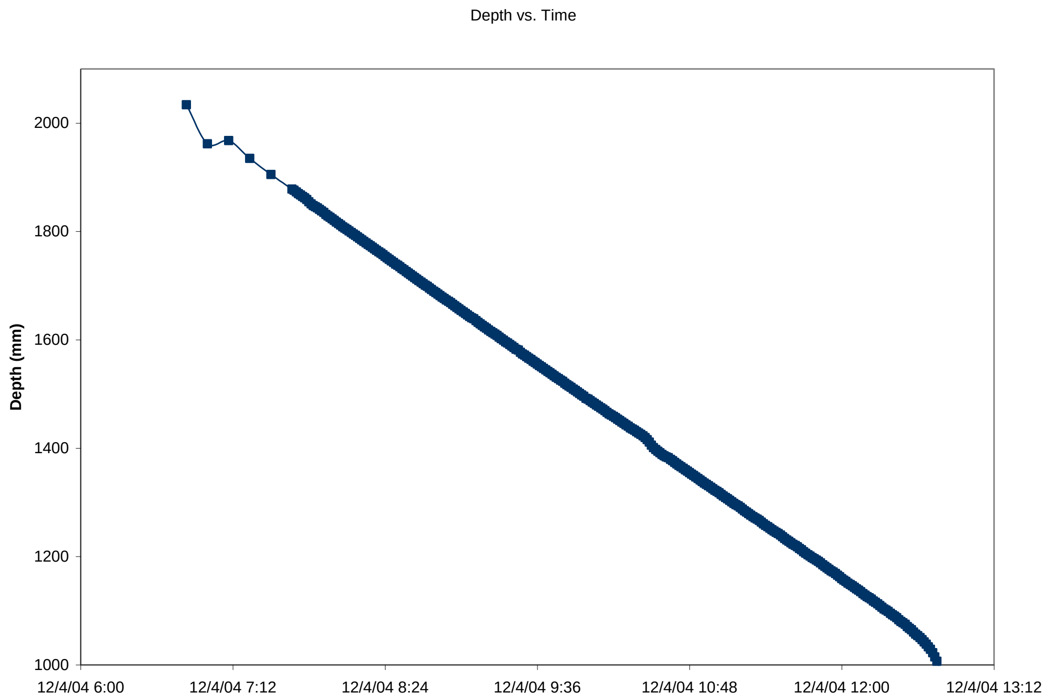

Figure 3 Depth of standing water vs. time for field scale falling head test of 12/4/04.

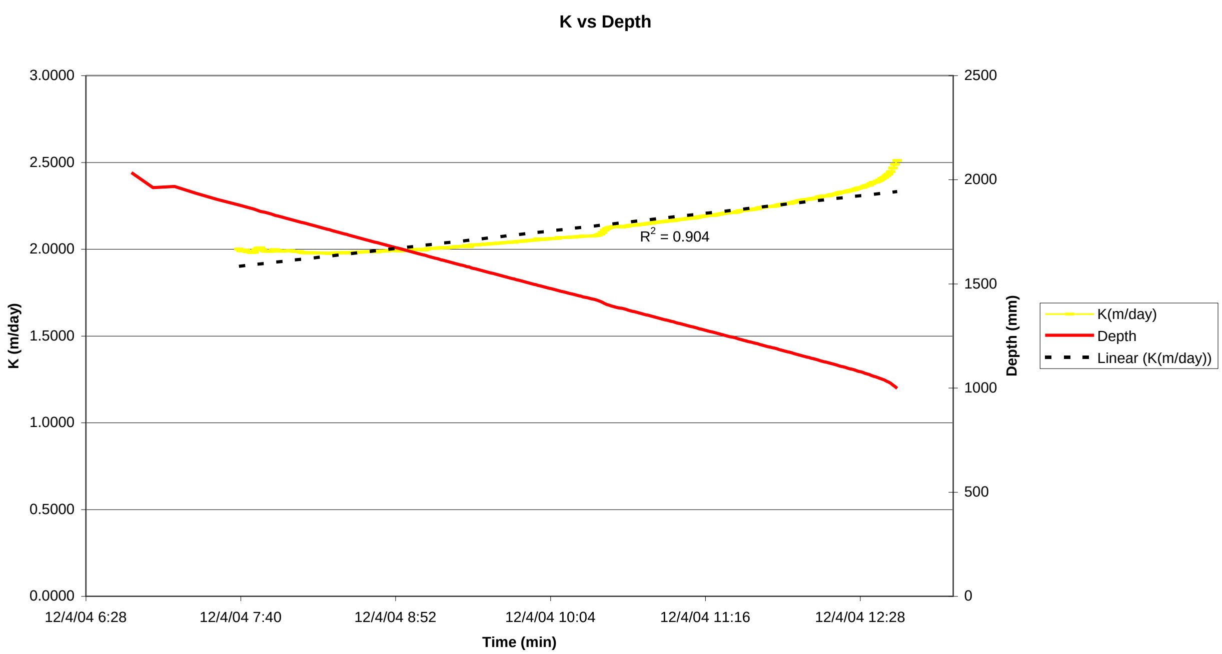

Figure 4. Hydraulic conductivity vs. depth for standing water portion of Cell 4. Trend line shows R^2 value.

These hydraulic conductivity values were compared to published data for evaluation (Fig. 5). Fig. 5 shows the mean range of conductivities for a variety of different substrates and strata.

According to Fig. 5, the range of hydraulic conductivity values that were achieved falls in the range of fine to coarse sand which fits well with estimates.

<u>Conclusions</u>

Over time the hydraulic conductivity of the substrate in vertical flow cells may decrease as pore spaces become obstructed. In this study, once the system was flushed and began to refill it was running as designed with no conductivity problem one month after flushing. The flushing of these systems may be a temporary solution to the problem of substrate clogging. An estimate of hydraulic conductivity was determined using a field scale falling head test.

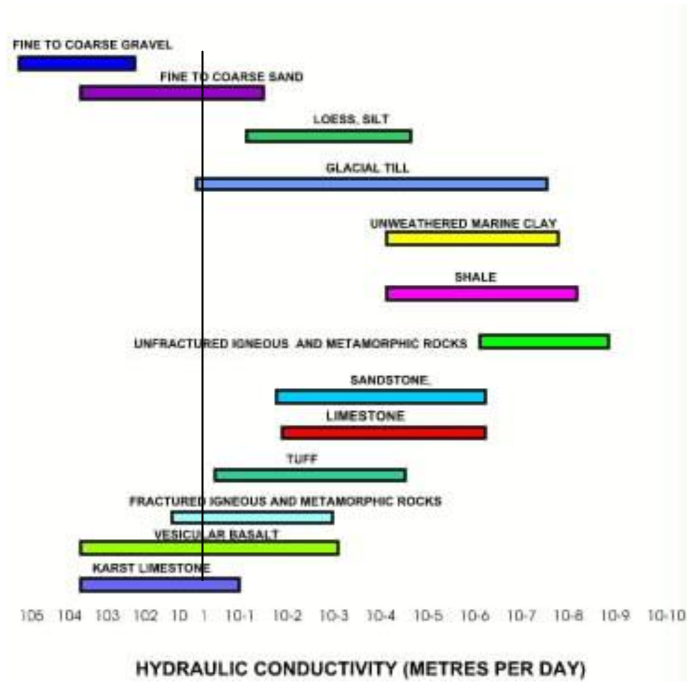

Figure 5 Diagram of typical hydraulic conductivities with the average conductivity for this experiment shown with the vertical line. From http://wvlc.uwaterloo.ca/biology447/modules/module7/images/7a_s1g5.jpg

Future research on this site will continue to examine the possibility of preferential flow within the cell. The system was drained in summer 2004 and substrate cores were obtained. Substrates will be analyzed for organic matter as loss-on-ignition, bulk density, particle density and metal concentrations. Additional substrate material was obtained for laboratory column hydraulic conductivity examinations. A network of 18 piezometers (9 nests at two depths) was installed in a grid pattern in cell 4, these piezometers will be used create a piezometeric head map of the pond. In addition, retention time within the pond will be determined using a tracer to examine preferential flow concerns.

References

Gusek, James J., Thomas R. Wildeman. 2002. A new millennium of passive treatment of acid rock drainage: advances in design and construction since 1988. In: Proceedings of the 2002 National Meeting of the American Society of Mining and Reclamation (Lexington, KY).
https://doi.org/10.21000/JASMR02010935

Hedin, Robert S., Robert W. Nairn and Robert L.P. Kleinmann. 1994. Passive Treatment of Coal Mine Drainage. U.S. Bureau of Mines Information Circular 9389. 37 pp.

Kepler, Douglas A. and Eric C. McCleary. 1997. Passive aluminum treatment success. In: Proceedings of the 18th annual West Virginia Surface Mine Drainage Task Force Symposium. (Morgantown, WV.)

Rose, Arthur and Jonathan Dietz. 2002. Case Studies in Passive Treatment Systems: Vertical Flow Systems. In: Proceedings of the 2002 National Meeting of the American Society of Mining and Reclamation (Lexington, KY).
https://doi.org/10.21000/JASMR02010776

Watzlaf, George, Karl Schroeder, Robert Kleinmann, Candace Kairies and Robert Nairn. 2002. The Passive Treatment of Coal Mine Drainage. In: Proceedings of the 2002 National Meeting of the American Society of Mining and Reclamation (Lexington, KY).

The above was not published in the 2002 Proceedings of ASMR but an article that appears to be this article was found in a publication of Watzlaf as the following:
Watzlaf, G. R, K. T. Schroeder, R. L. P. Kleinmann, C. L. Kairies and R. W. Nairn. 2004. The passive treatment of coal mine drainage. U. S. Department of Energy Report, DOE/NETL-2004/1202. Springfield, Va.: National Technical Information Service, 72 p. Available at ftp://ftp.netl.doe.gov/pub/Watzlaf/