Winter Bioretention System Infiltration Study

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Abstract

A study of four existing bioretention systems in Minnesota during three winter seasons shows that when good design principles are followed, the systems can work as well during cold weather as they do in warm weather. Data confirm that important design considerations include soil and vegetation type, sub-grade drainage, and watershed:bioretention basin area ratio. Important in situ factors leading to success are antecedent dryness, porous frost conditions and extent of biological activity.

Project Description/Methodology

Using bioretention systems for decentralized urban stormwater management has been recognized as a viable option for cold climates, but actual performance data are lacking. Most bioretention design and performance information is based on warm climate conditions where rainfall is the source of runoff. Many observations by practitioners suggest that these systems continue to infiltrate to varying degrees during the winter if designed, installed and maintained properly. However, little field research is currently available to quantify the winter performance of existing bioretention cells when snowmelt is the runoff source. A three-year study funded by the Water Environment Research Foundation (WERF) field-tested the cold climate hydrologic performance of four existing bioretention cells (Figure 1) in the greater Twin Cities, Minnesota region. Sites (Table 1) were selected based on varying design applications receiving runoff from parking lots, a residential street or a commercial development. Three cells operated as bioinfiltration systems with in situ soil types that varied from sand and silt loam to clay loam. One cell operated as a biofiltration system where the in situ soil was replaced with engineered soils (compost and coarse-washed sand) and under-drains. Native vegetation varied from herbaceous to woody. The primary hydrologic test consisted of releasing a “direct volume discharge” (DVD) of up to 6,000 gallons of synthetic meltwater to the bioretention cells and measuring the water movement into and through the system as the water receded. Infiltration rates were measured at the surface concurrent with three-dimensional electronic soil moisture measurements taken to a depth of three feet along horizontal transects. Both control and salt-dosed synthetic meltwater runoff were applied under varying frost depths and field conditions. The three-year effort collected data on site conditions including air, water and soil temperature, snow depth and frost penetration. Two- and three-dimensional graphic portrayals of inflow behavior help explain how water enters and moves through “frozen” bioretention systems. Attempts to document local behavior by using double-ring infiltrometers failed due to localized saturation and freezing.


Figure 1. Crystal Lake Bioretention Basin

The term *observed infiltration rate* is used to describe the actual measured distance (in inches per hour) that a pool of test water covering a cell bottom receded after the cessation of test water being added during a DVD test. It is not equivalent to, nor should it be or be converted into a *design infiltration rate.*

The term *calculated inflow rate* is used to describe the rate (in gallons per minute-gpm) at which the volume of the test water was absorbed into the soil from the initiation of water addition. It was calculated as the total volume of water added (in gallons) divided by time (minutes) starting at the first drop of water added until the test pool depth equaled zero. This number could not be calculated if water remained in a pool at the end of the test.

Table 1. Physical characteristics of the four bioretention cells studied.

Site	Year Built	Est. Surface Area (SF)	Max Pool Depth (ft)	Approx. Drainage Area (SF)	Drainage Area-to-Surface Area Ratio	Imperv. % of Drainage Area	Soil Profile	Estimated Veg. Ratio (% herb/ % woody)	Overflow – Under-drain
Crystal Lake (CL)	2003	400	1.0	7,850	19.6:1	42%	Silt loam Sand & Gravel	50/50	Overtops to adjacent street
Thompson Lake (T)	2003	3,600	0.93	68,900	19:1	45%	Compost Washed Sand Clay Fill	75/25	Central overflow structure to storm sewer; under-drain.
Cottage Grove (CG)	2002	380	1.0	1,700	4.5:1	100%	Sandy Loam Sand Sand & Gravel	100/0	Central overflow structure to storm sewer.
Stillwater (S)	1999	670	0.17	21,780	32.5:1	70%	Organic Loam Clay Loam Loamy Sand	0/100	Central overflow structure to storm sewer.

Results/Discussion

Detailed results for the three year studies are contained in the final WERF documents (Davidson et al., 2008 a and b). Table 2 summarizes the key findings on the movement of water into the soil.

Table 2. Test summaries.

Site	Number of DVD Tests	Observed Infiltration Rate Range [N*] (in/hr)	Calculated Inflow Rate Range [N] (gpm)	Comments
Crystal Lake (CL)	10	0.15 - 18.9 [10]	7 - 53 [7]	Well drained; no under-drain
Thompson Lake (T)	8**	0.7 – 4.2 [8]	38 – 54 [5]	Engineered soils with under-drain
Cottage Grove (CG)	7	0.3 – 13.2 [7]	4.2 – 9.6 [4]	Deep sand with overflow inlet
Stillwater (S)	6	0.2 – 3.7 [6]	4.9 [1]	Poor soils inhibit inflow; overflow inlet

* N = number of tests yielding this factor; Calculated Inflow Rate could not be determined when water remained after test

** Numbers from DVD tests on 3/21/2006 and 1/4/2007 were averaged for three separate locations within basin

Crystal Lake (CL)

Figure 2 illustrates receding pool depths over the course of each DVD test at the CL site with parenthetical infiltration rates. All of the DVD tests appear to draw down sufficiently, with the exception of the February 27, 2007 test which flattens out early due to concrete frost 1m deep. In addition it appears that early season (pre-March) infiltration curves do not flatten out at all and are very linear, but late season (March and later)

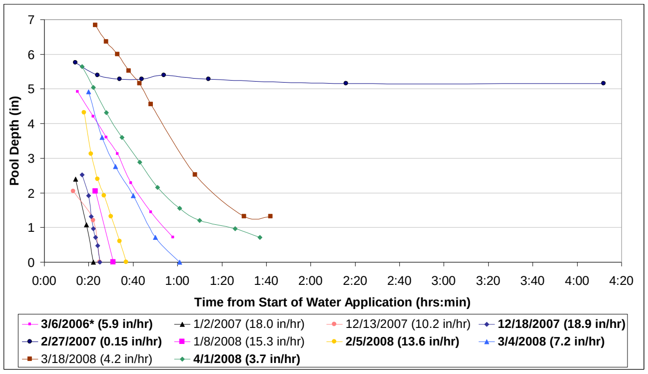
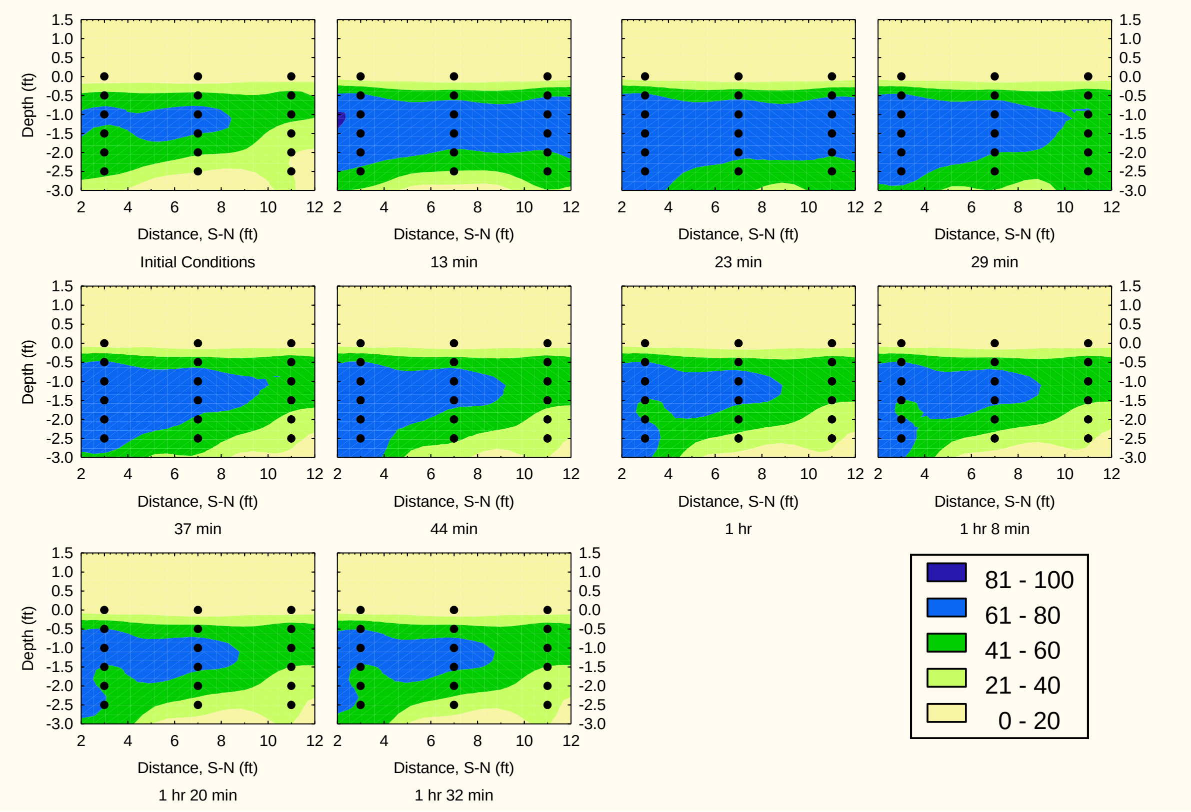


Figure 2. Crystal Lake site.

infiltration curves tend to flatten out, reaching an apparent maximum capacity. These results reflect the porous frost and low moisture conditions of pre-March versus the nearly saturated, yet relatively warm conditions later in the spring. In general, the Crystal Lake cell maintained its hydrologic function throughout the three winter field seasons.

The variability within and between DVD tests may be the result of preferential flow paths and the effects of micro-topography. Figure 3 displays plotted (AquaPro) soil moisture profiles for one DVD event at CL. In this case and others at this site, preferential flow appears to occur toward the adjacent road to the south, possibly caused by movement into the coarse sub-grade material used for the road.



Initial Conditions

13 min

23 min

29 min

37 min

44 min

1 hr

1 hr 8 min

1 hr 20 min

1 hr 32 min

Figure 3. South-to-north soil moisture profile from January 2, 2007, DVD test at the Crystal Lake bioretention cell.

Thompson Lake (TL)

Figure 4 summarizes the receding pool depths for each DVD test at TL. The top three infiltration curves are noticeably shallower in slope than the bottom nine curves. The upper three curves also reflect at least five inches of ponded water over measurable frost after 1.5 to 2.5 hours of testing was completed. Alternatively, the lower steeper slopes reflect complete (or nearly complete) drawdown with assistance from an under-drain.

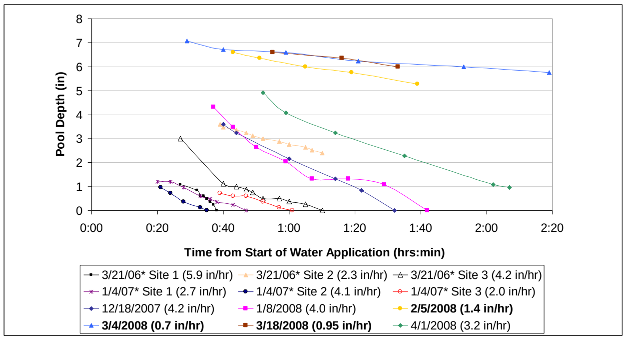


Figure 4. Thompson Lake site.

As was often the case at this site, water did not get to all parts of the large cell. Water was often observed moving to the west and infiltrating at the berm separating the bioretention cell from the adjacent walking path and lake. The movement of this water downward was not specifically documented, but is suspected to have been accommodated by the under-drain. Keeping side-slopes dry, and able to accept meltwater as water levels rise, is a basic design element to enhance performance.

Cottage Grove (CG)

Immediately noticeable from the pool depths tracked over time (Figure 5) at CG are the two groups of data with varying slopes. The three with the shallowest infiltration curves (February 2007 and 2008, and March 2008) had soil frost to a depth of over 1 m. The deep frost during the March 2008 test exhibited some spotty top thaw in the top five inches which appeared to provide no substantial hydrologic benefits. The four DVD tests exhibiting steeper infiltration slopes exhibited frost to a depth of 0.5 m with the exception of the March 2007 DVD test, which exhibited no frost.

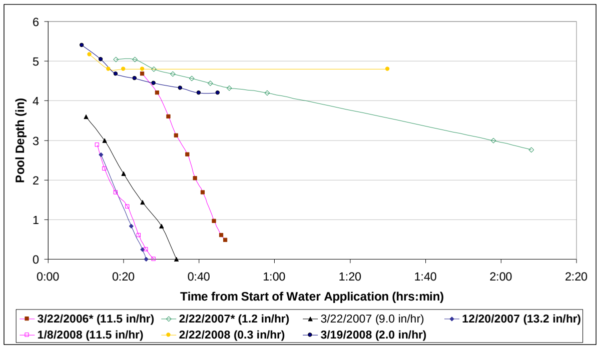


Figure 5. Cottage Grove site.

Antecedent soil temperatures and frost depth are keys to the varying performance of this sandy bioretention site. Soil temperatures for the DVD tests with the shallowest infiltration curves in Figure 5 were well below freezing. Even the 1 m deep soil temperatures, generally well insulated, are below freezing most likely due to the coarse sand nature of the bioretention cell soils. The varying performance despite the presence of frost corresponds to the distinguishing characteristics of soil frost (concrete, granular or porous). The December 2007 and January 2008 DVD tests likely were experiencing granular frost or even porous frost while DVD tests later into the testing season exhibited concrete frost from long periods of frozen temperatures. Limited correlations between 1-m soil temperatures and infiltration rates did, in fact, exhibit the highest correlation ($R^2 = 0.84$; n=6).

Stillwater (S)

This site was initially chosen for study because of its apparent failure to perform well during observations in warm weather. The site was installed in 1999 before basic successful design criteria were commonly used. Figure 6 displays the very low infiltration rates and inflow character of the Stillwater site. Note in Table 2 that inflow rates (gpm) could be determined only for a single DVD test (a non-melt test in October) because all other tests ended with standing water remaining in the cell after the test period ended.

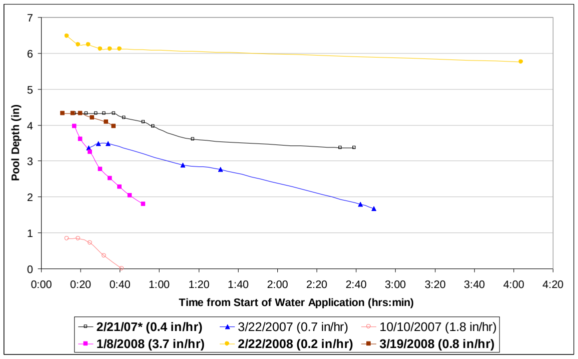


Figure 6. Stillwater site.

Site S was the poorest performing site studied. This is due to its poor soils and the failure of the original design to account for this. Replacement of the soils with an engineered mix and the use of an under-drain to allow this cell to function as a biofiltration system could improve its performance.

Combined Sites

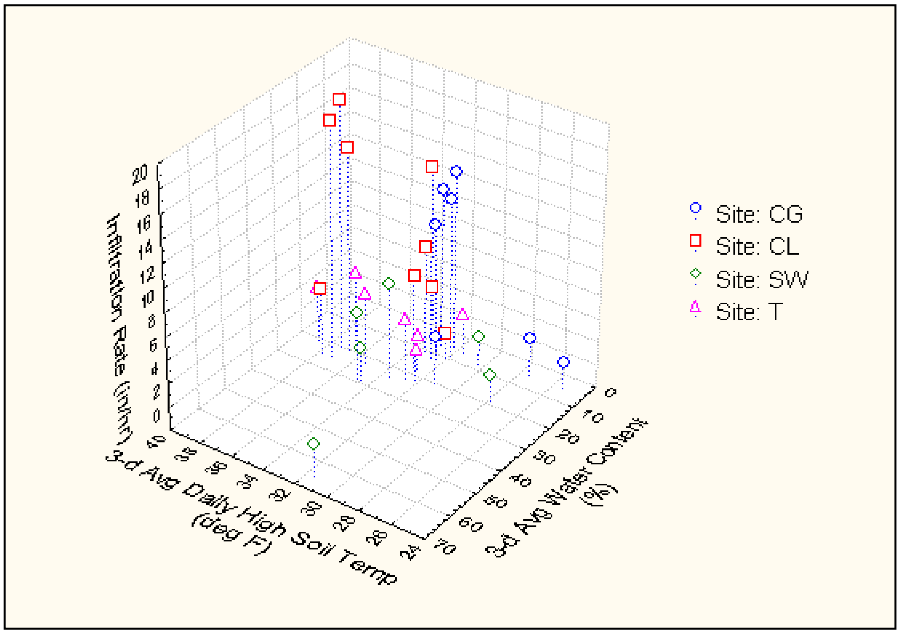


Figure 7. Combined effect of soil temperature and water content on infiltration rates among DVD tests at four bioretention cells.

Figure 7 illustrates a combined graphic for all four sites showing a three-dimensional graph of 3-day average soil moisture and temperature versus observed infiltration rate for all of the DVD tests. The graphic illustrates the importance of low moisture and higher temperatures in enhanced infiltration. Results from the site studies showed that when saturated soils met freezing soil temperatures (the definition of concrete frost), infiltration was severely inhibited. Contrastingly, when soils are dry and temperatures are high (relative to a cold climate condition) infiltration rates can be very high. This condition can be characteristic of melt events during periods of thaw throughout the winter and during the large end-of-season melt. The Crystal Lake site illustrated the extreme circumstance where low soil moisture content and high soil temperature can result in high infiltration rates. By definition, granular frosts can have higher infiltration rates than unfrozen soils due to preferential flow paths (see references listed in Davidson et al., 2008a).

Conclusions

1. Observed infiltration rates within bioretention cells can vary widely during any season. However, in this study the bioretention cells that performed well or not well under warm conditions were observed to also perform well or not well, respectively, under cold conditions.

2. The degree of infiltration of snowmelt water into cold climate bioretention is affected by soil moisture, soil temperature, soil texture and adaptations to it (e.g. engineered soil and under-drain), and biological permeability (root growth, animal and insect burrows). Hydrologic performance in this study appeared to be most strongly influenced by the sum of the combined factors rather than being dominated by any single factor. Sufficient data were not collected to allow for further single factor relevance.

3. The type of soil frost – concrete, granular or porous – more strongly influences bioretention performance than the presence or depth of frost. Additional details reported in LeFevre et al., 2009.

4. Bioretention cells with engineered soils and under-drains provide a predictable range of observed infiltration rates under most winter conditions.

5. General design and maintenance recommendations include:

- Designing for proper function during warm season conditions, keeping in mind deep-rooted vegetation, one-foot maximum depth, and frequent events.

- Avoiding fine textured soils containing silt or clay particles that infiltrate slowly, increasing susceptibility to freezing. If needed, over-excavate to remove in-situ, slow-draining soils and replace with engineered soils with little or no clay.
- Field testing prior to installation to confirm the design is appropriate (e.g. allow for the late addition of engineered soils and under-drain where in-situ soils are found to be poor).
- Consider installing an under-drain with an accessible cap or valve at its outlet to allow operation as either an infiltration system (valve closed) or a filtration system (valve open). Draw-down to dry the system and increase residence time for water quality treatment can be managed by adjusting the valve.
- Using conservative design infiltration rates, as opposed to short-term observed, event-based infiltration rates. Caraco and Claytor (1997) found that for successful infiltration of snowmelt, field infiltration rates need to be at least 0.5 in/hr; this study found no conflict with these design recommendations.
- Undertaking routine sediment/debris removal and plant rehabilitation

Acknowledgements

This WERF study was undertaken by a team from the Dakota and Washington Soil and Water Conservation Districts, and Emmons & Olivier Resources, with input from the Ramsey-Washington Metro Watershed District and Fortin Consulting.

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