Bioretention of Simulated Snowmelt: Cold Climate Performance and Design Criteria

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Abstract

One of the primary tools used in decentralized urban stormwater management is routing runoff to bioretention systems integrated into the landscape (Oberts, 2003). To date, observation suggests that bioretention systems continue to infiltrate during the winter to varying degrees; however, little field research is currently available to quantify their snowmelt infiltration performance. A three-year study funded by the Water Environment Research Foundation (WERF) field-tested the cold climate hydrologic performance of four existing bioretention cells in the greater Twin Cities, MN, region. Sites were selected based on varying design applications including parking lot runoff, street runoff in a residential setting and a commercial application, in soils from sand and sandy loam to clay loam. The primary hydrologic test consisted of applying up to 6,000 gallons of water to a bioretention cell under various frost conditions. The synthetic snowmelt infiltration rates at the surface were measured as the pool receded while dynamic soil moisture readings tracked the subsurface water movement through the soil profile. Data on air, water and soil temperature, snow depth and frost penetration were collected on site. Measured responses reveal that these bioretention cells maintained hydrologic function in cold climates including many cases where rapid infiltration occurred. The primary study findings are that bioretention systems designed successfully for warm climate conditions will likely perform well in cold climate conditions and a well draining soil-type is the single most important design characteristic. The type of frost, rather than the presence or absence of frost, strongly influences bioretention performance, restricting infiltration under concrete frost conditions and facilitating rapid infiltration under granular frost conditions. Under-drains affect both the range of infiltration rates and the overall function.

Background

One of the primary tools used in decentralized urban stormwater management is routing runoff to bioretention systems integrated into the landscape. Most bioretention design information is based on warm climate conditions where rainfall is the source of runoff. To date, observation suggests that these systems continue to infiltrate to varying degrees during the winter if designed, installed and maintained properly. Little field research is currently available to quantify the performance of existing bioretention cells during the winter when snowmelt is the runoff source.

A three-year study funded by the Water Environment Research Foundation and pioneered by Minnesota's Dakota County Soil and Water Conservation District field-tested the cold climate hydrologic performance of four existing bioretention cells in the greater Twin Cities, MN, region: Burnsville (*Crystal Lake*), West St. Paul (*Thompson Lake*), Cottage Grove and Stillwater. The sites were selected based on varying physical conditions and design applications. See Table 1 for site descriptions.

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

Site (appli-cation)	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 (residen-tial street)	2003	400	1.0	7,850	19.6:1	42%	Silt loam Sand & Gravel	50/50	Overtops to adjacent street
Thomp-son Lake (parking lot)	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 (parking lot)	2002	380	1.0	1,700	4.5:1	100%	Sandy Loam Sand Sand & Gravel	100/0	Central overflow structure to storm sewer.
Stillwater (com-mercial)	1999	670	0.17	21,780	32.5:1	70%	Organic Loam Clay Loam Loamy Sand	0/100	Central overflow structure to storm sewer.

Introduction

Field data on bioretention cell hydrology and site conditions were collected over three winter seasons (2005-06, 2006-07 and 2007-08). Manual field data were collected for winter performance assessment from October through April of each winter season. Automated data were collected year around. See Table 2 for an overview of data collection and instrumentation.

Hydrologic performance testing was conducted with direct volume discharge (DVD) tests at each site throughout the testing seasons to simulate a snowmelt event. These tests were scheduled at approximately two-week intervals depending on weather conditions. To simulate actual melt conditions, the test protocol required the test to be conducted when air temperatures were between 20 and 40°F.

Table 2. Data collected and measurement instrumentation at each bioretention cell.

Data Collected	Collection Interval	Instrument	Additional Detail
Air temperature	30-min	Thermometer (Campbell Scientific 107)	
Soil temperature	30-min	Type T Thermocouple Probe (Campbell Scientific 105T)	Measured at approx. 0, 18, 36-inch depths from the bottom of the cell.
Soil water content	30-min	Water Content Reflectometer (Campbell Scientific 616)	Measured at 6-inch and 12-inch depths; centrally located in the study cells.
Frost depth	Bi-weekly	Frost Tubes* (custom made)	Two installed per site: one centrally located in the bottom, one on the side-slope.
Snow depth	Bi-weekly	Ruler	Depth measured inside and outside each cell.
Water movement (soil moisture) through the soil profile	Periodic tests throughout study	DVD tests & AquaPro Soil Moisture Probe	Measures soil moisture via low frequency radio waves; Multiple vertical polypropylene tubes for the soil moisture probe were installed along a grid at each permanent study cell (Crystal Lake-7 tubes, Thompson-18, Cottage Grove-6, Stillwater-7); measurements were taken in 6-inch increments to a depth of 3 feet.
Infiltration rate	Periodic tests throughout study period	DVD tests Double-ring infiltrometer abandoned after first year due to freeze-up issues.	The study cell pool depth response was measured over time.
Sodium chloride affect	Variations tested throughout study	Differences in infiltration behavior observed	Different concentrations of salt added to DVD water to simulate road salt influence on infiltration behavior; sites measured with and without salt.

*A 0.01% fluorescein mixture in the frost tube turns red where frozen. The frost tubes were not found to be entirely consistent and sometimes were found frozen in their cradle. Frost depths, as a result, were based on a combination of frost tube measurements, where available, automated soil temperature measurements and soil excavation.

To conduct the DVD test, the start time was recorded and a known volume of approximately 200 to 6,000 gallons of test water was pumped or poured quickly into the study cell to create a pool depth across the bottom. Timed measurements of the receding pool depth were recorded to establish the observed surface infiltration rate. The tests were considered complete when visual observation verified that nearly all of the test water volume had infiltrated or in the case of slow rate of infiltration, after at least one hour of observation after adding the test water.

Three types of frost in soils have been identified and are frequently referenced in cold climate studies. *Concrete* frost occurs when a saturated soil freezes and creates an ice lens where little water movement is possible (Muthanna, 2007). Correspondingly, Xiuqing and Flerchinger (2001) and Granger et al. (1984) found that permeability of frozen soil was strongly affected by water content at the time of freezing. G*ranular* frost occurs when unsaturated soils with little soil moisture freeze and high permeability is maintained. *Porous* frost is the third and most permeable frost type. For purposes of this study, if soil temperatures were below freezing, soil frost was considered to be present unless field notes characterized the conditions to be otherwise.

Results and Discussion

Crystal Lake Bioretention Cell

The Crystal Lake bioretention cell was formerly studied for warm season hydrologic performance as one of 17 rain garden retrofits in a residential suburb (Barr, 2006). Field observations during warm weather confirm the cell consistently demonstrates rapid infiltration without an under-drain system.

Ten DVD tests were conducted at the Crystal Lake site over the three-winter study period. For every DVD test at the Crystal Lake site, 425 gallons of test water was applied to simulate a melt volume typically seen during winter and early spring events. The 425 gallons is equivalent to about 0.08 inches over the entire 7,850 SF drainage area or about 0.21 inches from the impervious fraction.

Figure 1 illustrates receding pool depths over the course of each DVD test with parenthetical surface infiltration rates and bold where soil frost was identified. The observed infiltration rate range on this site was 0.15 in/hr to 18.9 in/hr. All of the DVD tests draw-down trends are consistent with the exception of the 2/27/07 test which flattens out early. The 2/27/07 test had the slowest infiltration rate (0.15 in/hr) and the deepest frost penetration (36-inches) of all tests. Field observations from the 2/27/07 test indicate refusal of excavation due to frozen soils. The slow infiltration rate suggests that concrete frost likely formed as a result of the severe freezing temperatures and the 12-inch deep 18% soil water content observed several days prior to the test.

The 12/18/07 test (18.9 in/hr) and the 2/5/08 test (13.6 in/hr) are two cases where the infiltration rate was particularly high despite frost in the top 18-inches and refusal of excavation due to frozen soils. The rapid infiltration rate in the presence of frost suggests that granular or porous frost likely formed in the soil column. By definition, granular/porous frosts can have higher infiltration rates than unfrozen soils due to preferential flow paths.

The trend in infiltration curves in Figure 1 is defined by steeper slopes (faster infiltration) during pre-March DVD tests and shallower slopes (slower infiltration) during March/April DVD tests. This may be a function of the time of year resulting in antecedent standing water in the bioretention cell as was exhibited in both the March and April 2008 DVD tests. After repeated wetting throughout the winter, spring DVD tests may be responding with decreased infiltration rates even in the absence of frost. This time of year marks a point where soil moisture begins to rise steadily as soil thaws and the season changes to spring. For the March 18, 2008 DVD test, there was two inches of standing water prior to testing and incomplete drawdown within the 1.5 hours of testing (Figure 1). However, infiltration still occurred.

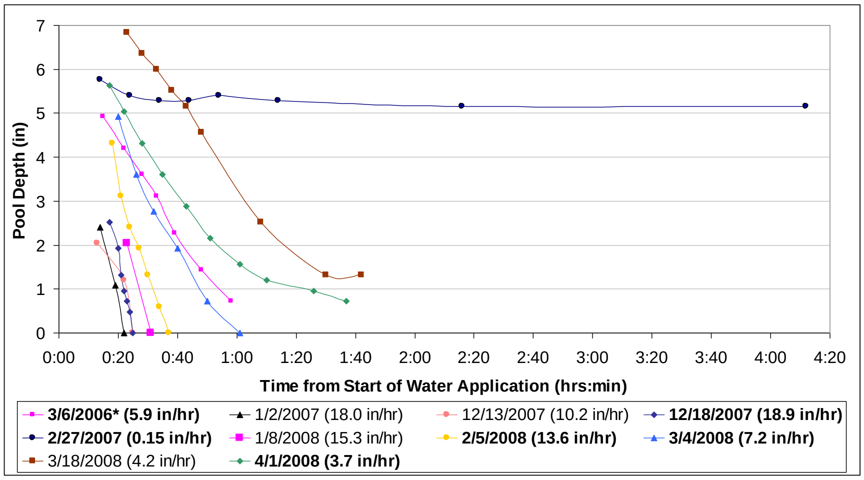

Figure 1. Drawdown and infiltration rates of DVD tests at the Crystal Lake bioretention cell; bold indicates the presence of soil frost.

Given that only one of 10 DVD tests at this site resulted in what might be characterized as concrete frost, the Crystal Lake site exhibited a low risk of restricted infiltration and was deemed to perform very well for treatment of snowmelt events. A study by Stenmark (1995) concluded that there exists only a small risk of total ice blockage (e.g. concrete frost) for air temperatures as low as 5 deg F during the snowmelt period. Though air temperatures throughout the three seasons of this study did drop below 5 deg F, average daily highs preceding DVD tests were significantly higher, reflective of the study objective to test synthetic melt events and are consistent with Stenmark’s findings.

Thompson Lake Bioretention Cell

Construction of the Thompson Lake Cell included replacement of clay soils to a depth of 2.5 feet with engineered soils consisting of 80% coarse washed sand and 20% organic compost. Field observations during warm weather indicate the cell functions effectively through reliance on an under-drain system.

Eight DVD tests were conducted at the Thompson Lake site. For most of the DVD tests, water stayed in the north end of the bioretention cell where soil moisture probes were installed. The volume of test water for this site varied from 2,000 - 6,000 gallons to simulate a melt volume typically seen during winter and early spring events. The 6,000 gallons is equivalent to about 0.14 inches over the entire 68,900 SF drainage area or about 0.31 inches from the impervious fraction.

Figure 2 illustrates receding pool depths over the course of each DVD test with parenthetical surface infiltration rates and bold where soil frost was identified. The observed infiltration rate range on this site was 0.7 in/hr to 4.2 in/hr. All of the DVD tests draw-down trends are consistent. Two tests (2/5/08 and 3/4/08) are remarkable for comparison. Both tests recorded refusal of excavation due to frozen soils. The 3/4/08 test had the slowest infiltration rate (0.7 in/hr) with a frost depth of 18-inches. The 2/5/08 test had the deepest frost penetration (36-inches) but recorded a faster infiltration rate of 1.4 in/hr. This comparison suggests that type of the frost has more influence on infiltration rates than the depth of the frost alone.

During the 1/8/08 DVD test, extensive bubbling from preferential flow paths was observed in the pool of test water. Preferential flow paths may be created, for example, by burrowing mice, worms or decaying plant roots (biological permeability) or by fractures in the frost. Preferential flow paths were identified in a Norway study simulating snowmelt over a heterogeneous coarse sandy unsaturated zone (French et al., 2002). French and Binley (2004) found that variations in micro-topography (distances of a few meters) were a driving force of preferential flow paths.

This site exemplifies the hydrologic benefits of replacing poorly draining in-situ soils with engineered soils and an under-drain system to create successful biofiltration where poorly draining soils or high groundwater levels would normally preclude successful infiltration (Davidson et al., 2008a). While biofiltration systems provide less volume reduction benefit, the slowed movement of infiltrating water through the soil column prior to discharge into the under-drain allows for such water quality treatment processes as filtration through the soil, adsorption to soil and vegetative matter, and microbial uptake (albeit limited) to occur (Oberts et al., 2000).

Overall the Thompson site exhibited a much narrower range of surface infiltration rates (0.7 in/hr to 4.2 in/hr) as compared to the Crystal Lake site (0.15 in/hr to 18.9 in/hr). This comparison suggests the hydrologic performance of biofiltration systems is more predictable than that of infiltration systems. In addition, the lowest infiltration rate at the Thompson site (0.7 in/hr) was higher than that of the Crystal Lake site (0.15 in/hr). Biofiltration systems may have a greater resistance to forming restrictive frost than infiltration systems with granular soils.

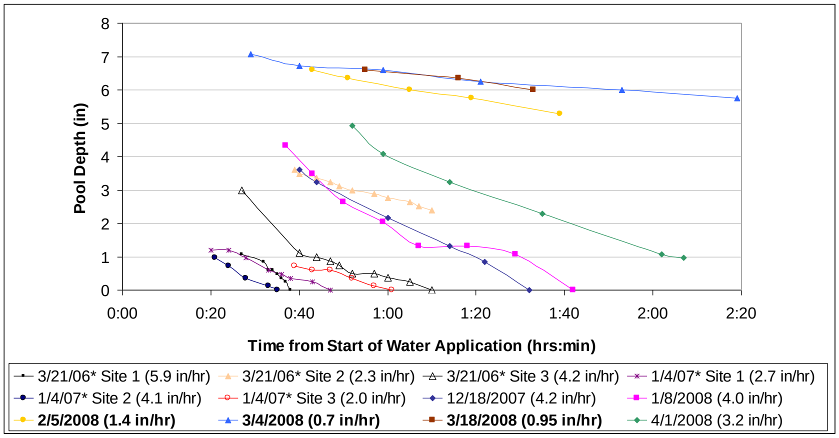

Figure 2. Drawdown and infiltration rates of DVD tests at the Thompson Lake bioretention cell; bold indicates the presence of soil frost.

Cottage Grove Bioretention Cell

Seven DVD tests were conducted at the Cottage Grove bioretention cell. The volume of test water for this site varied from 200 - 250 gallons to simulate a melt volume typically seen during winter and early spring events. The 250 gallons is equivalent to about 0.23 inches over the entire 1,700 SF drainage area or about 0.23

inches from the impervious fraction. Field observations during warm weather confirm the cell consistently demonstrates rapid infiltration without an under-drain system.

All of the DVD tests appear to draw down consistently with the exception of the 2/22/08 test which flattens out early (see Figure 3). The 2/22/08 test had the slowest infiltration rate (0.3 in/hr) with a frost penetration of 42-inches. It is possible that concrete frost formed in this case.

There are three tests (3/22/06, 12/20/07, 1/8/08) where the infiltration rate was particularly high (11.5 in/hr to 13.2 in/hr) despite soil frost to a depth of 18-inches. The rapid infiltration rate in the presence of frost, suggests that granular or porous frost likely formed in the soil column. Soil temperatures below freezing (used to determine the presence of soil frost) may not have always generated concrete frosts to the porosity of coarse sand.

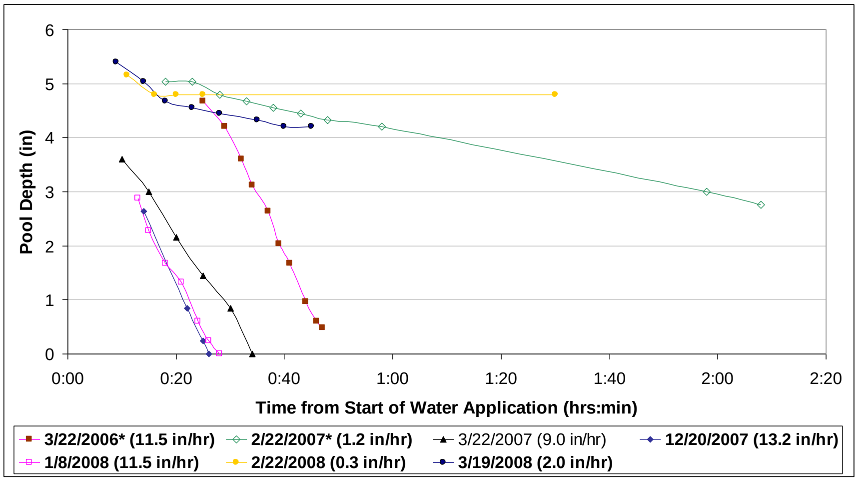

Figure 3. Drawdown and infiltration rates of DVD tests at the Cottage Grove bioretention cell; bold indicates the presence of soil frost.

Stillwater Bioretention Cell

The in-situ soils used to create the Stillwater Cell are a combination of poorly draining clay loams and sandy loams without compost amendments. A perforated 6 inch diameter outlet standpipe allowed the cell to overflow into a connected storm sewer system at a ponding depth of 0.17 feet, but it was plugged for DVD testing. Field observations during warm weather confirm the cell consistently demonstrated poor infiltration performance and often had saturated soils and extended surface pools residence times well beyond 24 hours.

Seven DVD tests were conducted at the Stillwater bioretention cell. The DVD test water volume added to the Stillwater bioretention cell (200 to 250 gallons) amounted to only 0.01 to 0.02 inches over the entire drainage area (21,780 SF). Figure 4 displays the very low infiltration rate range of the bioretention cell (0.2 in/hr to 3.7 in/hr) even with the minimal amount of water added and in the absence of soil frost. Where drawdown was observed based on pool depth measurements, infiltration of surface water is not readily identifiable in soil moisture profiles (Davidson et al., 2008b). It is likely that much of the observed drawdown was due to leakage observed at the plugged overflow outlet. The Stillwater cell was often wet-to-saturated prior to testing due to a poor ability to dry-out and provide infiltration of run-on. Stillwater shows that poor soil conditions result in poor winter performance, consistent with equally poor warm weather performance.

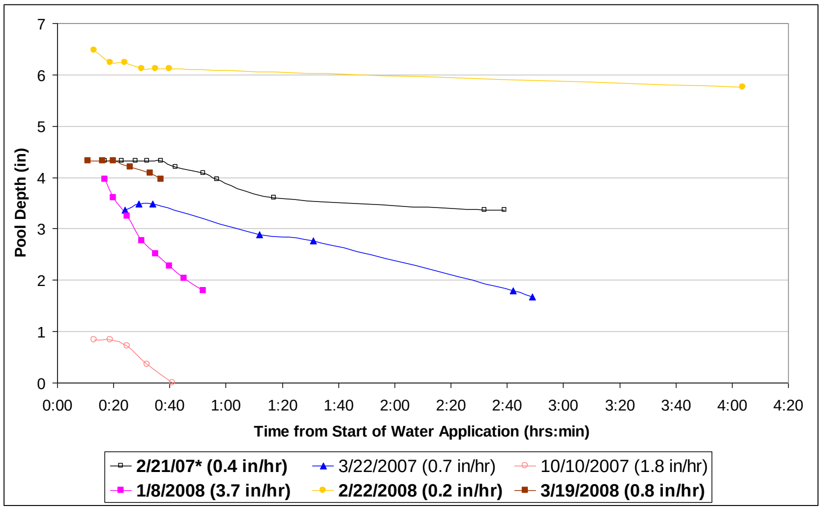

Figure 4. Drawdown and infiltration rates of DVD tests at the Stillwater bioretention cell; bold indicates the presence of soil frost

All Sites Combined

Overall, 32 DVD tests were conducted at four bioretention cells throughout the greater Twin Cities, MN, area. Hydrologic performance was generally sustained throughout the winter season, excluding the Stillwater bioretention cell where clay soils absent of an underdrain precluded both warm and cold season infiltration with no option for filtration. Concrete frost formation also limited surface infiltration under the test water volume and time constraints of this study. Study data also show a wide range of observed surface infiltration rates (0.15 – 18.9 in/hr), but indicate that infiltration does occur in cold climate conditions.

Figure 5 illustrates a strong causative relationship of the combined effect of soil temperature and soil water content on infiltration rates. The trend indicates that when saturated soils meet freezing soil temperatures (the definition of concrete frost), infiltration is restricted. Alternatively when unsaturated soils meet freezing soil temperatures (the definition of granular or porous frost) infiltration rates can be very high. The Crystal Lake site illustrated the extreme circumstance where low soil moisture content and both high and low soil temperature resulted in high infiltration rates. By definition, granular frosts can have higher infiltration rates than unfrozen soils due to preferential flow paths (Muthanna, 2007; Stoecker and Weitzman, 1960). The 18.9-in/hr infiltration rate at Crystal Lake exhibited soil frost to a depth of 18-inches, a probable example of either granular or porous frost, likely the case in many of these cold climate DVD tests.

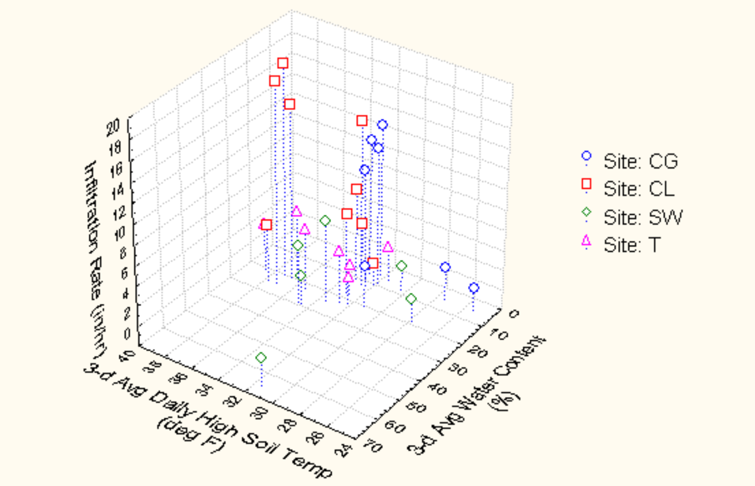

Figure 5 Combined effect of soil temperature and water content on infiltration rates among 32 DVD tests at four bioretention cells.

Conclusions

- Bioretention cells, if functioning properly in the warm season, function properly under cold climate conditions.
- The type of soil frost – concrete, granular or porous – more strongly influences bioretention performance than the presence or depth of frost.
- When saturated soils meet freezing soil temperatures (concrete frost), infiltration is restricted. When unsaturated soils meet freezing soil temperatures (granular or porous frost), infiltration rates can be very high.
- The importance of good soils during the growing season is widely understood. While the infiltration mechanism of good soils may be different in cold climates, good soils are equally, if not more, important under cold conditions.
- Under-drains are paramount to cold climate (and warm climate) function of bioretention cells with poor soils
- Bioretention cells with under-drains provide a more predictable range of infiltration as compared to functioning cells with no under-drain.
- Preferential flow paths are a mechanism for cold climate infiltration.
- Observed cold climate surface infiltration rates vary widely.

Design Recommendations

- Design for proper function during warm season conditions.
- Avoid fine textured soils containing silt or clay particles; they infiltrate slowly, increasing susceptibility to freezing. Over-excavate to remove in-situ, slow-draining soils and replace with engineered soils. The *Minnesota Stormwater Manual* (MN SSC, 2007) recommends that bioretention soil mixes contain less than 5% clay, preferably zero.
- Field test prior to installation to confirm the design is appropriate (e.g. allow for the late addition of an underdrain where in-situ soils are found to be poor).
- Install 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, if necessary, and residence time for water quality treatment can be managed by adjusting the valve.

- Conservative design infiltration rates, as opposed to observed, event-based infiltration rates, are necessary.
- 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.

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