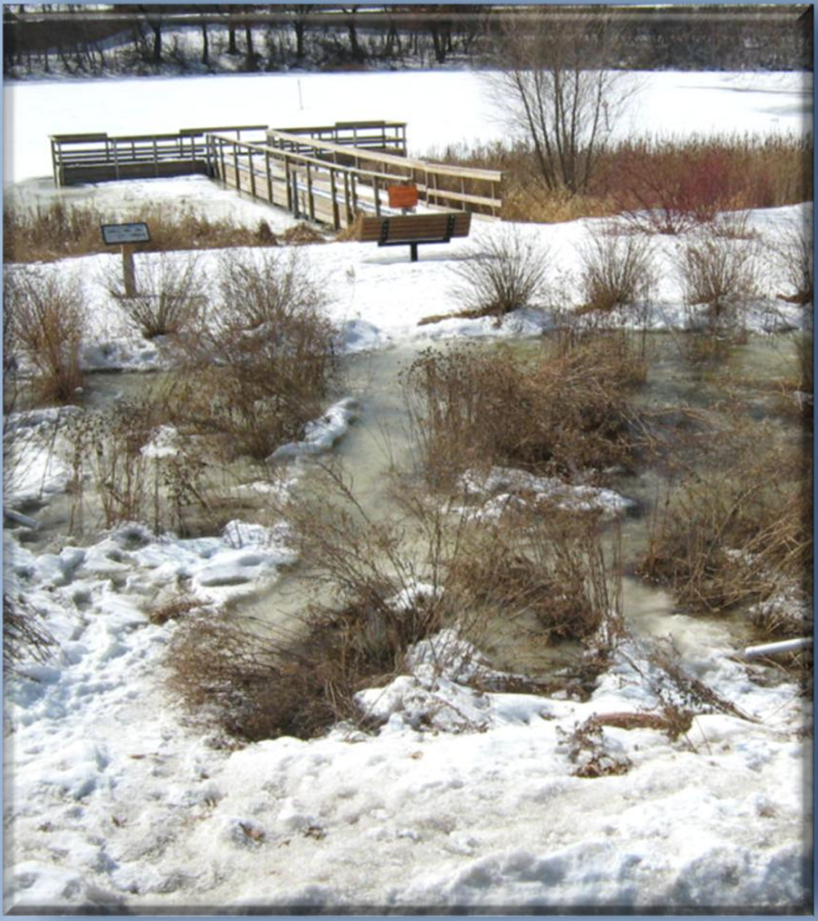
HYDROLOGIC BIORETENTION PERFORMANCE AND DESIGN CRITERIA FOR COLD CLIMATES



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ABSTRACT AND BENEFITS

Abstract:

One of the primary tools used in the decentralized approach to urban stormwater management is routing runoff to bioretention systems (rain gardens) integrated into the urban landscape. Most bioretention design information focuses on warm climate conditions with rainfall as the source of the runoff. This may be due to an assumption that bioretention systems become dormant and have little infiltration performance in the winter. Field observations suggest these systems can continue to infiltrate to varying degrees during the winter if designed, installed and maintained properly; however very little research is currently available to quantify the extent of their performance when using snowmelt as the runoff source under field conditions.

This Water Environment Research Foundation (WERF) hydrologic research project was a three-year (2005-2008) study that collected air temperature, soil temperature, and soil moisture data at four existing bioretention cells located in the Minnesota Twin Cities metropolitan area and conducted simulated snowmelt events to observe their hydrological performance responses under winter conditions. The measured responses reveal a dramatic range of performance including rapid infiltration during varying cold climate conditions.

The study used the scientifically based data to develop practical design, installation, and maintenance recommendations that optimize hydrologic performance of bioretention cells in cold climates.

Benefits:

- Expands knowledge of bioretention system infiltration/filtration performance under cold climate conditions.
- Demonstrates that bioretention cells remain hydrologically active in cold climates.
- Quantifies a range of observed infiltration rates under a varying cold climate conditions.
- Evaluates equipment needed to assess winter hydrologic performance.
- Provides practical recommendations to optimize infiltration/filtration performance in cold climates.

Keywords: Bioretention, cold climate, infiltration, filtration, winter

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EXECUTIVE SUMMARY

One of the primary tools used in the decentralized approach to urban stormwater management is routing runoff to bioretention systems (rain gardens) integrated into the urban landscape. While the use of bioretention systems as a component of stormwater management is rapidly increasing, the understanding of how these systems perform in the winter has not kept pace, even though cold climate conditions occur in a significant portion of the United States and the world.

Completed in October 2008, the *Hydrologic Bioretention Performance and Design Criteria for Cold Climates* was a three year (2005-2008) Water Environment Research Foundation (WERF) hydrologic research project that explored the movement of water into and through the soil profile of four existing bioretention cells located in the Twin Cities metropolitan area of Minnesota during cold climate conditions. The study collected air temperature, soil temperature, and soil moisture data and conducted simulated snowmelt events to measure the cells individual performance responses under full scale winter conditions.

Crystal Lake Bioretention Cell
Burnsville, Mn

Cottage Grove Bioretention Cell
Cottage Grove, MN

Thompson Lake Bioretention Cell
West St. Paul, MN

Stillwater Bioretention Cell
Stillwater, Mn

The study timeline was as follows:

- Season (2005-06) Test protocol, select sites, install equipment, collect data;
- Season (2006-07) Collect data and conduct infiltration testing;
- Season (2007-08) Collect data, conduct infiltration testing, analyze data, and report findings.

The goal of the study was to use the scientifically based data to develop practical recommendations and technical guidance that can be applied by stormwater professionals who design, construct and maintain bioretention systems operating under cold climate conditions. The study's recommendations were not meant to replace the design criteria already in use for warm climates, but rather to supplement those existing criteria with the knowledge gained to optimize designs for operating in cold climate conditions. The following summarizes the conclusions of the study.

1. Three of the four studied bioretention cells remained hydrologically active during cold climate conditions most of the time. The fourth cell, although infiltrating some water, appeared limited in both warm and cold weather due to its poor draining soils.

With the exception of the Stillwater cell, which has inherently poor soils, the data indicated the hydrologic performance of the studied cells was characteristically reliable throughout the study. At the Crystal, Thompson and Cottage Grove cells, the entire amount of Direct Volume Discharge (DVD) test water used to simulate a snowmelt event was absorbed into the cell within the test period 16 out of 25 tests (64%) clearly indicating these three cells were capable of infiltrating water during cold climate conditions most of the time. The Stillwater cell only absorbed the test water volume within the test period 1 out of 7 tests (14%) indicating limited performance most of the time.

2. The observed infiltration rates within each cell varied widely during the testing season.

In the largest sense, the observed performance responses of the bioretention cells were products of the natural cold climate conditions and soil conditions encountered during the study. Winter conditions consist of an ever changing variety of unpredictable weather events that set into motion a complex, interactive relationship between the various factors that drive the hydrologic functions within the bioretention cells. While the overall study data clearly showed the range of observed performance was reflective of the wide range of climate driven influences, the data did not show strong correlations between hydrologic performance and individually measured factors.

This study uses the term "observed infiltration rate" to describe the actual measured distance (in inches per hour) a pool of test water, covering a cell bottom, has receded after the cessation of test water being added during a DVD test. It was measured by observing water drawdown from a fixed reference mark versus time beginning when the addition of water ceased. In this fashion, it should be considered as part of the initial wetting stage rather than long-term or sustained infiltration. As used in this study, the observed infiltration rate accounts for the combined influences of surface hydraulic loading rate, filling of the interstitial area and the transmission rate occurring simultaneously across the test pool area. Most importantly, an "observed infiltration rate", as used in this study, is not equivalent to (or should not be converted into) a "design infiltration rate" commonly used to size infiltration systems. Design infiltration rates are used to predict a sustainable rate of flow based factors such as the least permeable soil layer within five vertical feet of the bottom of an infiltration area. Design infiltration rates are intentionally conservative due to variable (and sometimes unknown) soil conditions and the need for sustainable performance throughout the lifetime of the bioretention facility. The *Minnesota Stormwater Manual* (Chapter 8, page 195) provides guidance for design infiltration rates (MN Stormwater Steering Committee, 2007).

The range of "observed infiltration rates" spanned from very fast to virtually zero depending on the influencing factors. The Crystal Lake cell recorded the widest range of observed infiltration rates (18.9 to 0.15 in/hr), followed by the Cottage Grove cell (13.2 to 0.30 in/hr), the Thompson Lake cell (4.2 to 1.4 in/hr) and the Stillwater cell (3.7 to 0.20 in/hr). Characteristically, the fastest rates occurred early winter in the testing season and progressively slowed as the tests were completed later in the season toward spring. The data also showed the fastest infiltration rates occur when the soils were warm and dry; the infiltration rates decreased as the soils became colder and wetter. The data indicate that each bioretention cell operated within its own performance range unique to its specific location; however the very fast infiltration rates observed during some tests could not be relied upon for consistency all winter.

Within each bioretention cell, the influencing factors of soil temperature, soil texture and soil moisture combined to affect the observed infiltration rate dramatically. Of the monitored factors, the data indicate that soil temperature had the strongest correlation to performance and soil moisture the weakest. Overall, the data suggest that hydrologic performance was most strongly influenced by the sum of the combined factors. Due to the complex and interrelated nature of those factors, this study was not able to further define or quantify the individual relationship ratios of these factors tied to hydrologic performance and many questions remain.

Anecdotal observations indicated a key component linking these factors is soil texture and the permeability of frost. For example, a combination of cold, wet, and fine textured soils at the Stillwater cell seemed to be more susceptible to concrete frost than the corresponding cold, wet and coarse textured soils at the Crystal cell. The combination of soil moisture and soil temperature was the leading antecedent condition that drove the presence and type of frost. Where cold temperatures met wet soils, concrete frost was most likely to develop. Where soils were frost-free, independent conditions at varying degrees drove hydrologic performance. For instance, bioretention cells with wet soils prior to a simulated runoff event did not perform as well as a cell with antecedent dry soils.

3. ***The bioretention cells that performed well under warm conditions were observed to perform well under cold conditions; and the cell that did not perform well in warm conditions, did not perform well under cold conditions.***

The Crystal, Thompson and Cottage Grove cells had the fastest observed infiltration rates and clearly demonstrated successful operations under cold climate conditions. While the factors which most influenced that success were not well defined by this study, it was apparent these three functioning cells shared common characteristics such as free draining granular soils that were observed to perform well under warm climate conditions. Field observations concluded that expanding on the design components that optimize warm climate performance would likely optimize cold climate performance.

This simple finding suggested the best way to optimize performance for cold climate operations is to design, construct and maintain well performing warm climate systems. Further study effort was made to identify the design elements and functional characteristics of the three cells that functioned well in both cold and warm conditions and a guidance document was developed to accompany this study.

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CHAPTER 1.0

PURPOSE

1.1. Background

One of the primary tools used in the decentralized approach to urban stormwater management is routing runoff to bioretention systems (rain gardens) integrated into the urban landscape. Most bioretention design and performance information focuses on warm climate conditions with rainfall as the source of the runoff to be managed. This may be due to an assumption that bioretention systems become dormant and provide little water quality benefits in the winter. Field observations suggest these systems do continue to operate during the winter to some extent; however, very little research is currently available to quantify the extent of that performance when using snowmelt as the runoff source under field conditions.

Over the course of three years, this applied research project monitored four bioretention cells to better understand their hydrologic performance under winter conditions. Data collected during the study period was analyzed and used to develop recommendations that can be used to optimize system performance and address issues unique to cold climate operations. The goal of the study is to create a Cold Climate Bioretention Design Guidance document that provides criteria, practical information, and serves as a technical resource tool for stormwater professionals who design, construct and manage bioretention systems located in cold climates.

1.2. Problem Description

While the use of bioretention systems as a component of stormwater management is rapidly increasing, the understanding of how these systems perform in the winter is not, even though cold climate conditions occur in a significant portion of the United States and the world. Research to establish special design guidance and management strategies are needed because technical design criteria intended for warm conditions might not work well during cold conditions.

The runoff from snowmelt has characteristics different than those of rainfall runoff. (Marsalek et al., 2003; Novotny et al., 1999; UNESCO, 2000). The movement of pollutants in cold climates is further complicated by the complex freeze and thaw cycles that occur throughout the winter. The response of bioretention facilities during these mid-winter freeze and thaw cycles is limited and not well understood, even though observations have shown them to be effective. The complex melting pattern within the snow pack itself also creates different stages of water movement and associated management strategies. Early stages of the melt have high soluble pollutant content while later stages have high solids content (Colbeck, S.C., 1978, 1981, 1991; Jeffries, 1988; Marsh and Woo, 1984). Studies show infiltration can and does occur at the beginning of the melt (Buttle, 1990; Westerstrom 1984). These phenomena may require varied approaches to stormwater treatment, such as infiltration during the beginning of the melt to capture the soluble pollutants and detention at the end of the melt to capture the solids.

There are many unanswered questions regarding the performance of these systems. In particular, cold climates present additional questions regarding the hydrologic function and mechanisms of bioretention practices during long periods of cold weather and snowmelt events. In cold climates, during any given year, snowmelt runoff is often the largest volume event and rain-on-snow events can exacerbate this situation (Oberts, 2003). Bioretention systems that treat winter snowmelt runoff have been used with apparent success, but factors influencing success have not been thoroughly researched or documented. Of particular concern are the hydrologic effects of frozen soils, salt loads, snow cover and storage, and top thaw. Individually and in combination, these complex and interrelated factors are integral to winter conditions.

The focus of this applied research study has been narrowed to collect data from existing bioretention systems to observe the hydrologic performance responses to uncontrolled winter conditions. Underlying this study is the effort to address many questions/concerns that regularly spark discussion among cold-climate design professionals. The four major questions are:

1. Are bioretention systems hydrologically functional in the winter?
2. What range of hydrologic performance is likely during cold climate conditions?
3. Which factors most affect winter hydrologic performance?
4. Can systems be designed to optimize cold climate performance?

The goal of this study is to answer these questions and develop practical guidance recommendations for stormwater professionals who design and maintain bioretention systems operating under cold climate conditions.

1.3. Statement of Available Literature

Literature from the U.S., Canada, and northern Europe is laying the foundation for cold climate bioretention research. It is beginning to shed light on hydrologic mechanisms and system design for successful implementation. Research explores bioretention characteristics that drive hydrologic performance including, among others: seasonal climate, antecedent moisture conditions, quality of ice formation in soils, frozen inlets/outlets, soil media, frost heave and plant growing season length. Research also includes water quality treatment in cold climates and the effects of soil and runoff temperature, snowmelt characteristics, biological activity, settling velocities, pollutant loads, de-icing chemicals, and sediment loads. Findings contribute valuable design and maintenance implications and provide insight regarding the data collected in this study.

1.4. Conduct of Study

This Water Environment Research Foundation (WERF) hydrologic research project was a three-year (2005-2008) study structured to explore the movement of water into and through the soil profile of several existing bioretention systems during cold climate conditions.

The essence of this study was to conduct simulated snowmelt events at a series of existing raingardens and measure their individual performance responses under full scale winter conditions. Testing dates were assigned at approximately two week intervals with the intent of capturing the climatic conditions that occurred on the scheduled day without bias to weather patterns or antecedent conditions. If the climate conditions on the assigned test day did not meet the test protocol, the test day was rescheduled for two days later.

The study sites were existing cells with established mature vegetation. No special preparations were made to the sites prior to the study. To keep test performance as realistic as possible, each site was monitored in its *as is* condition. Regular maintenance such as weeding and trash removal was allowed during the three year study, but soil disturbing activities were not.

Since each site has unique characteristics such as soil textures, pool depths, and wetted surface area that drive its performance, the performance data collected were site specific. The study recognized that designs vary from site to site and thus performance varied widely from site to site. For example, some sites had inherently faster infiltration rates due to granular soils, whereas some sites inherently drained slower because of tighter soils. The study avoided labeling one raingarden *better than the other*. Likewise, the study data should not be used to compare one site's performance against another but rather compare a specific site's performance against itself as climatic and other factors change through the testing season.

Four bioretention cells in the Twin Cities Metropolitan Area of Minnesota were selected for the study (Figure 1-1). The following criteria were used in their selection:

- The sites must be a fair representation of the type of bioretention cells construction and vegetation typical of the region, without preference being given to their level of performance prior to testing.
- To provide a sampling of different bioretention applications the selected sites should have a combination of various existing conditions and settings that are normally found in the region (such as granular/clay soils, residential/commercial settings, large/small size, fast/slow soils, with/without under-drains).
- The sites must have mature vegetation and have been in continuous operation long enough for its level of performance to have stabilized prior to testing. (At least two years)
- The sites must be easily accessible by vehicle during the winter.
- The site owners must grant permission and some assurance the site would remain in service without modification throughout the three year study period.
- Systems without vegetative biological components such as sand filters were not considered.

At each site throughout the study, an automated data logger collected year-round continuous data for soil temperature, air temperature, and soil moisture. Manual testing included double-ring infiltrometers (discontinued after year one) and direct volume discharge (DVD) tests (conducted in all three years) that simulated snowmelt events. The DVD test data included timed measurement of the receding pool depth against a fixed elevation and soil depth moisture probe readings in years two and three throughout cross sections of the cell to record soil moisture changes during the drawdown of the surface pool to develop a three dimensional representation of the wetting front. Full site descriptions and study protocol are described in Chapters 2 and 3, respectively.

A summarized timeline of key events is provided below:

- During the first study season (2005-06) the test protocol, site selection and installation of the automated monitoring equipment was completed and some manual testing was completed. Due to freezing issues, use of the double-ring infiltrometer was discontinued.
- During the second study season (2006-07) automatic data collection occurred; however, extreme climatic conditions not reflective of desired melt conditions prevented most of the scheduled manual testing. The protocol to use soil depth profile moisture probe readings was developed and the moisture probe tubes were installed at the sites.
- During the third study season (2007-08) automatic data collection occurred, most of the manual testing was conducted, the data was analyzed and this report was completed.

Findings reported herein are meant to reach designers, scientists, regulators, and the general public for improved bioretention design, operation, and maintenance for optimized cold climate performance. A separate design guidance document will also accompany this report.

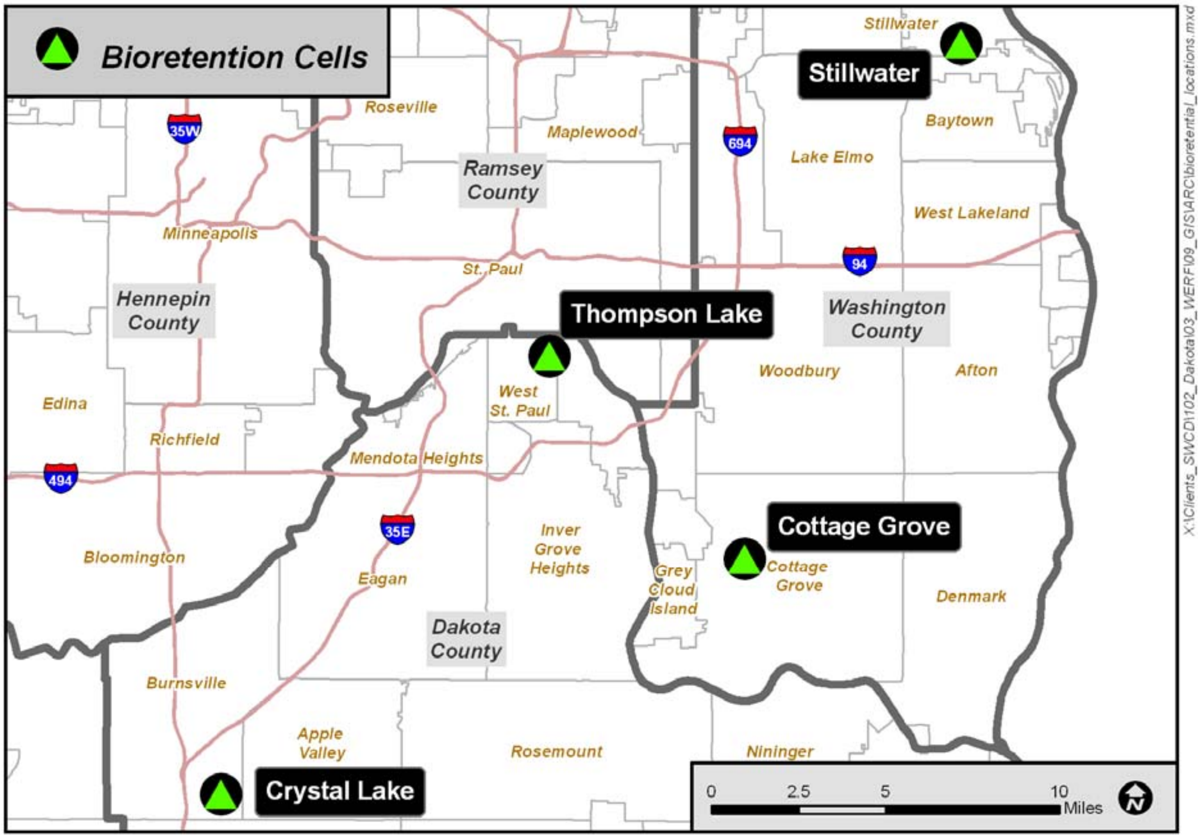

Figure 1-1. Location in the greater Twin Cities region of the four bioretention cells studied.

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CHAPTER 2.0

SITE DESCRIPTIONS

2.1. Introduction

Each of the four bioretention cells is located in the greater Twin Cities, MN, area (see Figure 1-1). The region's precipitation can be described by the 2- and 100-year 24-hour rainfall events which total 2.8 and 5.9 inches, respectfully. The 100-year snowmelt event is 7.2 inches over 10 days. For purposes of this study, cold climate areas are defined by low winter temperatures, length of growing season, and depth of snow (Caraco and Claytor, 1997). Existing bioretention cells were selected to provide a variety of designs and applications. The sites exhibit a wide spectrum of soil types, some in situ, some amended or engineered. Three sites were designed as bioinfiltration systems; one site was a biofiltration system with an under-drain. Vegetation varied at the sites and included herbaceous, woody, or a combination. Each received runoff from impervious pavement and some also receive runoff from adjacent lawns. Typically this study refers to the study sites as bioretention cells, although these systems could also be called other terms such as raingardens or rainwater basins. Table 2-1 summarizes the physical characteristics of each study site.

Table 2-1. 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 - Underdrain
Crystal Lake	2003	400	1.0	7,850	19.6:1	42%	Silt loam Sand & Gravel	50/50	Overtops to adjacent street
Thompson Lake	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	2002	380	1.0	1,700	4.5:1	100%	Sandy Loam Sand Sand & Gravel	100/0	Central overflow structure to storm sewer.
Stillwater	1999	670	0.17	21,780	32.5:1	70%	Organic Loam Clay Loam Loamy Sand	0/100	Central overflow structure to storm sewer.

2.2. Crystal Lake Bioretention Cell

Installed in 2003, the Crystal Lake bioretention cell (raingarden) is located in Burnsville, Minnesota. This site was selected to represent a small, infiltration system located in a residential setting. The 400 square foot (SF) cell is positioned within the boulevard area adjacent to a low traffic residential street and is surrounded on all sides with maintained turf grass. The plant matrix within the cell includes approximately equal coverage of herbaceous plants (feather reed grass, purple dome aster, daylily and Siberian iris), woody vegetation (arborvitae, nearly wild rose and Anthony Waterer spiraea) and about five percent cover of sedum. The vegetation appeared to be healthy and thriving during the growing seasons, although dormant during this study (Figure 2-1 and Figure 2-2).

Figure 2-1. Photo of the Crystal Lake bioretention cell during the growing season looking west.

Figure 2-2. Photo of the Crystal Lake bioretention cell during winter looking northeast.

The contributing drainage area is approximately 7,850 square feet (0.18 acres) of which 42% is impervious surface. The cell capacity accepts the first 0.9 inch of runoff depth from 3,275 square feet of impervious surface for a runoff treatment volume of 246 cubic feet within a surface pool approximately 0.6 feet deep. The most likely runoff pollutant constituents and sources are sediment, oils, trace metals, chlorides from the street, excess nutrients (phosphorous/nitrates), fecal bacteria, and herbicides from landscaped areas.

Runoff enters the cell through a curb-cut opening into a rounded bottom cell with gently sloping sides. The maximum pool depth is 1.0 feet. No subdrain exists and the system overflow point is back through the curb-cut opening. The system is an off-line design that bypasses high flows. Under extreme flows, the pool elevation equals the gutter elevation.

The cell was created by excavating into the in-situ soils approximately 2.5 feet, grading and shaping the side slopes, placing a lift of topsoil, and covering with wood mulch.

The field verified soil profile is:	0-1" - wood mulch
	1-12" - silt loam organic topsoil
	12- 30"+ - in situ, clean, well graded coarse sand & gravel
	Mottled soils were not observed

Warm weather field observations confirmed this site infiltrates very quickly and usually does not have extended pool residence times beyond 24 hours. Warm climate infiltration testing was conducted as part of another study (Asleson, 2007). Prior to residential development, the general area was used for gravel mining and underlying free draining coarse granular materials are common to the area.

As a related aside, this site is one of 17 raingardens retrofitted into an existing neighborhood with traditional curb and gutter drainage system. In 2006, the City of Burnsville completed a paired watershed study that compared reduced runoff volume characteristics of the retrofit watershed with the non-retrofit watershed. The study found that runoff from the retrofitted watershed was reduced between 89% and 92% (Barr Engineering Company, 2006).

2.3. Thompson Lake Bioretention Cell

Installed in 2003, the Thompson Lake bioretention cell (raingarden) is located in West St. Paul, Minnesota. This site was selected to represent a large, filtration system located in a public land use setting. The cell is positioned between a county park parking lot and a bituminous walking trail paralleling Thompson Lake. The 3,600 square foot cell is surrounded on three sides by bituminous surfaces; the fourth side is an upland native planting area. The plant matrix within the cell is a variety of herbaceous plants at about 75 percent cover (stiff goldenrod, Culver's root, New England aster, Monarda, yarrow, little bluestem and a variety of sedges) and woody plants at about 25% cover (including silky dogwood, red dogwood, and willow). The site originally had a wood mulch cover but little remains. The vegetation appeared to be healthy and thriving during the growing seasons, although dormant during this study (Figure 2-3, Figure 2-4 and Figure 2-5).

Figure 2-3. Photo of the Thompson Lake bioretention cell and curb-cuts during the growing season looking northwest.

Figure 2-4. Photo of the Thompson Lake bioretention cell during the growing season looking south.

Figure 2-5. Photo of the Thompson Lake bioretention cell during winter looking southwest.

The contributing drainage area is approximately 68,900 square feet (1.6 acres) of which 45% is impervious surface. The cell capacity accepts the first 0.5 inch of runoff depth from 30,900 square feet of impervious surface for a runoff treatment volume of 1,287 cubic feet within a surface pool approximately 0.36 feet deep. The most likely runoff pollutant constituents and sources are sediment, oils, trace metals, chlorides from the parking lot, excess nutrients (phosphorous/nitrates), fecal bacteria, and herbicides from landscaped areas.

Runoff enters the cell through two curb-cut openings near the north end of the cell. East to west, the cell is level and has gently sloping sides. However, along the north south axis, the bottom of the cell does slope slightly with the north end being 0.2 feet lower in elevation than the south end. To distribute flows across a broader area, a third curb-cut was added after the first study season. Of the 3,600 square foot cell, only the northern 1,300 square feet was monitored since the test pool rarely extended into the higher southern portion of the cell. During testing, the northern area proved to encompass the extent of the inflow, dispersion, and drawdown. This alters the “effective” drainage area-to-surface area ratio for the study from 19:1 to 53:1.

The maximum pool depth is 0.93 feet. The system has subdrains located both north and south with below-grade connections to a concrete storm sewer pipe (Figure 2-6). Although not shown in the photo, a similar subdrain was installed on the north side of the storm sewer pipe. The system overflow point is a 6-inch diameter PVC standpipe also connected to the storm sewer pipe. The system is a modified on-line design that allows flows to enter the cell and overflow into the standpipe outlet. Under extreme flows, the pool will back up and enter the catch basin located between the curb-cuts and flow directly west to the lake.

Historically the general area was a fringe wetland cove connected to the lake. Sometime in the late 1950’s the area was filled with compacted clay materials to facilitate the construction of the parking lot. Due to the very low permeability characteristics of the fill material used, the Thompson Lake site was designed to be a retrofit biofiltration system that relied on the biological and chemical processes occurring within imported engineered soils to provide water quality treatment and subdrain system to pass drainage through the system and discharge into the lake. The cell was created by over-excavating approximately three feet of clay fill and replacing with coarse wash sand without fines, grading and shaping of the side slopes to create a confining berm along the west edge, placing a lift of leaf litter compost (no topsoil) and covering with wood mulch.

The field verified soil profile is:	Traces of wood mulch 0-5" - compost 5-21" - imported coarse washed sand 21"+ - in situ compacted clay fill Extensive mottled soils were observed in the clay layer

Warm weather field observations confirmed that this site filters very quickly and usually does not have extended pool residence times beyond 24 hours. Warm climate infiltration testing was conducted as part of another study (Asleson, 2007).

Figure 2-6. Photo (looking south) of the construction of the Thompson Lake bioretention cell under-drain installation above clay soils within the amended soil layer and connected to existing storm sewer.

2.4. Cottage Grove Bioretention Cell

Installed in 2002, the Cottage Grove bioretention cell (raingarden) is located in Cottage Grove, Minnesota. This site was selected to represent a small, infiltration system located in a commercial (transit) setting. The cell is located within a depressed parking lot island of a large mass-transit Park and Ride facility. The 380 square foot cell is surrounded on all sides by bituminous surfaces. The plant matrix within the cell is a variety of herbaceous plants (Little bluestem, Indian grass, Gold flame spirea, feather reed grass, black-eyed susan). The vegetation appeared to be healthy and thriving during the growing seasons; it was dormant during this study. Young ash trees (as shown in Figure 2-7) were present only at the beginning of the study and were removed some point in 2006 (Figure 2-7 and Figure 2-8).

Figure 2-7. Photo of the Cottage Grove bioretention cell during the growing season looking north (trees were removed early-on during the first winter testing season).

Figure 2-8. Photo of the Cottage Grove bioretention cell during winter looking northwest.

The contributing drainage area is approximately 1,700 square feet (0.04 acres) of which 100% is impervious surface. The cell capacity accepts the first 2.4 inches of runoff depth from 1,700 square feet of impervious surface for a runoff treatment volume of 340 cubic feet within a surface pool approximately 0.89 feet deep. The most likely runoff pollutant constituents and sources are sediment, oils, trace metals, and chlorides from the parking lot runoff.

Runoff enters the cell through depressed concrete ribbon curbs at its perimeter. The bottom of the cell is slightly rounded with gently sloping sides. The maximum designed pool depth is approximately 1.0 feet. No subdrain exists and the system overflow point is the elevation on the catch basin rim. However, due to some leakage through cracks located lower on the rim structure, small outflow began when the actual pool depth was approximately 0.5 to 0.75

feet. The system is an on-line design that allows high flows to cross the cell and enter the catch basin.

The cell was created as part of the new construction of the Park and Ride facility. The underlying soils are predominantly sand with some sandy loam at the surface that transitions within 12 inches to medium-grained sand, and sand and gravel (probably fill from the adjacent parking lot). This bioretention cell does not have a mulch top layer.

The field verified soil profile is: 0-12" - sandy loam
2-30" - sand
30"+ - sand & gravels

Warm weather field observations confirmed that this site infiltrates very quickly and usually does not have extended pool residence times beyond 24 hours. Warm climate infiltration testing was conducted as part of another study (Asleson, 2007).

2.5. Stillwater Bioretention Cell

Installed in 1999, the Stillwater bioretention cell (raingarden) is located in Stillwater, Minnesota. This site was selected to represent a small, infiltration system located in a commercial setting. The cell is located within a landscaping area adjacent to a commercial business parking lot. The 670 square foot cell is surrounded on all sides by maintained turf grasses. The plant matrix within the cell is a variety of woody shrubs (yellow twig dogwood, redosier dogwood and black chokeberry). The vegetation appeared to be healthy and thriving during the growing seasons, although dormant during this study (Figure 2-9 and Figure 2-10).

Figure 2-9. Photo of the Stillwater bioretention cell during the growing season looking northeast.

Figure 2-10. Photo of the Stillwater bioretention cell during winter looking northwest.

The contributing drainage area is approximately 21,780 square feet (0.50 acre) of which approximately 70% is impervious surface. Design information for cell sizing was not available for this site. An estimate of its as-built runoff treatment volume capacity of 114 cubic feet was made by multiplying its pool depth of 0.17 feet times its surface area of 670 square feet. Dividing the estimated capacity by its tributary impervious surface of 15,246 square feet indicated the cell would begin to overflow into its outlet standpipe after the first 0.09 inch of runoff depth. The most likely runoff pollutant constituents and sources are sediment, oils, trace metals, chlorides from the parking lot, excess nutrients (phosphorous/nitrates), and herbicides from landscaped areas.

Runoff enters the cell through a curb-cut opening into a rounded bottom cell with gently sloping sides. The maximum pool depth is 0.17 feet. No subdrain exists and the system overflow point is through a 6 inch diameter PVC standpipe connected to the site storm sewer system. Note that an attempt was made in year two of the study to seal this outlet connection and raise the pool depth, but the seal was not totally effective, so some seepage out continued. The system is an on-line design that allows high flows to cross the cell and enter the standpipe outlet.

The cell was created by excavating into the in-situ soils and grading and shaping the side slopes. Imported engineered soils were not used.

The field verified soil profile is: 0-2" - organic loam
2-6" - clay loam
6"+ - loamy sand

Warm weather field observations confirmed this site infiltrates very slowly, and usually has extended pool residence times well beyond 24 hours. The soils within the cell were compacted and it was noted the bottom of the cell was layered in wet leaf litter from the woody vegetation. Additional dual ring infiltrometer tests with litter removed also resulted in very slow infiltration rates indicating the leaf litter was not the likely cause. Due to standing water, warm climate infiltration testing could not be conducted as part of another study (Asleson, 2007).

Note that the presence of the standpipe outlet was not known during the March 22, 2006 Direct Volume Discharge (DVD) test. The observed infiltration rate of 6.1 inches/hour recorded was later deemed erroneous due to flows entering the standpipe during the test and should be disregarded. During subsequent DVD tests, attempts were made to close off the overflow standpipe to prevent artificial drawdown; however, the seal on the pipe inlet was not tight and some leakage was observed.

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CHAPTER 3.0

DATA COLLECTION AND PROCESSING

3.1. 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. The methods and type of data collected are described in this chapter.

3.2. Data Collection Protocol and Instrumentation

A variety of data were collected at each bioretention site to comprehensively monitor site conditions and hydrologic performance during three winter seasons of testing.

- Automated year round data: Campbell Scientific data loggers recorded continuous data on soil temperature, air temperature and soil water content as shown in Table 3-1.
- Seasonal bi-weekly data: Frost depth and snow depth were measured manually. Double-ring infiltrometers testing was conducted during the first season only and discontinued due to freezing.
- Seasonal bi-weekly data: Direct volume discharge (DVD) tests (discussed below) were used to identify the hydrologic performance of each bioretention facility during the testing season. An AquaPro soil moisture probe was used during DVD tests in years two and three to test soil moisture movement throughout the soil profile. During DVD tests, infiltration rates and inflow rates were manually measured as the surface pool receded.

Table 3-1. Data collected and measurement instrumentation at each bioretention cell site.

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 0 m, 0.5 m, and 1.0 m 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	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-8); 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.

3.2.1. Direct Volume Discharge (DVD) Tests

Hydrologic performance testing was conducted with 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. The test protocol required the test to be conducted when air temperatures were between 20 and 40°F and when climatic condition appeared capable of producing a snowmelt event. Since testing with a known volume of water was critical to measurements, care was taken to avoid run-on flows during the DVD tests. In terms of creating a simulated snowmelt event, the DVD test performed well during the study and the results were deemed to be a realistic reflection of the hydrologic performance occurring at the time of the test.

Tests were run provided there was not a deep pool of standing water in the cell (in which case the test was cancelled for that day); no special provisions were made for antecedent site conditions. The DVD tests were conducted with the site conditions that were found to exist on the day of the test without bias.

Before each test, two sets of soil moisture measurements were taken prior to water input to capture the antecedent soil moisture conditions. Site conditions were also recorded prior to testing (e.g. snow cover, frost depth, test water temperature), and Campbell Scientific data loggers were downloaded

To conduct the DVD test, the start time was recorded and a known volume of approximately 200 to 6,000 gallons of test water (well water in most cases, sometimes lake water) was pumped or poured quickly into the study cell to create a pool depth across the bottom.

As measured against a fixed object, timed measurements of the receding pool depth were recorded to establish the observed infiltration rate. Concurrent with the receding pool, repeated soil profile moisture measurements were taken via a grid of access tubes that laterally and longitudinally transected the site. The moisture readings at each tube were taken in 6-inch increments to approximately 36 inches of depth to track the wetting front moving through the soil profile during the DVD test. 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. Longer duration tests to establish the hydraulic conductivity curve of the soils were beyond the scope of the study.

The soil moisture probe (AquaPro) instantaneously calculated and recorded the soil moisture content via low frequency radio waves in the soil through one meter long polypropylene access tubes. The soil moisture probe provided valuable data to record the changes in soil moisture before, during and after the DVD tests. In addition, soil moisture readings were taken between DVD tests as well.

As part of calibrating the probes for use in the study, it was determined the probe readings differed when measuring soil in frozen versus unfrozen conditions. Therefore, soil moisture probe readings were not used to record long term soil moisture contents, but rather only used to track the relative change in moisture conditions during a period of time limited to a specific DVD test. Also, the harsh winter conditions challenged the durability of the moisture probes. The probes used in the study were replaced several times due to cracking.

While the effects of road salts on cold climate bioretention cells is was beyond the scope of the study, concentrations of chloride (Cl) from 99 to 1,184 mg/L were added to the test water in the form of NaCl for select DVD tests. This concentration range is typical of Cl runoff during runoff events in the Twin Cities region. At the Cl concentration used, the study was not able to observe a behavioral difference in the recorded observed infiltration rates.

3.2.2. Observed Infiltration Rate and Calculated Inflow Rate

For purposes of this study, two distinct types of measurements are used to quantify the movement of water into and through the soil profile: *observed infiltration rate* and *calculated inflow rate*. In context of this study, each term has been given a specific meaning.

Observed Infiltration Rate

This study uses the term *observed infiltration rate* to describe the actual measured distance (in inches per hour) that a pool of test water covering a cell bottom has receded after the cessation of test water being added during a DVD test. It was measured by observing water drawdown from a fixed reference mark versus time since the end of water addition. In this fashion, it should be considered as part of the initial wetting stage rather than long-term or sustained infiltration. As used in this study, the observed infiltration rate accounts for the combined influences of surface hydraulic loading rate, filling of the interstitial area and the transmission rate occurring simultaneously across the test pool area. The observed infiltration rate of any given DVD test is affected temporally by site characteristics and site conditions antecedent to the time of the test (e.g., wet or dry, cold or warm). By flooding the cell bottom, the observed infiltration rate is an indicator of overall cell performance that is inclusive of the highly variable rates located spatially throughout the cell as evidenced by Asleson (2007) at three of the four WERF study sites.

In some cases, the observed infiltration rates were surprisingly fast. The high rates were considered to be reflective of the unsustainable speed at which a wetting front is moving through unsaturated soils. The use of observed infiltration rate in this report is site and DVD test day specific.

Most importantly, an *observed infiltration rate*, as used in this study, is not equivalent to, nor should it be or be converted into a *design infiltration rate* commonly used to size infiltration systems. Design infiltration rates are used to predict a sustainable rate of flow based factors such as the least permeable soil layer within five vertical feet of the bottom of an infiltration area. Design infiltration rates are intentionally conservative due to variable (and sometimes unknown) soil conditions and the need for sustainable performance throughout the lifetime of the bioretention facility. The *Minnesota Stormwater Manual* (Chapter 8, page 195) provides guidance for design infiltration rates (MN Stormwater Steering Committee, 2007).

Calculated Inflow Rate

This study uses the term *calculated inflow rate* to describe the rate (in gallons per minute) in 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. The calculated inflow rate is an indicator of overall cell performance. On some occasions the duration of the DVD tests were extended beyond the one hour range to observe water movement to zero depth. On other occasions, it became obvious that zero depth would not be achieved within a reasonable timeframe and the *calculated inflow rate* could not be determined. The use of the calculated inflow rate in this report is site and DVD test day specific.

To consider hydrologic performance in terms of permeability, *calculated inflow rate* can be divided by the cell area. Dimensional units of gallon per minute per square foot are a useful way to consider relative differences in hydrologic performance to permit comparisons between DVD tests and other bioretention systems.

3.3. Data Collected by Season

Each winter field season lead to better testing practices. Table 3-1 listed a breakdown of the data that were collected during each of three winter field seasons. The field season generally started in October and continued into April. The climate dictated exactly when each DVD testing season would begin and end. Overall, 33 DVD tests were conducted; ten DVD tests were conducted at the Crystal Lake site, eight at Thompson Lake, seven at Cottage Grove and eight at Stillwater. Note that the March 22, 2006 DVD was deemed to be erroneous.

During Season 1 (winter 2005-06), only one DVD test (in March) was conducted per site since the focus this year was on monitoring equipment installation and testing via a series of double-ring infiltrometers (see next section). Due to problems with freezing and, at times preferential thawing as described below, double-ring infiltrometer testing was not conducted beyond Season 1.

During Season 2 (winter 2006-07) unusually warm weather delayed the beginning of DVD testing until January. Unusually cold weather then halted DVD testing until near the end of February. However, the soil moisture tubes were installed and measurements were taken on a bi-weekly basis and during most DVD tests.

During Season 3 (winter 2007-08), the greatest number of DVD tests were performed. Seven tests were performed at Crystal Lake, six at Thompson, four at Cottage Grove and five at Stillwater. Season 3 also included a supplemental DVD test at one of the bioretention cells located at the Ramsey-Washington Metro Watershed District (RWMWD) office. The RWMWD cell was newly established and was selected to compare to the findings from the four WERF test cells.

Table 3-2. DVD test dates for each bioretention cell site.

Site	Season	DVD Test Dates
Crystal Lake	1	3/6/2006*
	2	1/2/2007
		2/27/2007
	3	12/13/2007
		12/18/2007
		1/8/2008
		2/5/2008
		3/4/2008
		3/18/2008
		4/1/2008
Thompson	1	3/21/2006*
	2	1/4/2007*
	3	12/18/07
		1/8/2008
		2/5/2008
		3/4/2008
		3/18/2008
		4/1/2008
Cottage Grove	1	3/22/2006*
	2	2/22/2007*
		3/22/2007
	3	12/20/2007
		1/8/2008
		2/22/2008
		3/19/2008
Stillwater	1	3/22/2006*°
	2	2/21/2007
		3/22/2007
	3	10/10/2007$^{\Delta}$
		12/20/2007
		1/8/2008
		2/22/2008
		3/19/2008
Ramsey-Washington Metro Watershed District	3	2/5/08*

*No corresponding soil moisture measurements.
$^{\Delta}$ Climate was not representative of snowmelt conditions.
° Overflow through unplugged outlet (2-inches above cell bottom) during testing; plugged for all other Stillwater tests.

3.4. Lessons Learned from Early (Discontinued) Double-Ring Infiltrometer Tests

The hand- made double-ring infiltrometers where designed to determine cold weather infiltration rates. Two 10-inch double-ring infiltrometers were installed at each site at the beginning of the study; one in a central location at the bottom of the cell and the other located as a satellite as far from the center infiltrometer as possible while still remaining in the bottom of the cell. The intent was to use double-ring testing to determine infiltration rates. During the first winter season, tests were conducted bi-weekly using 25 to 35 gallons of test water when air temperatures were between 20 and 40º F. As with the DVD tests, the infiltrometers were utilized to indicate infiltration during the initial wetting stage with no pre-wetting. It became apparent after the first season of study that the double-ring infiltrometer was not providing reliable results due to ice buildup inside of the rings not typical of the rest of the cell. Figure 3-1 illustrates an extreme example of the problem with freezing. Additionally, preferential thawing from heat reflected off the infiltrometer occurred at times, with flow sometimes infiltrating downward through locally thawed pathways (see Figure 3-2). The use of double-ring infiltrometer testing was discontinued after Season 1 at all sites.

Figure 3-1. Photo of freezing associated with double-ring infiltrometer testing preventing use for study.

Figure 3-2. Photo of preferential thawing and flow around metal double-ring infiltrometers.

3.5. Data Processing Tools

After data were downloaded from automated data loggers, field observations were collected and then both were analyzed using Microsoft Excel and STATISTICA software packages (StatSoft, Inc., 2008). STATISTICA was used for interpretation of soil moisture data varying both temporally and spatially throughout DVD tests. STATISTICA also provided interpolation of soil moisture data between monitoring points within the soil profile. Soil moisture graphics per time generated from STATISTICA appear in Chapter 4 and Appendix A.

CHAPTER 4.0

RESULTS AND DISCUSSION

4.1. Introduction

Data from the four study and one supplemental bioretention sites have provided substantial insight into the mechanisms and driving forces of cold climate hydrologic performance. A data table for each DVD test (grouped by site) is presented in this chapter as results from each site are discussed. Data include field notes, antecedent conditions (e.g. soil moisture, air temperature, snow cover), test conditions (DVD volume, chloride concentration if added, soil moisture changes) and observed infiltration rates. In addition, each bioretention cell has a corresponding figure illustrating surface pool drawdown of each DVD test and a corresponding table identifying correlations (R-squared values) between infiltration rates and antecedent site characteristics.

All soil moisture profiles from DVD tests are available in Appendix A. However, trends and representative findings are discussed and illustrated here. Soil moisture profiles from each test include a set of soil moisture readings collected at particular times as water infiltrated. At least one soil moisture profile represents the initial conditions and is labeled accordingly. The point that water began contributing to a bioretention facility is referenced as 0 hours throughout all graphs and discussion. The method of distance-weight least squares with a low stiffness factor of 0.1 was used to interpolate soil moistures throughout the soil profile. Soil moisture profiles are grouped by study site, test date and monitoring-tube transect.

An individual soil moisture profile taken from the set of profiles from the February 2, 2007, DVD test at the Crystal Lake bioretention cell is shown in Figure 4-1. This figure is provided to illustrate how the bioretention cell profile corresponds to the data; the soil profile is also identified in this case. Black points represent raw data points, each of which represents only one soil moisture reading. Data interpolation beyond the extent illustrated in Figure 4-1 is less helpful and is without enough raw data for accurate interpolation.

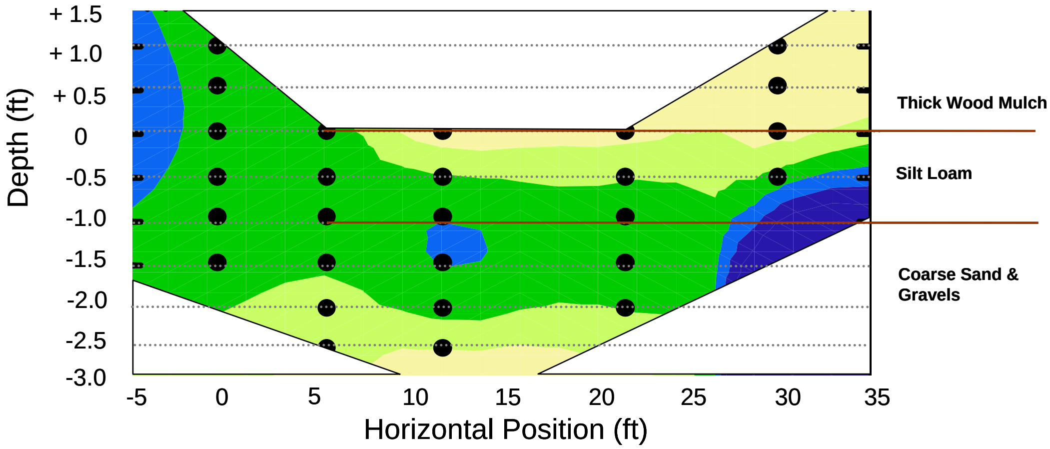

Figure 4-1. Physical representation of soil moisture profile data as it relates to bioretention cell shape and indicating acceptable extents of data interpolation; colorations represent varying ranges of percent soil moisture; the corresponding soil profile is provided on the right-hand side.

Three types of frost in soils have been identified and are frequently referenced in cold climate studies (Muthanna, 2007). *Concrete* frost occurs when a saturated soil freezes and creates an ice lens where little water movement is possible. 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. By contrast, *granular* 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 are below the freezing point and the movement of water is observed to have greatly slowed or stopped; it is presumed that concrete frost conditions have likely developed. If soil temperatures are below the freezing point and the movement of water is observed to continue into the soil profiles; it is presumed that granular frost conditions have likely developed. The study does not distinguish between the terms granular and porous frost.

4.2. Crystal Lake Bioretention Cell

4.2.1. Introduction

Ten DVD tests were conducted at the Crystal Lake site over the three-year study period. For every DVD test at the Crystal Lake site, 425 gallons of test water was applied. The addition of 425 gallons of water at Crystal Lake represents about 0.08 inches over the entire 7,850 SF drainage area or about 0.22 inches from the impervious fraction. A hydrologic analysis performed with HydroCAD® software (HydroCAD Software Solutions LLC, 2006) found that this is approximately 15% of a 1-year, 24-hour rainfall event when the entire drainage area is contributing. Although this is a limited amount of added water dictated by transport capability, it does reflect a typical melt volume seen during winter and early spring events.

As noted in Chapter 3, *observed infiltration rates* were not recorded until the DVD tank was completely emptied (taking anywhere from 20 to 30 minutes). Water could have infiltrated quickly at the onset and not be counted in the observed infiltration rate. The use of the *calculated inflow rate* in Table 4-1 is an attempt to differentiate between two methods. That is, the *observed* *infiltration rate* represents the rate (in inches per hour) of water moving into the soil after cessation of the test water application; the *calculated inflow rate* represents the total gallons per minute of water absorbed by the system from the initiation of test water application. The latter accounts for all the water applied, whereas the former accounts for only the water that infiltrates during the study period. Table 4-1 indicates the antecedent conditions and lists the observed infiltration and calculated inflow rates for 10 DVD tests.

Table 4-1. Site conditions and infiltration rates for DVD tests at the Crystal Lake bioretention cell.

DVD Test Date (season number)	Observed Infiltration Rate (in/hr)	Calculated Inflow Rate (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth [Δ] (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in test water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/6/2006* (1)	5.9	9.9	31.5	32.7	34.9	16.9	17.8	0.5	35.5	50.5	1.2	0	425	
1/2/2007 (2)	18	53	37.1	36.3	38.1	28.3	20.8	0	38.4	47.2	3	0	425	
2/27/2007 (2)	0.15	N/A**	31.3	31.7	33.4	11.1	8.7	1	29.5	41.4	13.2	0	425^	
12/13/2007 (3)	10.2	14.5	N/A	N/A	N/A	N/A	N/A	0	N/A	56	9	0	425	
12/18/2007 (3)	18.9	17	31.3	38.7	41.9	22.7	17.4	0.5	24.1	50	9.6	127	425	1/2-in frozen layer near double-ring infiltrometer but thawed underneath; also thawed where snow is uncompacted.
1/8/2008 (3)	15.3	13.7	33.2	37.1	40.1	23.2	17.1	0	37.3	47	10.8	1,184	425	Currently calm and foggy; snow areas frozen where compacted based on excavation; not frozen where uncompacted.
2/5/2008 (3)	13.6	11.5	29.9	33.2	36.4	8.9	8.4	0.5	27.7	41.2	12	592	425	1 - 2 inches of snow yesterday; frozen soils throughout basin based on excavation.
3/4/2008 (3)	7.2	7.0	30.8	33.2	35.8	10.1	11.1	0.5	27.5	40.8	18	592	425	Dry; ground frozen based on excavation.
3/18/2008 (3)	4.2	N/A**	32.4	32.4	33.3	11.4	12.3	0	34.1	46.7	33	592	425	3 inches of snow last night; 2 inches standing water cell; cell still semi-frozen following DVD test, possible surface frost.
4/1/2008 (3)	3.7	N/A**	46.6	33.2	33.6	29.3	21.2	0.5	43.6	38.5	6.6	254	425	6 inches of snow last night; half thawed-half frozen basin bottom based on excavation; some water standing in bottom of garden upon arrival; surface frost.

* No soil moisture data.

[Δ] Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

** Not able to be determined because of standing water at end of test period.

4.2.2. Infiltration Rates

Figure 4-2 illustrates receding pool depths over the course of each DVD test at the Crystal Lake 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. 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) infiltration curves tend to flatten out, reaching an apparent maximum capacity. The infiltration rate range on this site was 0.15 in/hr to 18.9 in/hr and the equivalent flow range was 4.5 gpm to 53 gpm. In general, the Crystal Lake cell maintained its hydrologic function throughout the three winter field seasons.

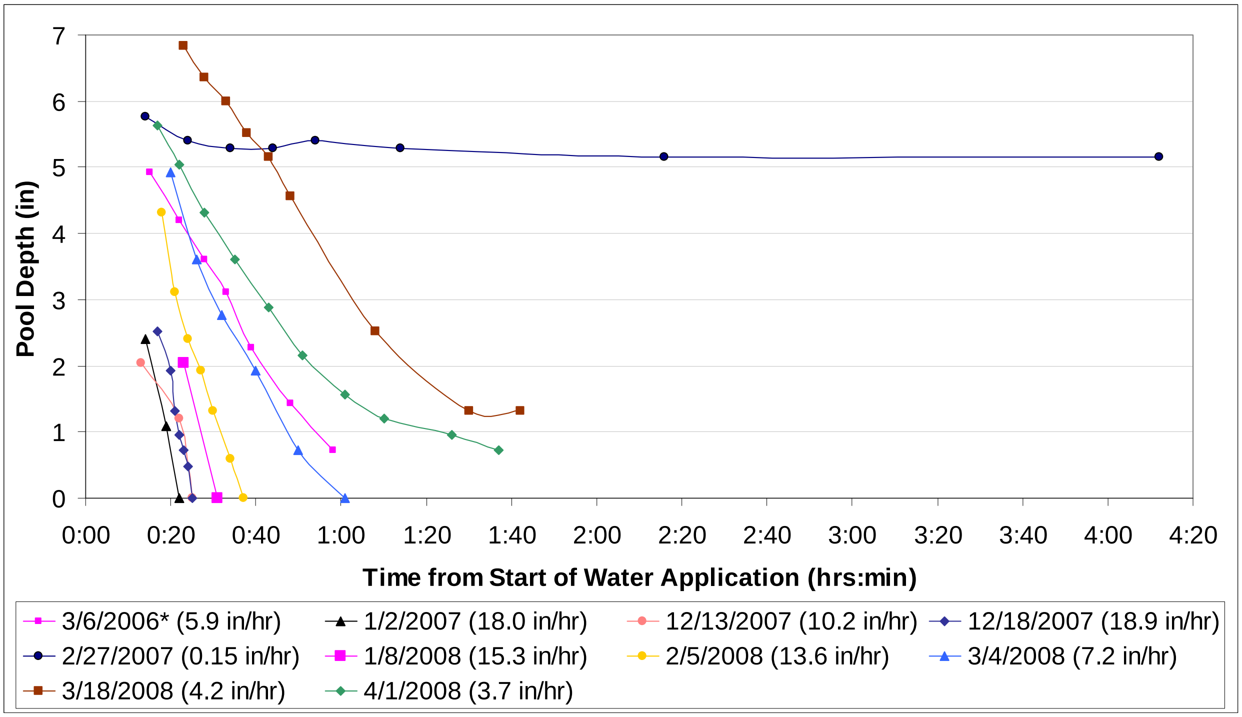

Figure 4-2. Drawdown and infiltration rates of DVD tests at the Crystal Lake bioretention cell.

The February 27, 2007, DVD test (long flat infiltration curve) stands apart from all other DVD tests at this site. The February 27, 2007, test had the deepest frost penetration (to 1 m) of all tests (Table 4-1 and Figure 4-3), and the cell experienced freezing of saturated soils. Figure 4-4 illustrates some of the antecedent conditions over time within the winter 2006-2007 testing season (note that figures of this type have been generated for reference for all testing seasons and can be found in Appendix B). In Figure 4-4, the 18% soil water content (12-inch depth) observed just prior to severe freezing temperatures (around January 30, 2007) was likely enough moisture to create a concrete frost. Field observations from the February 2007 event confirm refusal due to frost when attempting excavation. The February 2007 DVD test may have been the only event tested under concrete frost conditions, whereas the frost experienced during other DVD tests may have been more of the granular type based on field observations, soil temperature and soil moisture recordings (Table 4-1).

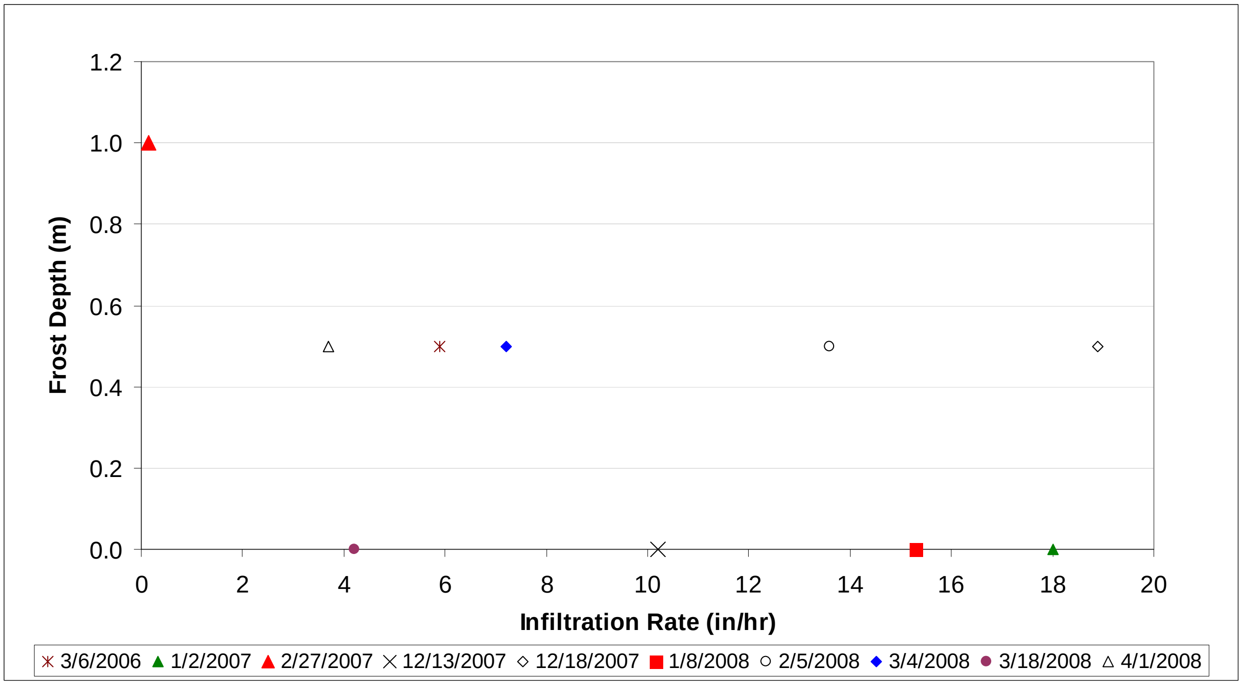

Figure 4-3. Effects of frost depth on infiltration rates at the Crystal Lake bioretention cell.

In Table 4-1, field notes from four events (12/18/07, 1/8/08, 3/18/08 and 4/1/08) identify partially frozen, partially thawed soils. Some of these dates are reported with a frost depth of zero which brings attention to the fact that frost depth was determined based on frost tubes (when functional) and cross-checked against soil temperature readings and field notes. In the case where soil temperatures were above freezing, frost depth is reported as zero. However, in some of these cases, field notes from onsite excavation support the presence of partially-frozen, partially-thawed soils. These four events are clear instances where more of a granular or porous frost is present. Two of these tests, the December 2007 and January 2008 DVD tests exhibited the highest infiltration rates of all the Crystal Lake DVD tests. The other two tests (March and April 2008) exhibited standing water in the cell prior to DVD testing. Antecedent soil moisture presumably reduced their infiltration rates.

The trend in infiltration curves in Figure 4-2 defined by steeper slopes (faster infiltration) during pre-March DVD tests and shallower slopes (slower infiltration) during March/April DVD tests may be a function of time of year and 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. This time of year marks a point where soil moisture begins to rise steadily as soil thaws and the season changes to spring. Antecedent moisture under warm conditions may be cause for a relatively low infiltration rate in the absence of frost. For the March 2008 DVD tests, though water content at 6- and 12-inch depths was not notably higher, there was certainly saturation in the uppermost soil layer (2 inches of standing water prior to the DVD test). However, note that infiltration does occur (see Figure 4-2), though water does not completely recede within the 1.5 hours of testing.

Two studies by Stenmark (1992 & 1995) concluded that there exists only a small risk of total ice blockage for air temperatures as low as 5 deg F during the snowmelt period. Though air temperatures throughout the three seasons of testing did drop below 5 deg F, average daily highs preceding DVD tests were significantly higher (see Table 4-1), reflective of the study objective to test synthetic melt events. Given that only one of 10 DVD tests at this site resulted in what might be called total ice blockage, the Crystal Lake site did exhibit a low risk of total ice blockage and was deemed to perform very well for treatment of snowmelt events.

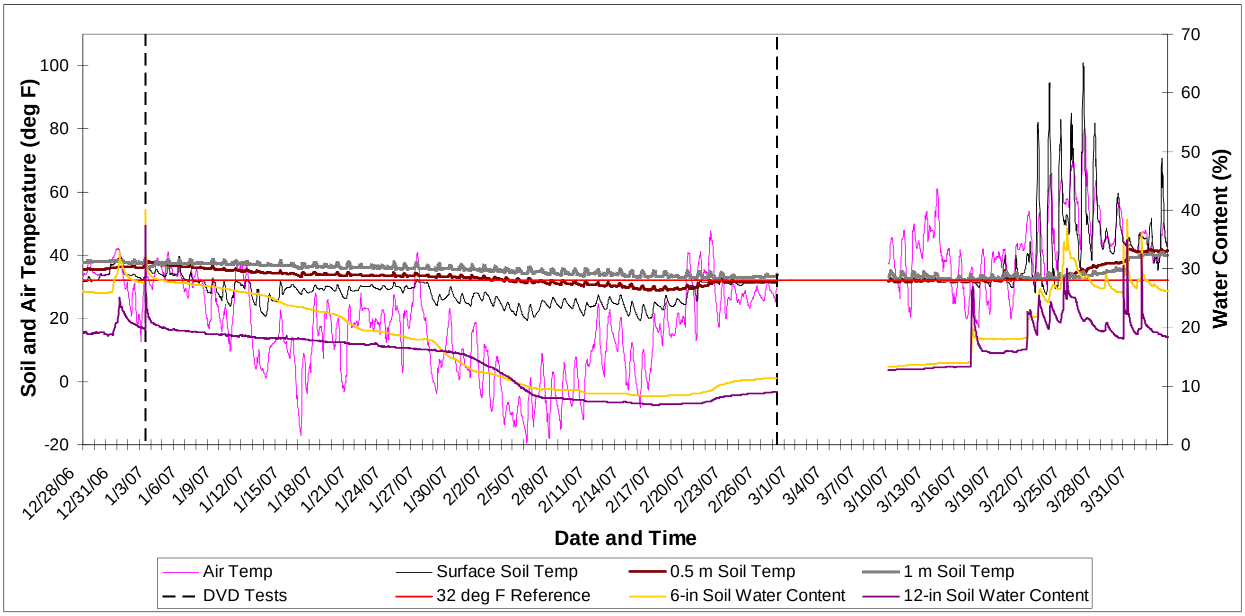

Figure 4-4. Antecedent soil water content and soil and air temperatures during Season 2 (Winter 2006-2007) at the Crystal Lake bioretention cell (see Appendix A for other years and study sites; dashed vertical lines represent DVD tests).

Figure 4-3 and field notes from Table 4-1 illustrate that, the mere presence of frost does not dictate hydrologic performance. In the presence of, presumably, concrete frost for the February 2007 DVD test, the infiltration rate was poor. However, all other DVD tests indicate a wide variation of infiltration rate in the presence and absence of frost. In fact, the Crystal Lake bioretention cell exhibited some very high infiltration rates and overall, performed the best of the four bioretention cells even with frost often around the 0.5-m depth.

There are two cases where the infiltration rate was particularly high in the presence of frost as exhibited in Figure 4-3 (12/18/07 and 2/5/08 at 18.9 in/hr and 13.6 in/hr, respectively). The frost depth was in the top 0.5-m of the soil. As was determined for the December 2007 DVD test, frost for the February 2008 DVD test may also have been a granular or porous frost. By definition, granular frosts can have higher infiltration rates than unfrozen soils due to preferential flow paths. Preferential flow paths may be created, for example, by burrowing mice, worms or decaying plant roots or by fractures in the frost. In fact, bubbling of the infiltrating water in the cell was witnessed at the site even in the presence of ice (Table 4-1). This bubbling was also witnessed at Thompson Lake where the photo in Figure 4-5 was taken. Preferential flow paths were also witnessed during a simulated snowmelt study in two plots in a heterogeneous coarse sandy unsaturated zone in Norway (French et al., 2002). Soils at the Crystal Lake site are coarse sand and gravel in the 1- to 3-ft range. When vertical preferential flow paths are established by mice, decaying plant roots or other biological components, it is sometimes referred to as biological permeability. This explains some of the permeability available during cold weather seasons.

Figure 4-5. Photo of air escape from a mouse hole (biological permeability) during a DVD test with frost present.

A change in the stability of thermal temperatures during the winter to the instability at the beginning of the snowmelt period (Figure 4-4) is characteristic of cold climates (French et al., 2002). Near-surface soil temperatures tend to peak daily on a larger scale as spring approaches (mid-March during Season 2) and, likewise, soil water content begins to rise.

Soil water content spikes occur from simulated snowmelt events only where high infiltration rates were observed, and soil moisture does not return to pre-event conditions until 1 to 3 days later. Soil water content from DVD tests where the worst infiltration rates were observed (from DVD tests on 3/4/08, 3/18/08 and 4/1/08) experienced little to no soil water content peak. These events correspond to the DVD soil moisture readings (to be discussed) that show little to no change in soil moisture throughout the test.

Table 4-2 illustrates the correlations (R-squared values) between infiltration rates and various site characteristics at the time of, or prior to, the DVD test. These correlations are expected to aid in defining bioretention characteristics that drive cold climate hydrologic performance. However, the only notable correlation to infiltration rates of the Crystal Lake bioretention cell is soil temperature at the 0.5-m and 1-m depths. As soil temperature increases, infiltration rate increases. The surface soil temperature does not correlate with infiltration rates. This may be explained by the sensitivity of the surface soil temperature to highly variable air temperature including, but not limited to, diurnal patterns and changing daily high and low temperatures. Not surprisingly, the greater the depth of frost, the lower the infiltration rate (Table 4-2) although, as discussed above, Figure 4-3 illustrates that it is the one instance of concrete frost that drives this otherwise nonexistent trend. Again, the type of frost seems to be more important than the mere presence of frost.

Table 4-2. Correlations (R-squared values) between infiltration rates and various site characteristics at the Crystal Lake bioretention cell.

Site Characteristic		Crystal Lake R^2-value
Soil Temperature (Avg 3-d Daily High)	Surface	0.02 (-)
	0.5 m	0.79 (+)
	1 m	0.84 (+)
Frost Depth		0.22 (-)
Test Water Temperature		0.14 (+)
Snow Cover		0.11 (-)
Soil Water Content (3-d Average)	6-inch	0.17 (+)
	12-inch	0.12 (+)
Chloride Concentration		0.03 (+)
Air Temp (Avg 3-d Daily High)		0.04 (-)

No site characteristics apart from 0.5-m and 1-m deep soil temperatures correlate to infiltration rates at the Crystal Lake site. However, each site characteristic will be discussed in terms of what correlations might be expected with a larger data set. In regard to test water temperature, there may not have been enough variability in test water temperature in order for trends to become apparent. If actual snowmelt temperatures do not exhibit great variability, it is not likely to be a driving factor in bioretention performance. Alternatively, a weak positive correlation has been found by Xiuqing and Flerchinger (2001) who used test water in the range of 39 to 48 deg F which was generally comparable to that of these WERF tests. Xiuqing and Flerchinger (2001) found that after 80 to 90 minutes of testing with 48 deg F water, infiltration rates in frozen bioretention soils exhibiting granular frost approached those of thawed soils.

Infiltration rates did not correlate with air temperature (Figure 4-2). However, Muthanna et al. (2008) found that increased air temperatures did result in increased infiltration rates. Certainly air temperature drives soil temperature which ultimately contributes to the presence of frozen soil. The 3-day average daily high prior to the DVD test was used in this analysis. A more extensive analysis of antecedent air temperatures might capture the anticipated correlation. For example, examining the length of time temperatures below freezing are sustained in the three days prior to testing.

It is intuitive that snow cover would provide insulation from the cold and, therefore, prevent frost. However, as with air temperature, more important than absolute snow depth at the time of snowmelt is the length of time certain depths of snow are maintained. During certain tests (e.g. January 8, 2008) excavation at the field site identified preferentially thawed soils where undisturbed snow cover was present (Table 4-1). Where snow was compacted, for example, from foot traffic, soils were often frozen.

4.2.3. Soil Moisture Profiles

Soil moisture profiles graphed from the soil moisture probe data from DVD tests also contribute understanding to bioretention system function in cold climates. All of the test probe results are shown in Appendix A. Soil moisture probe transect locations are shown in Figure 4-6.

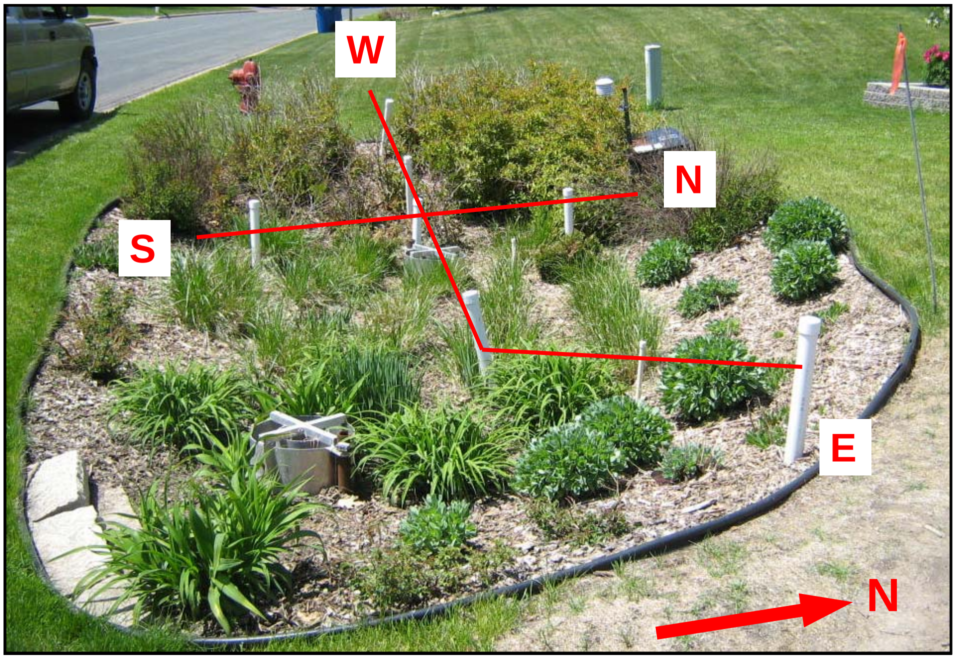

Figure 4-6. Soil moisture probe transects for the Crystal Lake bioretention cell.

The January 2, 2007, DVD test is illustrated in Figure 4-7 for the transect running south to north and in Figure 4-8 for the transect running west to east. This DVD test is a good example of snowmelt event behavior under mild, pre-frozen soil conditions. Water moves through the topsoil efficiently. The south-north profile identifies a water plume at 1 m deep that spread quickly to the north from the water application area on south side next to the road. Within about 1 ½ hours, water moves entirely back to the south resulting in a final soil moisture profile almost identical to that of the initial conditions. The road sub-grade is adjacent to the bioretention cell soil media. This graph illustrates that the water is likely draining to the open-graded road sub-grade and downward. The west-to-east profile reinforces the movement to the southeast of the cell as seen in the south-north profile (Figure 4-8). Somewhat tubular flow appears to cross in from the south, expand northward, and then contract and disappear again to the south. It appears from this DVD test that water moves within the sandy loam layer and then eventually breaks through and drains out the sand and gravel layer. It is possible that a layer of fines exists at the bottom of the loam layer and is slowing downward movement and forcing lateral flow.

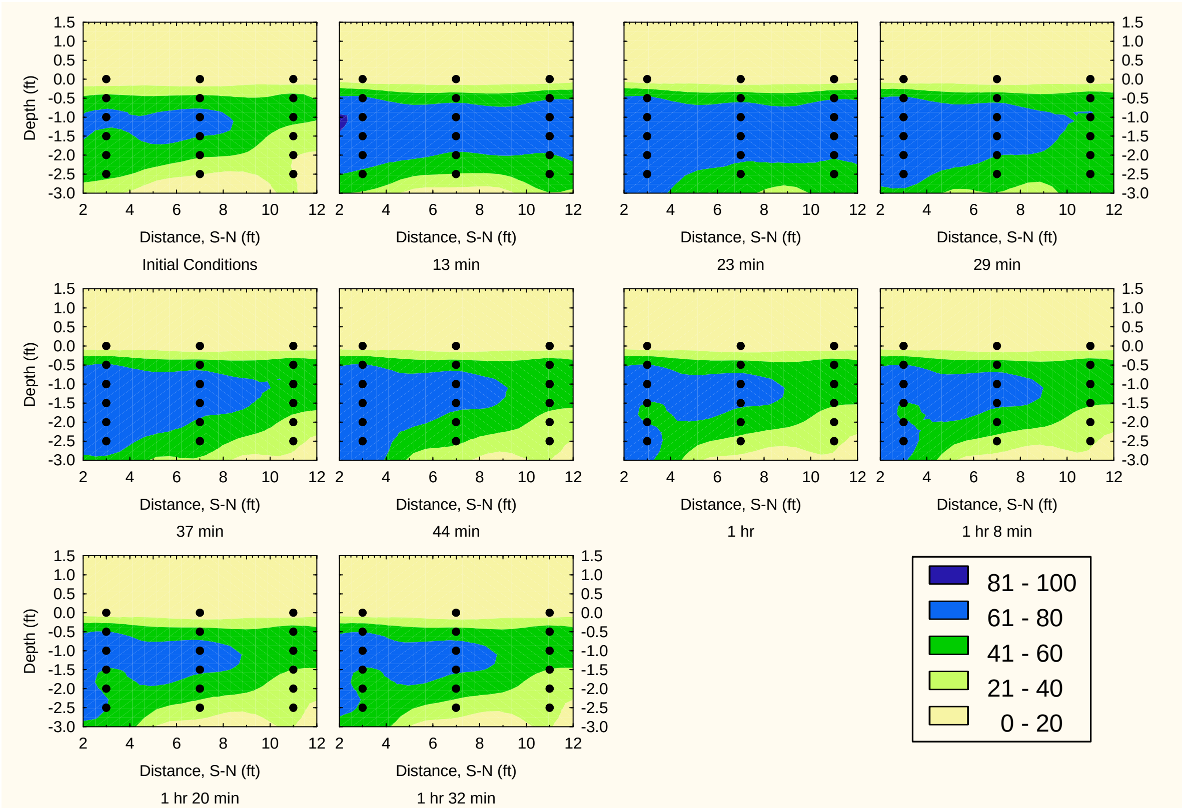

Figure 4-7. South-to-north soil moisture profile from January 2, 2007, DVD test at the Crystal Lake bioretention cell.

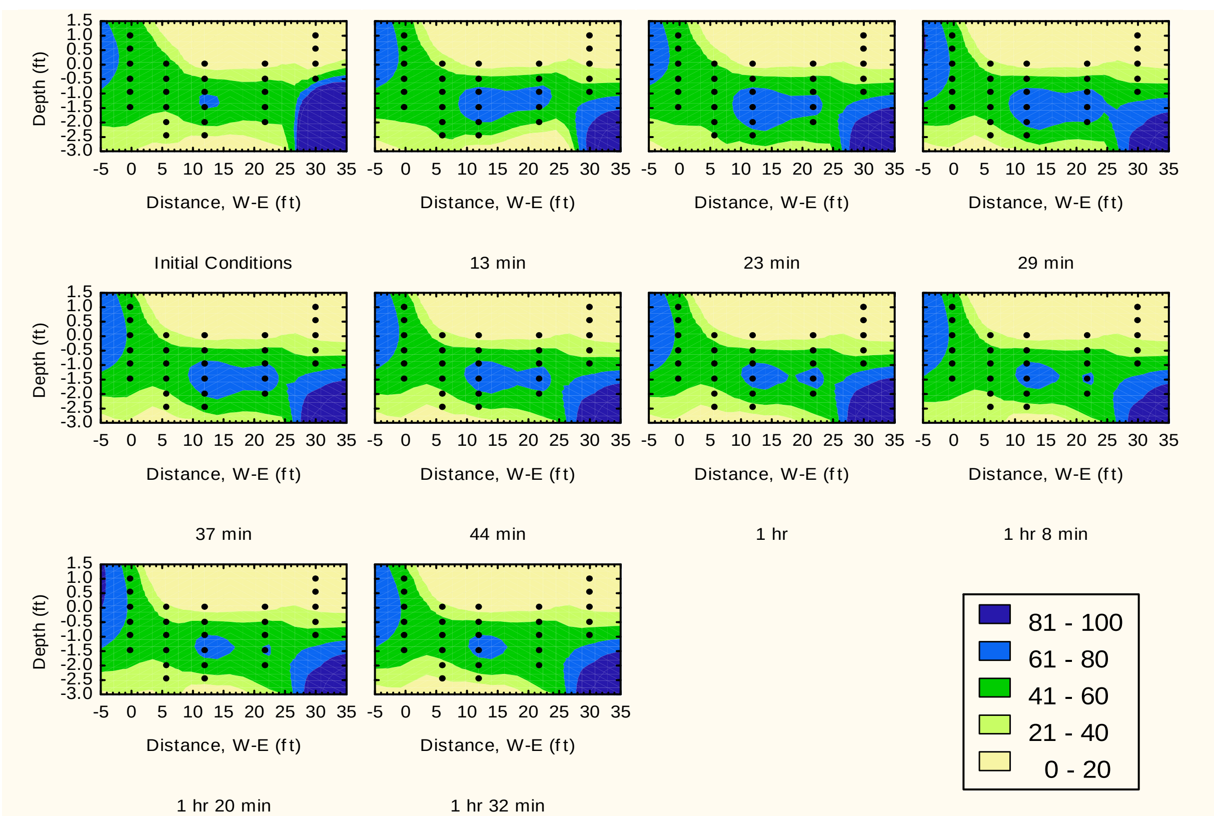

Figure 4-8. West-to-east soil moisture profile from January 2, 2007, DVD test at the Crystal Lake bioretention cell.

Contrast the January 2007 DVD with the February 27, 2007 DVD test (Figure 4-9) where antecedent soil moisture and temperature conditions are likely to have created concrete frost 1 m deep in the cell, as previously described. The test occurred during a snowmelt event where some water from the street was also entering the bioretention cell. Soil moisture readings indicate effectively no changes from the initial conditions, with the exception of surface ponding, for up to over a day later (29 hour and 20 minutes). The surface appears to be ponding at the probe at the 21-foot horizontal distance which is one of the low spots. What appears to be some minor breakthrough is likely due to the curve fitting rather than the field conditions (note some missing raw data points). As hypothesized above, frost characteristics of the cell on this date inhibited infiltration.

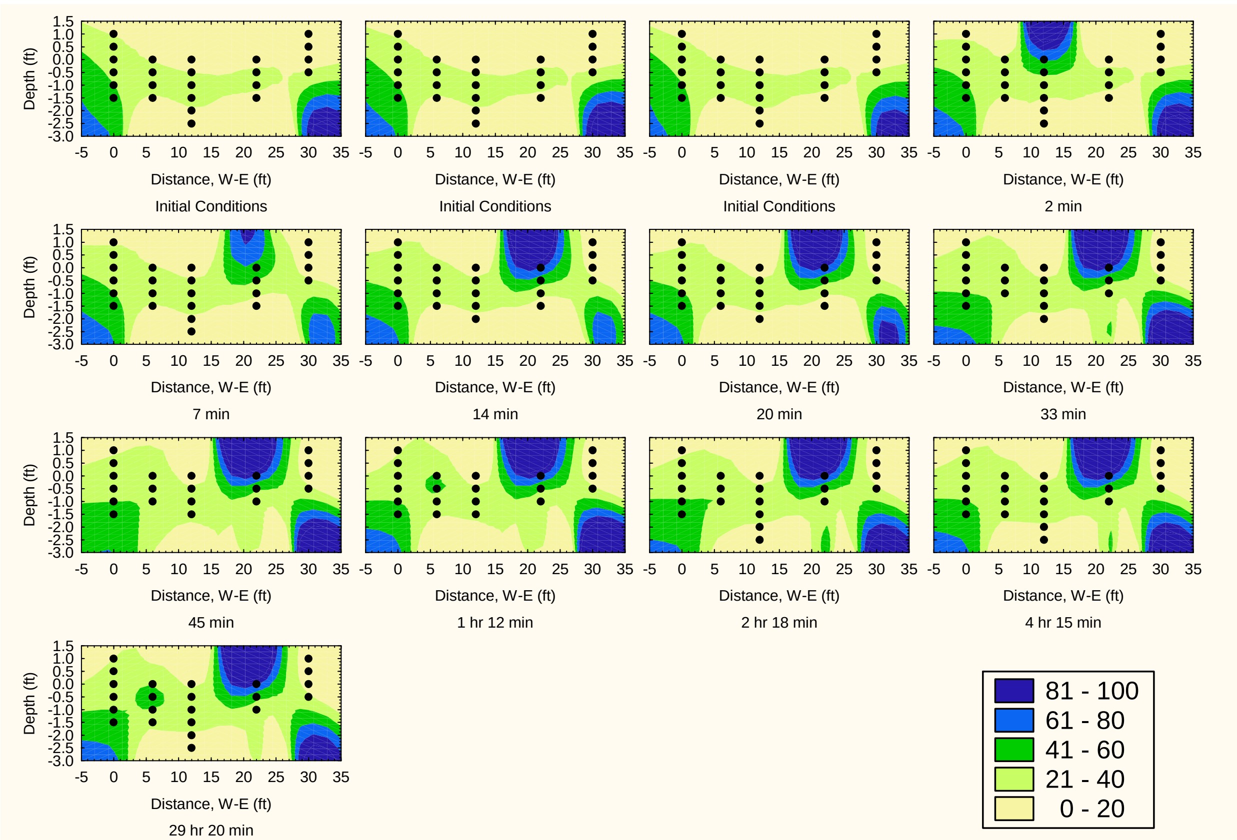

Figure 4-9. West-to-east soil moisture profile from February 27, 2007, DVD test at the Crystal Lake bioretention cell.

Soil moisture profiles from the December 13, 2007, and December 18, 2007 DVD tests (see Appendix A) represent good spread and downward movement of water through the soil profile. They are more classic and less favoring of the sub-grade of the adjacent road. The west to east profiles show tubular flow as did the early January 2007 profile. Overall, the soil moisture profiles make evident the cell is functioning well in cold climate. The December 18th test exhibited approximately 0.5 m of frost while the December 13th test exhibited none.

The soil moisture profiles from various DVD tests exhibit preferential flow paths likely established due to freezing and thawing, animal or human tracks or varying micro-topography. During the February 5, 2008, DVD test (see Appendix A) all of the water infiltrated and eventually disappeared in the same direction to the southeast, but took a course through the probe at the 21-foot distance (west to east profile) as it has done in previous DVD tests. Similar flow movement is observed in the soil moisture profiles from the March 4, 2008 DVD test. By contrast, the January 8, 2008, infiltration water appears to have taken a path through the probe at the 12-foot distance rather than the 21-foot distance. French and Binley (2004) found that variations in micro-topography (distances of a few meters) were a driving force of infiltration.

The March 18, 2008, west to east soil moisture profile (see Appendix A) also shows evidence of preferential flow paths due to soil type. The water that penetrates may be flowing in a particularly porous part of the sub-grade. Note that tubular flow sets up at about 1-foot mark which is where sandy loam and sand and gravel meet; perhaps a preferential flow path in the loam is serving as a flow entrance into the sands and gravels, then all drains out to south.

4.3. Thompson Lake Bioretention Cell

4.3.1. Introduction

Eight DVD tests were conducted at the Thompson site. Table 4-3 indicates the antecedent conditions and lists the observed infiltration and calculated inflow rates for eight DVD tests. For most of the DVD tests, water stayed in the north end of the bioretention cell where soil moisture probes were installed (see Figure 4-10 for reference). This is because the volume of water added was small compared to the available storage capacity within the cell. The volume of infiltration water added during the DVD tests for this site varied from 2,000 - 6,000 gallons. The 6,000 gallon volume is equivalent to 0.15 inches of runoff from the whole watershed. When converted to snow, this would be the equivalent of a 1.5-inch snowmelt event, a small event, but reflective of mid-winter snowmelt events. At 45% imperviousness, runoff would be closer to 0.3 inches of runoff assuming that no runoff would likely occur from adjacent grassed park areas.

The watershed area draining to the 3,600 SF bioretention cell is 68,900 SF (1.6 acres), or a drainage area-to-surface area ratio of about 19:1. During the course of the study, inflowing DVD water only covered the entire bottom once on March 18th, 2008. For the other eight DVD tests, the test pool covered about 1,300 SF of the northerly area of the cell. This increased the effective drainage area-to-surface area ratio to 53:1. Even though this is a very large ratio, the volume of test water added was small compared to what could be expected from even a one-year frequency event. This very high watershed ratio, low volume of added water and relatively large capacity of the bioretention cell, have some effect on the cell's ability to absorb high flow volumes even at moderate infiltration rates, as discussed in a later section.

Figure 4-10. Photo of the Thompson Lake bioretention cell looking north with automated monitoring station in the foreground.

Table 4-3. Site conditions and infiltration rates for DVD tests at the Thompson Lake bioretention cell.

DVD Test Date (season number)	Observed Infiltration Rate (in/hr)	Calculated Inflow Rate (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth^Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/21/2006* (1)	4.1•	38	33.9	35.2	36.7	21.3	23.7	0	38.6	51.1	7.8	0	2,000^	Solid snow cover in basin; no standing water; 2.5 deg C (36.5 deg F) water temp at infiltrometer while still pouring out (slushy); capillary movement into snow observed; possible movement of water laterally, rather than into soil.
1/4/2007* (2)	2.9•	42.5	36.5	39.0	40.5	15.1	26.9	0	36.3	47.0	1.8	0	2,000	No standing water in cell.
12/18/2007 (3)	4.2	54	N/A	N/A	N/A	N/A	N/A	N/A	24.5	31.8#	7.2	100	5,000	Heard water rushing through drain system beneath bioretention cell after about 20 min of DVD test; wet surface area extended from row B to row E.
1/8/2008 (3)	4	52	34.7	37.2	39.2	12.9	19.8	0	37.6	34	6	1081	5,321	At about 13:40 saw extensive bubbling and sub-drains flowing.
2/5/2008 (3)	1.4	N/A**	28.9	31.7	34.1	5.1	6.6	1	29.8	30.8	9	479	6,000	Filled to within 1/2 inch of overflow; ground frozen based on excavation; little to no bubbling observed during fill; sub-drains not flowing at 1:57pm; running water heard in overflow sub-drain and catch basin; observed water running from discharge pipe into lake.
3/4/2008 (3)	0.7	N/A**	30.4	32.2	33.9	30.2	13.0	0.5	32.6	30.2	6	802	3,586	Stopped filling bioretention cell when water reached the top of the overflow pipe; ground frozen based on excavation; no bubbling during fill; no sub-drain flow from sub-drain at beginning or end of test.

* No soil moisture data.

Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

• Average of 3 sites.

\# Average of temperatures from all other Thompson tests using lake water.

** Not able to be determined because of standing water at end of test period.

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DVD Test Date (season number)	Observed Infiltration Rate (in/hr)	Calculated Inflow Rate (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth^Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/18/2008 (3)	0.95	N/A**	31.9	32.3	34.0	16.6	18.9	0.5	37.1	31.9	3	518	5,547	Ground frozen except in flow-path of west curb-cut based on excavation; baseflow noted from west plug (none from east); bark leaf debris on top of overflow grate (evidence of full capacity?); bottom basin frozen (based on excavation) except near curb-cut inlets; only water standing at west curb-cut flow into basin.
4/1/2008 (3)	3.2	53	32.2	32.2	33.7	15.8	29.3	0	45.7	31.5	6	0	6,700	Ground thawed in spots to about 6-in deep based on excavation; small pool at curb- cuts; frost in spots; observed sub-drain flows from filling of bioretention cell.

* No soil moisture data.

^Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

• Average of 3 sites.

Average of temperatures from all other Thompson tests using lake water.

** Not able to be determined because of standing water at end of test period.

4.3.2. Infiltration Rates

Figure 4-11 summarizes the receding pool depths for each DVD test after all the test water was emptied into the bioretention cell. It provides an efficient tool to visually identify the DVD tests with the lowest infiltration rates. The top three infiltration curves are noticeably shallower in slope than the bottom nine curves. The upper three curves also result in at least five inches of ponded water after 1.5 to 2.5 hours of testing is complete. Alternatively, where steeper slopes were present (higher infiltration rates) complete (or nearly complete) drawdown occurred.

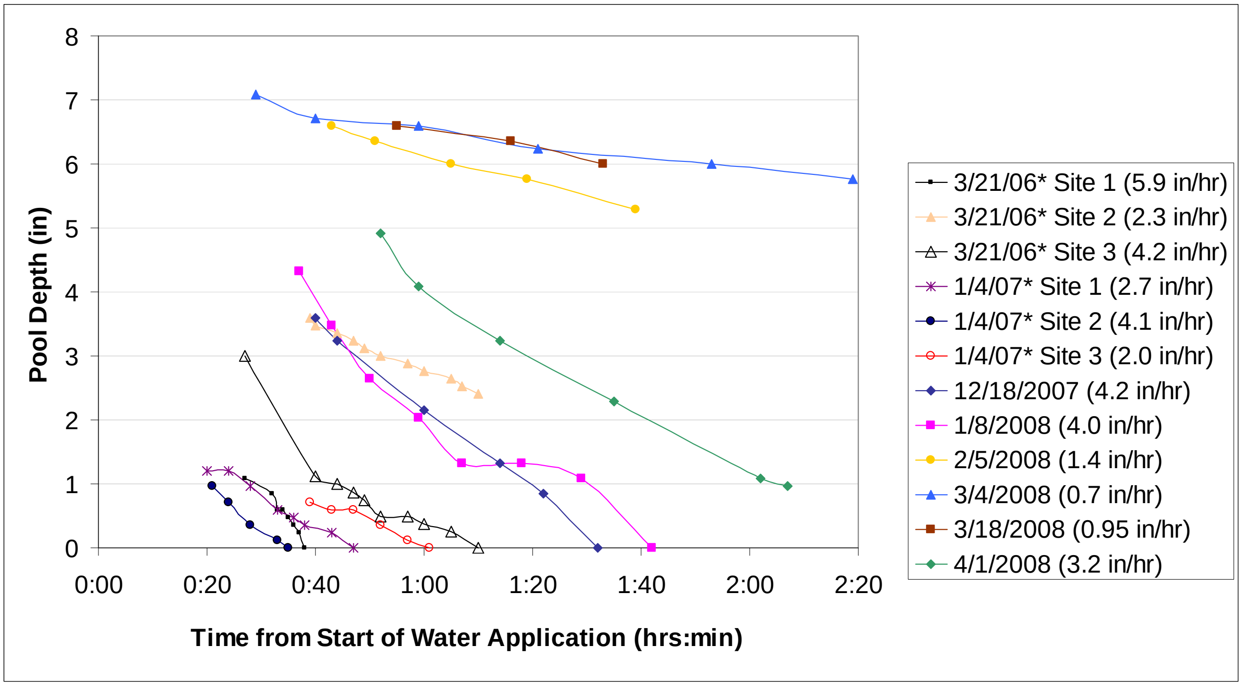

Figure 4-11. Drawdown and infiltration rates of DVD tests at the Thompson Lake bioretention cell.

The three curves with the shallowest slopes were the only sites that exhibited measurable frost and had the lowest infiltration rates (2/5/2008, 3/4/2008 and 3/18/2008 with infiltration rates of 1.4in/hr, 0.7 in/hr and 0.95 in/hr, respectively). In this case, the mere presence of frost appears to be a factor in hydrologic performance. Generally, where frost is present, slopes are shallow and ponding water remains (Table 4-3) after approximately 1.5 – 2.5 hours of testing. However, presence of frost may not be the only determining factor; character of the frost appears to influence infiltration rate. Soils during the April 1, 2008, DVD test actually did exhibit partially frozen, partially frost-free soils (Table 4-3) through which water, clearly, was able to penetrate and near-complete drawdown occurred (one inch of water remained at the end of the test). This may have been more of a late season, granular frost. The other DVDs were exhibiting a concrete frost based on field notes indicating refusal during excavation tests and no bubbling of infiltration test water (Table 4-3). The concrete frost may have prevented water from reaching the under-drain.

Drawdown data from the first and second DVD tests (March 21, 2006, and January 4, 2007) illustrate the spatial variability of infiltration rates. Drawdown data from three different locations was taken for each of these two DVD tests resulting in variable observed infiltration curves and rates (see Figure 4-11). For example, infiltration rates from the March 2006 test varied most from 2.3 in/hr to 5.9 in/hr with an average of 4.1 in/hr. The variability within a single DVD test may be the result of preferential flow paths and the effects of micro-topography as found by French et al. (2002) and French and Binley (2004). Since this is a large site and relatively shallow compared to the Crystal Lake site, the basin (cell) morphometry is more varied and quite likely influencing localized infiltration. Preferential flow paths may also have been the result of biological permeability or breakthroughs to the under-drain system. Field notes indicate that during drawdown, bubbles formed as holes (primarily mouse holes) filled (see Table 4-3). In some cases, whirlpools formed as water penetrated air pockets.

Drawdown data from the March 2008 and February 2008 DVD tests illustrate the temporal variability of infiltration rates even in the presence of presumably concrete frost. The March 2008 DVD test exhibited a 0.5-m deep of frost and an infiltration rate of 0.7 in/hr. The February 2008 DVD tests exhibited twice the infiltration rate at twice the depth of frost (1.4 in/hr and 1-m deep frost).

Horizontal water movement was evident in the March 21, 2006 DVD test. As shown in Figure 4-11, the March 2006, DVD test infiltrated completely at two of the three locations tested within the bioretention cell. There was no soil frost present, recent daytime highs were above freezing (see Table 4-3), and the infiltration water temperature was high (51.1 deg F). As was generally the case, water did not get to the south end of the cell. Water moved to the west and infiltrated at the berm separating the bioretention cell from the adjacent walking path and lake. This lateral movement and infiltration may be an indication that slopes tend to drain more readily and remain free of soil frost with the onset of freezing temperatures.

Noting the difference between infiltration rates and inflow rates described in Chapter 4.2.2, the data in Table 4-3 indicate that an inflow rate of 38 to 54 gpm was obtained for those DVD tests where no standing water was left at the end of the test period. For several of the tests noted in Table 4-3, inflow rate could not be determined because an unmeasured volume of water remained at the conclusion of the test. In a later discussion (Chapter 5), the high inflow rate relative to moderate infiltration rate is explained as a function of cell size.

Table 4-4 illustrates the correlations (R-squared values) between infiltration rates and various site characteristics at the time of, or prior to, the DVD test. Based on the correlation analysis, infiltration rates are correlated most with frost depth and antecedent soil temperatures (the average 3-day daily high). Infiltration rate did not correlate conclusively with any other site characteristic.

Table 4-4. Correlations (R-squared values) between infiltration rates and various site characteristics at the Thompson Lake bioretention cell.

Site Characteristic		**Thompson R^2-value**
Soil Temperature (Avg 3-d Daily High)	Surface	0.45 (+)
	0.5 m	0.36 (+)
	1 m	0.34 (+)
Frost Depth		0.62 (-)
Test Water Temperature		0.19 (+)
Snow Cover		0.05 (+)
Soil Water Content (3-d Average)	6-inch	0.03 (-)
	12-inch	0.39 (+)
Chloride Concentration		0.12 (-)
Air Temp (Avg 3-d Daily High)		0.01 (+)

4.3.3. Soil Moisture Profiles

Profiles for all eight Thompson Lake events are contained in Appendix A. Select examples are discussed below. Soil moisture probe transects are shown in Figure 4-12.

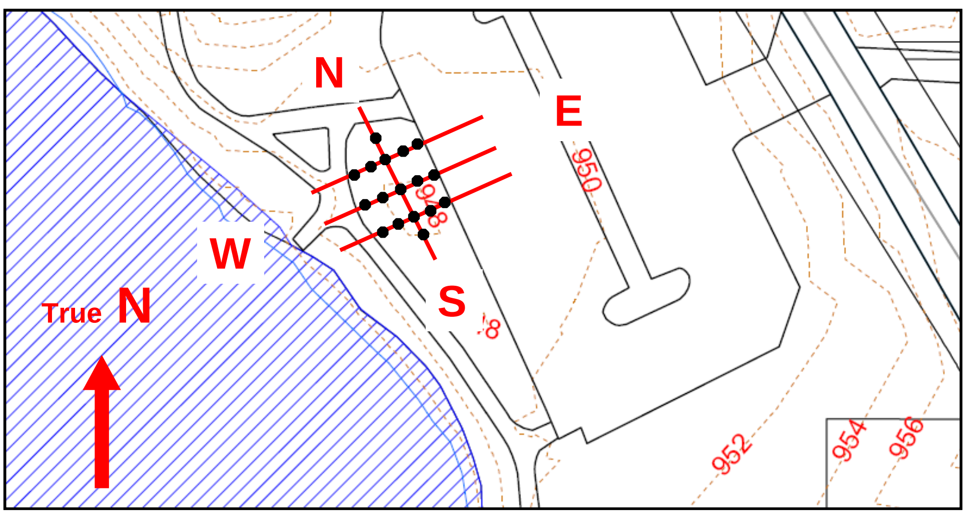

Figure 4-12. Soil moisture probe transect locations for the Thompson Lake bioretention cell.

Comparing the first two DVD tests to the December 18, 2007 DVD test, a comparable infiltration rate of 4.2 in/hr is exhibited and complete drawdown occurs (with the exception of Site 2 in March 2006). In this case about 5,000 gallons of water was applied to the study cell and the under-drain was running after 20 minutes from the initial input of test water. This is exhibited clearly in the south to north soil moisture profile (Figure 4-13) where, at the 37 minute mark, water has penetrated the top soil layers. The wetness at the bottom of the soil measurements is found in the initial conditions and is likely the result of the soil clay layer retaining moisture from the high groundwater table. The bottom blue shape changes slightly after water is applied implying that some water may have bypassed the under-drain. However, clearly the under-drain is a functioning tool for drawdown. It is evident that the major drawdown mechanism is filtration as opposed to infiltration, since the excess water is drained off via the under-drain connection to the storm sewer outlet.

From the west to east profile (northern transect) (Figure 4-14), it is clear that water does not reach the transect until at least 17 minutes have passed from the time of filling. Surface water is gauged by the moisture sensors by the 37 minute mark (if not, before). By the time an hour has passed, the surface water has mostly receded and movement of moisture to the west appears. The water that was not collected by the under-drain appears to travel in the direction of the lake. Note the bowl shape of the initial conditions.

The middle transect of the west to east profile (Figure 4-15), appears to illustrate reduced moisture near the under-drain at the 37 minute mark when the water finally progresses across the basin to this point. At the 37 minute mark, the broader width of water contact (from 5- to 30-feet) may be the result of the channel effects taking place on the north transect of the west to east profile. Along this transect a beaten path has been made from frequent park user foot traffic through the bioretention cell. Water is easily conveyed along the path to the lowest point (the center) of the transect creating more localized ponding. Note again the movement westward toward the lake in the north transect of the west to east profile (Figure 4-16).

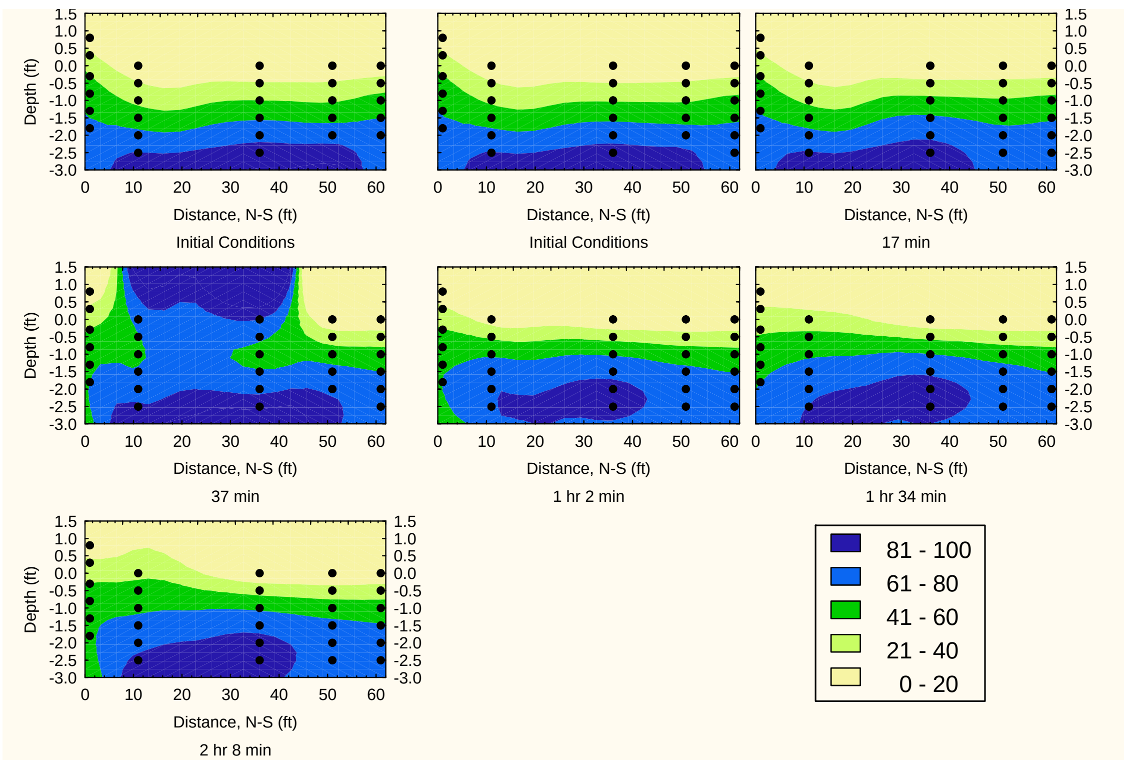

Figure 4-13. South-to-north soil moisture profile from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

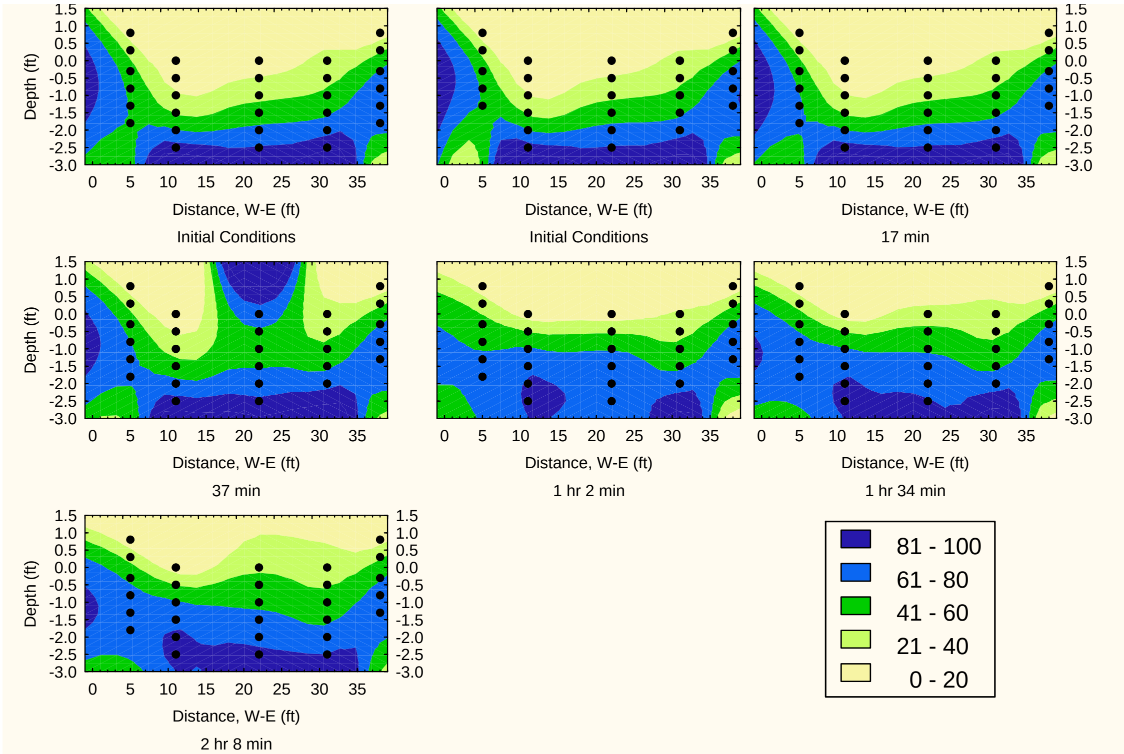

Figure 4-14. West-to-east soil moisture profile from the north transect from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

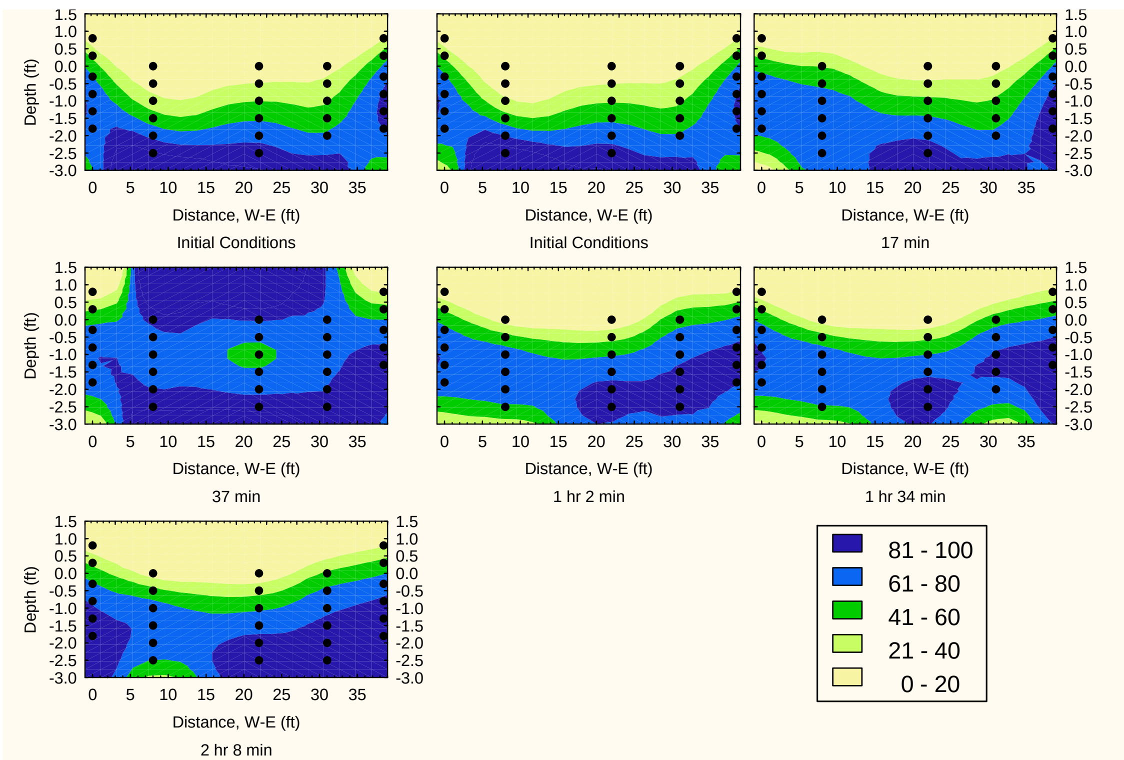

Figure 4-15. West-to-east soil moisture profile from the middle transect from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

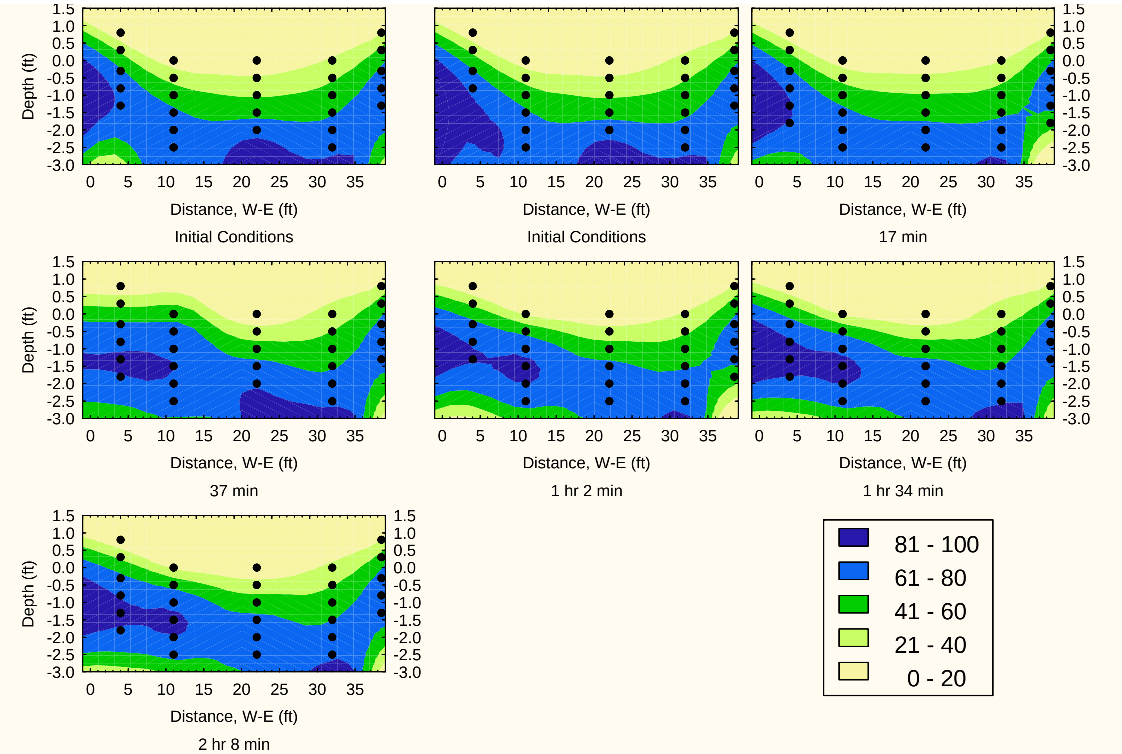

Figure 4-16. West-to-east soil moisture profile from the south transect from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

Prior to the February 5, 2008, DVD test, a substantial air temperature and surface soil temperature drop occurred (see Table 4-3 or Appendix A for more detail). As a result, ponded water remained on the surface likely due to a concrete frost layer (see Figure 4-11). In all of the soil moisture profiles (see Appendix A), the soil moisture profile exhibits very little change. Large blocks of area where no data were collected (no black dot on the graphic) are the result of interpolation beyond a reasonable range and are not reliable for discussion. However, it is still evident that with the exception of slight soil moisture changes at the surface due to water application, water does not appear to move through the soil. No bubbling as evidence of biological permeability was observed. However, there was some flow through the under-drain (Table 4-3). It is possible that at a depth of 1 foot (at the 37 foot mark) the north-to-south transect is again exhibiting evidence of the under-drain drawing moisture out of the surrounding soil. However, 1.5 hours later surface soil moisture remains high and water is still ponding to a depth of about 5.5 inches.

Similar results are evident in the March 4, 2008, DVD test (see Appendix A). Soil excavation confirms the presence of frozen soils during this DVD test, and in this case no under-drain flow was apparent. It is likely, then, that concrete frost was present such that perforations had no source water or were frozen across. Again, soil temperature remained below freezing for an extended period prior to the test (see Table 4-3 or the Appendix for more detail).

The soil moisture profile from the April 1, 2008, DVD test (Figure 4-17) appears to indicate some soil movement through the soil between the horizontal distances of 5 and 20 feet. Interestingly the clay layer appears not to be saturated as in previous DVDs which may be the result of draining during the rising temperatures just prior to the DVD test (see Appendix A) or to unseasonably dry weather that drew down the level of the lake. Once again this DVD test exhibits nearly complete drawdown during the test (Figure 4-11), leaving about one inch behind when the test ended.

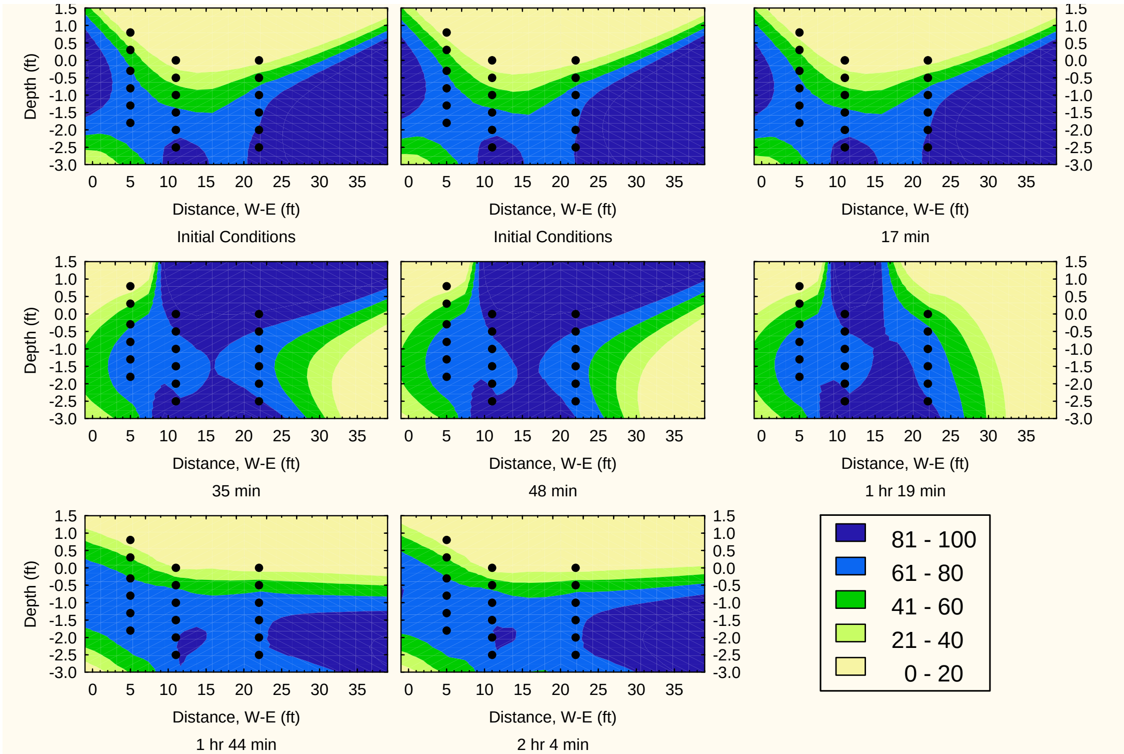

Figure 4-17 West-to-east soil moisture profile from the north transect from April 1, 2008, DVD test at the Thompson Lake bioretention cell.

Overall this site has a much narrower range of infiltration rates (0.7 in/hr to 4.2 in/hr) as compared to the Crystal Lake site. Though soil moisture profile data show multiple DVD tests with little to no water movement through the soil, this site exemplifies the benefits of a sub-drain for sites with poor soils. Where water movement occurred, the drain was a functioning element. Even though infiltration, in reality, did not account for much volume loss, the bioretention site's filtration mechanism provides water quality treatment. Also general reliability occurred for 40-60 gpm entering the cell soil and filtering through to the drain in many cases. See further discussion in Chapter 5.

4.4. Cottage Grove Bioretention Cell

4.4.1. Introduction

Seven DVD tests were conducted at the Cottage Grove bioretention cell. Table 4-5 indicates observed infiltration and calculated inflow rates for seven DVD tests and site conditions prior each test. Table 4-6 illustrates the correlations (R-squared values) between infiltration rates and various site characteristics at the time of, or prior to, the DVD test. These correlations are expected to help define the bioretention characteristics that drive cold climate hydrologic performance.

The volume of test water applied varied from 200 to 250 gallons. This represents 0.19 inches and 0.24 inches, respectively, of runoff from the drainage area. As previously indicated, this limited volume is reflective of typical melt events during the winter and early spring seasons. Similar also to previous discussions, this volume used only a very small portion of the available capacity of the bioretention cell.

Table 4-5. Site conditions and infiltration rates for DVD tests at the Cottage Grove bioretention cell.

DVD Test Date (season number)	Observed Infiltration Rate (in/hr)	Calculated Inflow Rate (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth^Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/22/2006* (1)	11.5	4.2•	31.2	32.1	32.7	6.8	10.7	0.5	37.5	N/A	10	0	200^	Heavy water content of snow; basin completely full of snow; may be frost to 1m but on borderline.
2/22/2007* (2)	1.2	N/A**	29.8	26.3	26.5	2.9	6.2	1.5	45.6	53.4	0	0	200	Some ice in basin from previous day; some water seeped through overflow structure cracks.
3/22/2007 (2)	9.0	6.2	33.8	32.5	32.5	5.7	12.4	0	47.0	32.0	0	0	200	Frost tubes frozen in ground.
12/20/2007 (3)	13.2	9.6	28.9	31.7	36.4	3.1	7.2	0.5	27.1	50.0	6.5	99	250	
1/8/2008 (3)	11.5	6.7	32.0	32.4	34.7	3.9	7.8	0.5	38.1	49.6	7	99	250	
2/22/2008 (3)	0.3	N/A**	23.1	24.6	28.4	3.4	6.4	1.5	12.1	50.9	4.5	110	225	Main cluster frost tube frozen in ground, layer of ice at bottom of basin.
3/19/2008 (3)	2.0	N/A**	32.0	30.8	30.7	8.0	32.2	1.5	37.6	N/A	0.25	124	200	Some water went through outlet structure cracks.

* No soil moisture data.
^Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

** Not able to be determined because of standing water at end of test period.

• Extrapolated since zero depth was nearly achieved by end of the test.

4.4.2. Infiltration Rates

Immediately noticeable from the pool depths tracked over time (Figure 4-18) 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 (Table 4-5). The deep frost during the March 2008, DVD 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 half a meter with the exception of the March 2007 DVD test, which exhibited no frost.

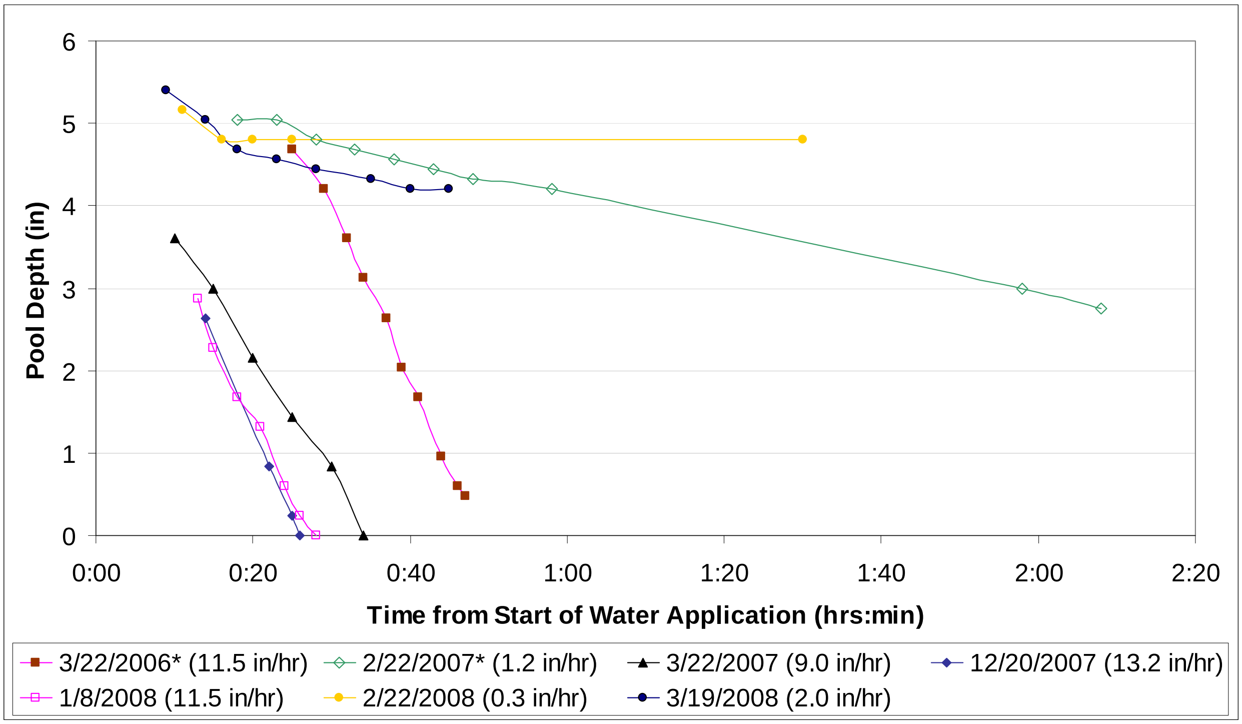

Figure 4-18. Drawdown and infiltration rates of DVD tests at the Cottage Grove bioretention cell.

Antecedent soil temperatures and frost depth (data largely based on soil temperature) tell the story of the varying performance of this bioretention site. Soil temperatures prior to the DVD tests with the shallowest infiltration curves were well below freezing (Table 4-5). 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. During the December 20, 2007, and January 8, 2008, DVD tests, surface soil temperatures were below freezing, but 1-m deep soil temperatures were above freezing temperatures. 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. Correlations between 1-m soil temperatures and infiltration rates did, in fact, exhibit the highest correlation (Table 4-6). However, there were no apparent excess moisture contributions that would have saturated the soil to develop a concrete frost, and data indicate no correlation between three-day average soil water content and infiltration rate (Table 4-6).

Table 4-6. Correlations (R-squared values) between infiltration rates and various site characteristics at the Cottage Grove bioretention cell.

Site Characteristic		Cottage Grove R^2-value
Soil Temperature (Avg 3-d Daily High)	Surface	0.20 (+)
	0.5 m	0.68 (+)
	1 m	0.84 (+)
Frost Depth		0.77 (-)
Test Water Temperature		0.09 (-)
Snow Cover		0.41 (+)
Soil Water Content (3-d Average)	6-inch	0.00
	12-inch	0.07 (-)
Chloride Concentration		0.02 (-)
Air Temp (Avg 3-d Daily High)		0.04 (+)

For the February 22, 2007, DVD test, a large jump in soil water content at the 1-ft depth was apparent as a result of the DVD water input (see Appendix A). However, the soil water content at the 0.5-foot depth barely changes. Given that the readings are half-hourly, this may imply that the water pushed through the 6-in depth to the 12-in depth quickly and settled there, a likely scenario given the sandy nature of this cell. Some drawdown during this DVD test may have been the result of observed seepage through cracks in the outlet control structure, but evidence from the soil water content data indicates infiltration did occur. This test exhibited the second lowest infiltration rate of 1.2 in/hr, and water remained ponded at a depth of near 2.5 inches. Ponding could be due to clogging after added water froze in the soil column. In addition, this DVD test began with some ice in the basin from the previous snowmelt [note high temperatures in the three days preceding the DVD test (Table 4-5)], which may have precluded complete infiltration of the DVD test water. Alternatively, the infiltration that did occur (the best of the three worst tests) may be the result of the porosity of the sandy soils and, therefore, the resistance to concrete frost formation.

Table 4-5 shows that inflow rates for the tests achieved a range of about 4 to 10 gpm. As with previous test cells, the inflow volume was reflective of a typical melt event and the capacity of the cell was only slightly used.

4.4.3. Soil Moisture Profiles

Soil moisture probe transect locations are shown in Figure 4-19. As a general note, water was applied from the northwest edge to the north corner of the Cottage Grove bioretention cell.

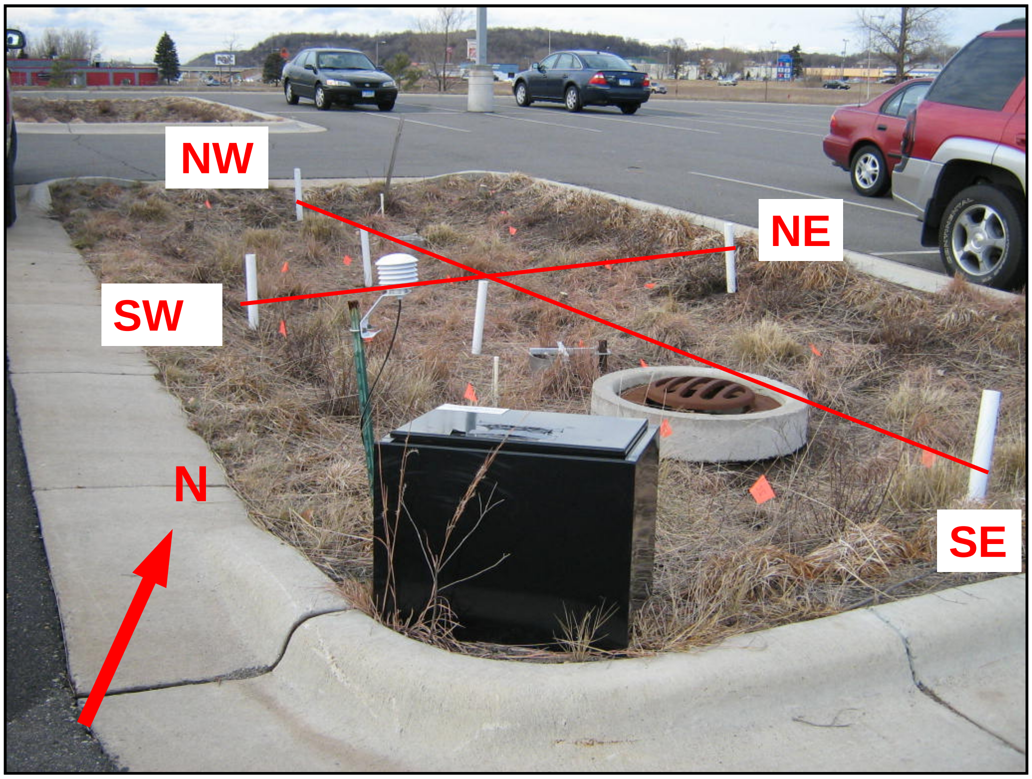

Figure 4-19. Soil moisture probe transect locations for the Cottage Grove bioretention cell.

On October 10, 2007, during a pre-season sample DVD test, 200 gallons were applied to the Cottage Grove site, and it infiltrated as the water entered (in 10 minutes) precluding any pooling depth measurements. It infiltrated at a flow rate of approximately 20 gpm. Only two days prior, over an inch of rain had fallen (between 10/5 and 10/8). However, there were no apparent adverse effects related to antecedent moisture conditions, likely due to the porous soils. The October 2007 DVD test is probably a good characterization of how the basin works for rainfall during the growing season. In fact, dry-out of the trees which were ultimately removed was likely due to infiltration rates that were excessively high for establishment of certain vegetation. During warm season testing, Asleson (2007) found that the Cottage Grove bioretention cell had the highest saturated hydraulic conductivity near the dead and dying trees where decaying roots likely provided preferential flow paths.

The March 22, 2007, DVD test soil moisture profiles (Figure 4-20 and Figure 4-21) illustrate the water application point. Though measured pool depth recedes quickly (9 in/hr), there is very little evidence of moisture change in the soil profile after the 16 minute mark. Figure 4-18 illustrates that water receded completely in approximately 30 minutes. The 29-minute soil moisture profile may be the state of the profile after the water already passed through given the high infiltration capacity as demonstrated in the October 2007 pre-season DVD test. The small amount of change in the March 2007 soil moisture profile is probably not the result of water seeping through at an immeasurable rate, but more the result of the low volume of water (200 gallons) that was applied to the cell, which was then held in the soil media without ever seeping through the bottom of the tested profile.

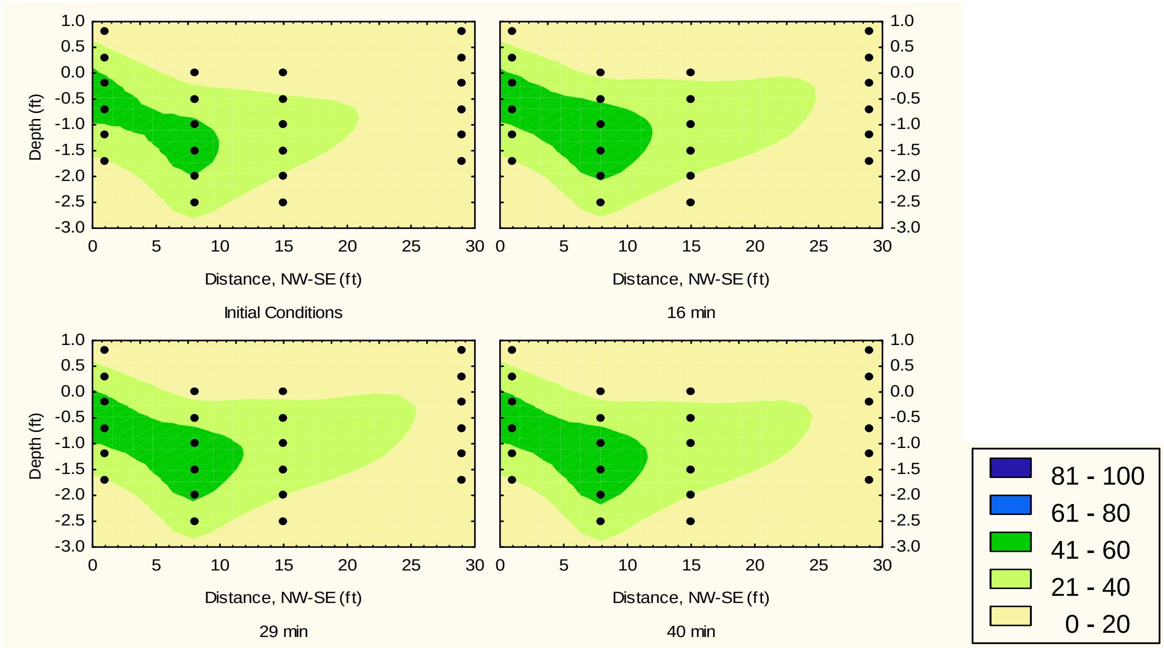

Figure 4-20. Northwest-to-southeast soil moisture profile from March 22, 2007, DVD test at the Cottage Grove bioretention cell.

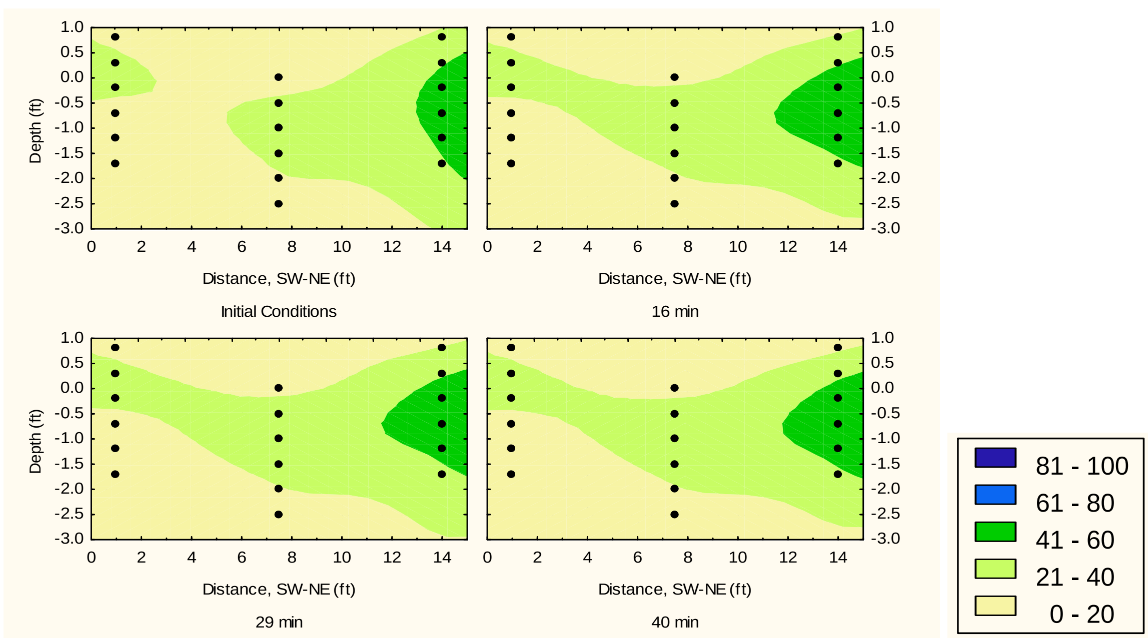

Figure 4-21. Southwest-to-northeast soil moisture profile from the northern transect from March 22, 2007, DVD test at the Cottage Grove bioretention cell.

Looking at the soil moisture profiles from the December 20, 2007, DVD test (Figure 4-22 and Figure 4-23), it is apparent that water quickly spreads from the northwest to the southeast (note dark blue pattern change). However, in both transects, the water never seeps completely through. This is likely evidence of the same effects seen in the March 22, 2007 event where too little DVD water was used to see how that water ultimately moves down and out of the system. Instead it is all held in the interstitial area. Again, the blue is related to the location of dumping of the water. Along the southwest to northeast transect (Figure 4-23) it does not travel far. Note that though the March 2007 test did not exhibit soil frost and the December 2007 test did, similar results occurred. Sand is less likely to exhibit concrete frost as compared to denser, finer-grained soil media because water drains from the pore space more readily.

Data from the January 8, 2008, DVD test (see Appendix A) exhibits similar trends as the March 2007 and December 2007 profiles. At the 12-minute mark it appears that water moved through the column readily. However, the test water applied to the top of the basin may have been just enough increase in soil moisture to tip the mathematical interpolation of the lower soil moisture measurements to the next higher moisture range. Overall, the same patterns are observed as in earlier DVD tests.

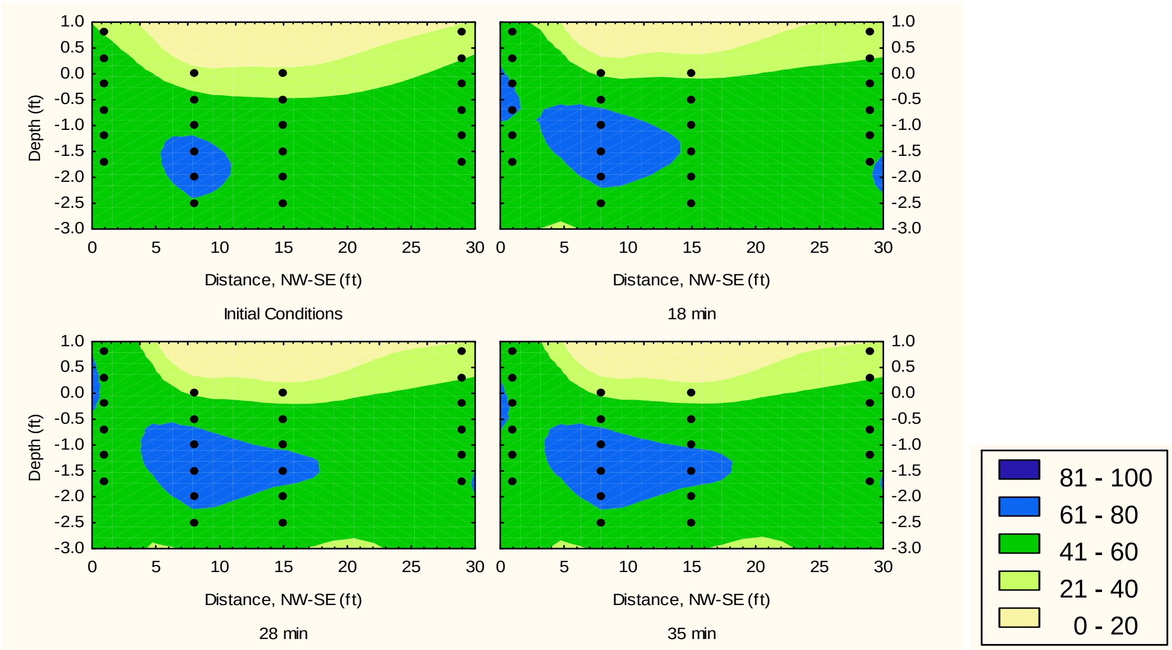

Figure 4-22. Northwest-to-southeast soil moisture profile from December 20, 2007, DVD test at the Cottage Grove bioretention cell.

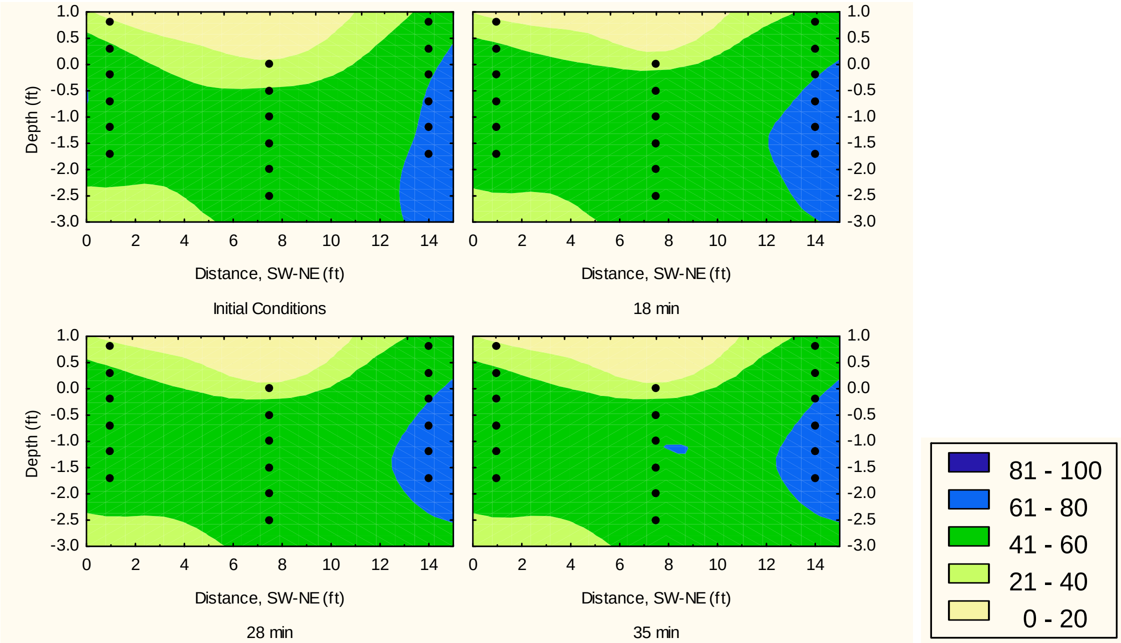

Figure 4-23. Southwest-to-northeast soil moisture profile from the northern transect from December 20, 2007, DVD test at the Cottage Grove bioretention cell.

Frozen soils up to greater than 1 m deep on February 22, 2008, appear to preclude infiltration during this test (see Figure 4-24 and Figure 4-25). No soil moisture changes are evident except for evidence of ponding at 14 minutes which spreads throughout the lowest area of the basin by the 27 minute mark and apparently recedes after an hour and a half. In this case the infiltration water was 51 deg F and the soils were good sands, yet still ice could prevent infiltration. Indeed, infiltration water temperature did not correlate with measured infiltration rates (Table 4-6). The lateral movement of water across the surface may not have extended far enough to reach the side slopes which may have provided unfrozen soil for penetration. As in the March 21, 2006, DVD test at Thompson Lake, water that moves horizontally is expected to find vertical movement at the sides in the cases where the basin bottom is frozen and the sides are not. Again, not enough test water was utilized to capture this infiltration mechanism.

The March 19, 2008, DVD test soil moisture profiles exhibit similar trends as the February 22, 2008, DVD test (see Appendix A). The apparent five inches of top thaw at this site did not appear to facilitate infiltration and penetrate the apparent concrete frost below. Again, some drawdown may have been the result of seepage through the outlet control structure cracks.

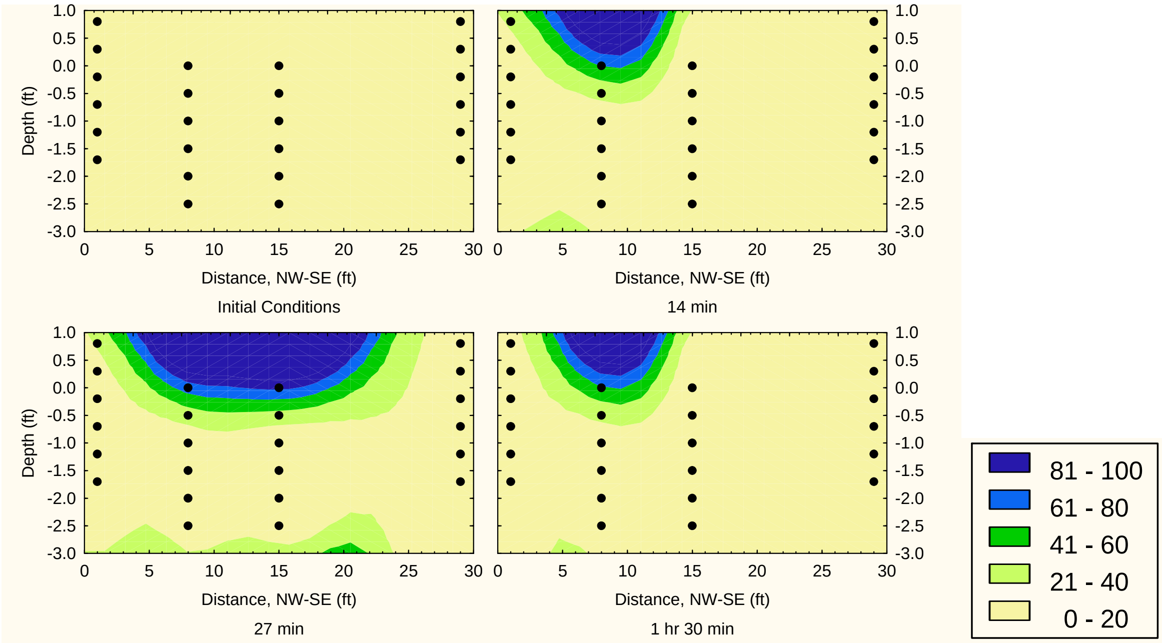

Figure 4-24. Northwest-to-southeast soil moisture profile from February 22, 2008, DVD test at the Cottage Grove bioretention cell.

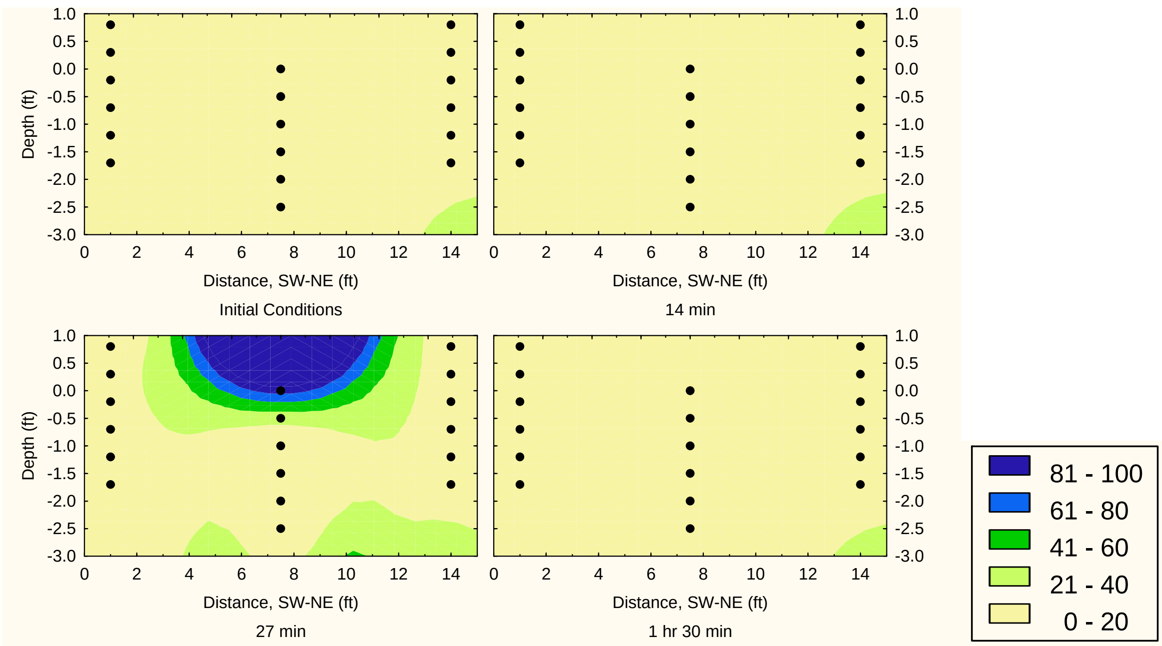

Figure 4-25. Southwest-to-northeast soil moisture profile from the northern transect from February 22, 2008, DVD test at the Cottage Grove bioretention cell.

The overall range of infiltration rates is, again, high (0.3 in/hr to 13.2 in/hr). DVD tests at this site could have provided more information if soil moisture measurements were taken for a longer time period and more water was applied to the cell. Not enough water was ever applied to utilize the total surface area of the relatively small bioretention cell (380 SF). For future testing, it may be that utilizing the total surface area is more important that utilizing the equivalent of a particular frequency storm event unless comparison between a variety of storm events is a specific goal. While the porosity of sand was an apparent benefit to dry antecedent conditions, even sands can freeze to the extent that infiltration is prohibited (e.g., February 22, 2008, DVD test). However, with a greater volume of water applied, local ice presence might be overcome through infiltration along the side-slopes. With so little water, infiltration water pooled preferentially in small pools rather than over the entire cell. The end result, however, was that typical melt events infiltrated.

4.5. Stillwater Bioretention Cell

4.5.1. Introduction

Eight DVD tests were conducted at the Stillwater bioretention cell. This site was overall problematic from the start. The overflow drain pipe (less than 2 inches off the ground) is located on the west side and seeped water out of the system even after it was plugged (after Season 1). In addition, the soils are quite poor consisting of a mix of clays and loam. More specifically, the top layer consisted of fine organics, then clay loam and a series of sandy lean clay with some gravel encountered and some fine sand at the eastern end of cell. It was selected as a site that was predicted to perform poorly when compared with the other sites.

The DVD test water volume added to the Stillwater bioretention cell amounted to only 0.01 to 0.02 inches over the entire drainage area. Even with the minimal amount of water added, the cell did not infiltrate much water.

Table 4-7 indicates the antecedent conditions and lists the observed infiltration and calculated inflow rates for all eight DVD tests. However, note that the March 2006 observed infiltration rate of 6.1 in/hr is due to excessive flow into the outlet pipe and is artificially high.

Table 4-7. Site conditions and infiltration rates for DVD tests at the Stillwater bioretention cell.

DVD Test Date (season number)	Observed Infiltration Rate (in/hr)	Calculated Inflow Rate (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth [Δ] (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/22/2006*° (1)	6.1	N/A**	32.7	32.7	35.2	30.9	17.3	0.5	38.4	48.2	5.25	0	N/A	Outlet pipe is taking most (or all) of the water out of the garden; pipe is 6-in diameter; spotty ice up to 17 inches deep.
2/21/2007* (2)	0.4	N/A**	29.4	28.5	32.9	10.0	5.9	1	35.6	43.9	0	0	250	Some meltwater in basin previous to DVD test; poured water on parking lot - had to clear curb cut for it to get to cell; snowmelt from the parking lot added to pool depth at last pool depth reading.
3/22/2007 (2)	0.7	N/A**	37.9	32.2	33.6	33.0	24.3	0	47.4	N/A	0	0	200	Possible 7-inch top thaw.
10/10/2007•	1.8	4.9	67.4	65.7	65.7	36.2	21.5	0	66.8	N/A	0	0	200	Ground may be saturated from 1.5 inches of rain on 10/5 - 10/8.
12/20/2007 (3)	N/A	N/A**	31.4	35.9	39.4	24.1	13.9	0.5	27.0	38.3	6	124	200	Soil moisture probe started to quit operating, no infiltration measurements.
1/8/2008 (3)	3.7	N/A**	31.8	34.9	37.7	33.2	24.2	0.5	37.6	38.7	4.5	99	250	2-inch frost in frost tube.
2/22/2008 (3)	0.2	N/A**	23.6	28.1	31.9	21.9	15.3	1.5	12.4	37.8	2.5	99	250	
3/19/2008 (3)	0.8	N/A**	31.7	30.4	32.4	74.0	57.3	1.5	37.2	N/A	0	124	200	Main frost tube frozen in ground.

* No soil moisture data.

° Overflow through unplugged outlet (2-inches above bioretention cell bottom) during testing; plugged for all other tests. The 3/22/06 observed infiltration rate of 6.1 in/hr is artificially high.

Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

• Not utilized for correlations because not within the 'winter' months.

** Not able to be determined because of standing water at end of test period.

4.5.2. Infiltration Rates

Table 4-7 and Figure 4-26 display the very low infiltration rates and inflow character of the DVD tests. Note in Table 4-7 that inflow rates (gpm) could not be determined for a single DVD test (with the exception of the October 2007 non-winter comparison test) because all tests ended with standing water still in the cell. The highest infiltration rate (6.1 in/hr) occurred from the first winter of testing on March 22, 2006. During this test only, the overflow outlet was open and artificial drawdown occurred, precluding infiltration. After Season 1, the overflow outlet was plugged. However, it was observed that some leakage occurred through the plugged overflow throughout Seasons 2 and 3.

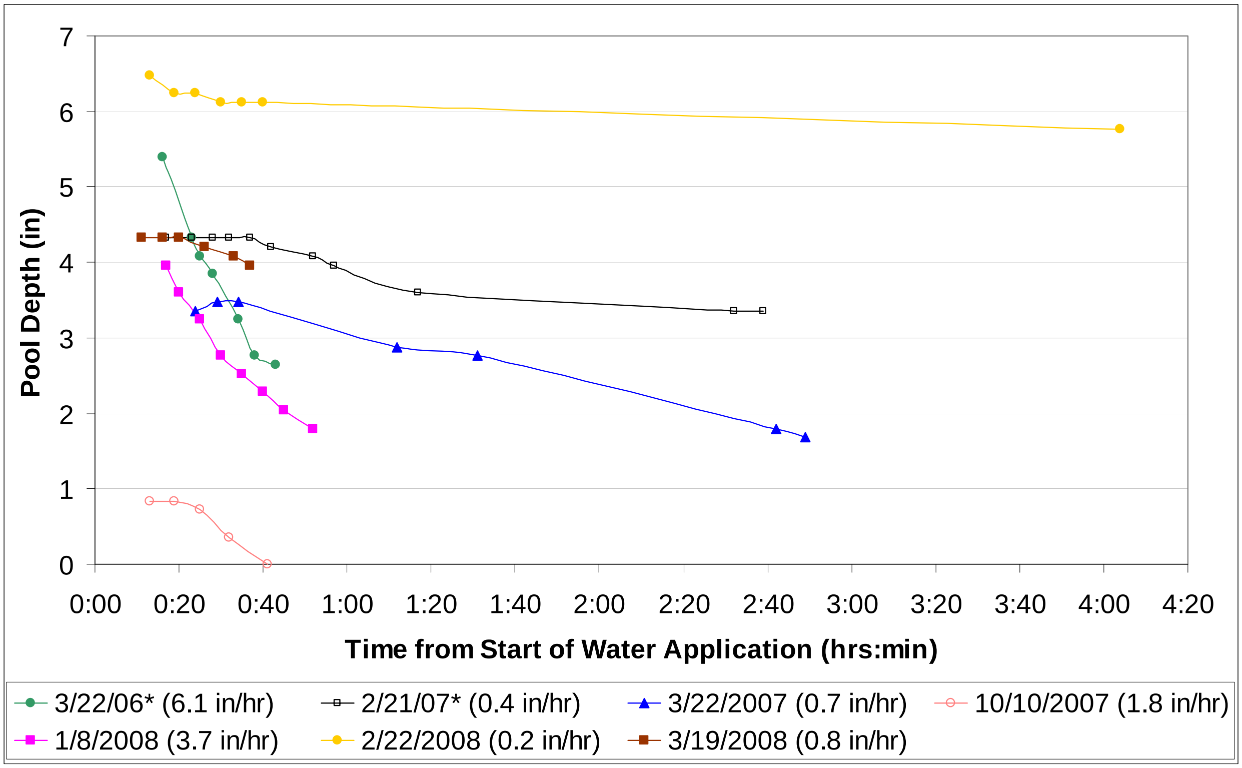

Figure 4-26. Drawdown and infiltration rates of DVD tests at the Stillwater bioretention cell.

Table 4-8 illustrates the correlations (R-squared values) between infiltration rates and various site characteristics and antecedent conditions for each DVD test. Soil water content, chloride concentrations and air temperature have no correlation to measured infiltration rates (Table 4-8). However, as found at other sites, soil temperature (especially at the 0.5 m and 1 m depths) had a relatively strong positive correlation with infiltration rates. Test water temperature and snow cover had a higher correlation to infiltration rates than that of any other site. The greater the snow cover and test water temperature, the greater the rate of infiltration. The weak negative correlation to frost depth (R-squared value of -0.19) correlation is noticeably influenced by the highest infiltration rate (6.1 in/hr) where frost was present but the outlet overflow was unplugged completely (March 2006 DVD test). Trends should also be considered lightly given the observed (and unknown rate of) leakage when the drain was plugged.

Table 4-8. Correlations (R-squared values) between infiltration rates and various site characteristics at the Stillwater bioretention cell.

Site Characteristic		Stillwater R^2-value
Soil Temperature (Avg 3-d Daily High)	Surface	0.07 (+)
	0.5 m	0.49 (+)
	1 m	0.55 (+)
Frost Depth		0.19 (-)
Test Water Temperature		0.34 (+)
Snow Cover		0.68 (+)
Soil Water Content (3-d Average)	6-inch	0.00
	12-inch	0.01 (-)
Chloride Concentration		0.04 (-)
Air Temp (Avg 3-d Daily High)		0.08 (+)

4.5.3. Soil Moisture Profiles

DVD test water was dumped at the curb-cut on southeast side of the cell. The characteristics of the Stillwater bioretention cell behavior can be accurately summarized by the January 8, 2008, soil moisture profiles (Figure 4-28 and Figure 4-29). In general, little to no changes in soil moisture occurred as a result of the contribution of DVD test water. During some DVD tests, including the one shown here, high saturation was evident at a depth of about one foot prior to and during DVD testing. This was consistent with a soil survey where standing water was encountered at a depth of approximately 11 inches. The Stillwater bioretention cell has a poor ability to dry-out and provide infiltration of run-on. Where drawdown was observed based on pool depth measurements, infiltration of surface water is not readily identifiable in soil moisture profiles. It is likely that much of the observed drawdown was due to leakage observed at the plugged overflow outlet.

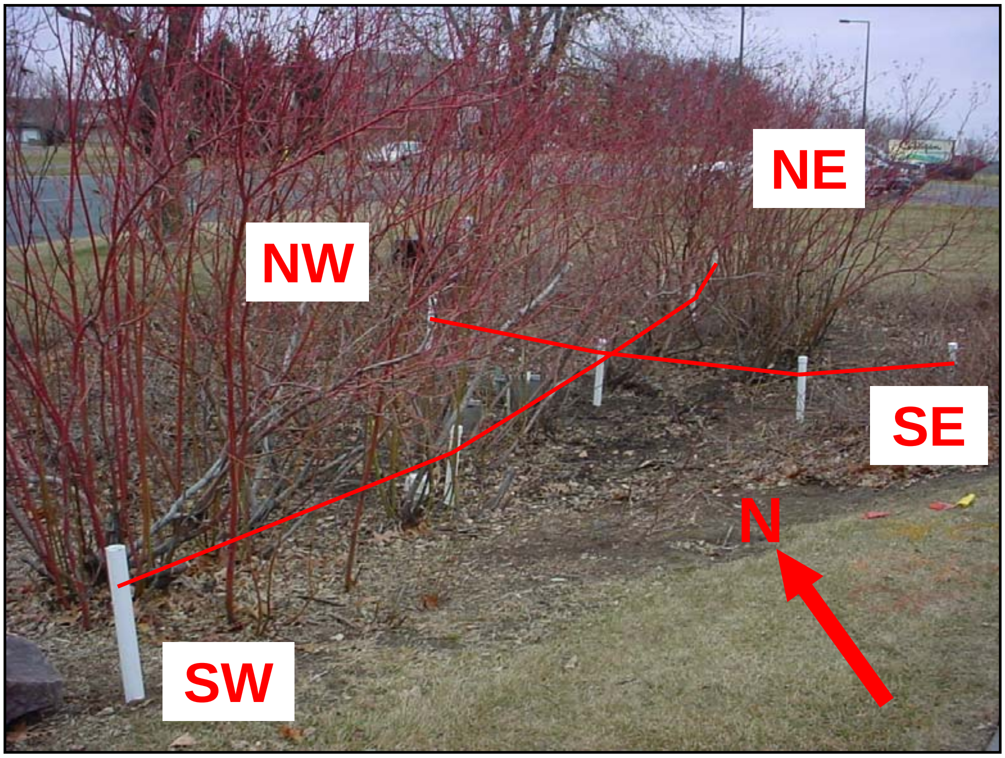

Figure 4-27. Soil moisture probe transect locations for the Stillwater bioretention cell.

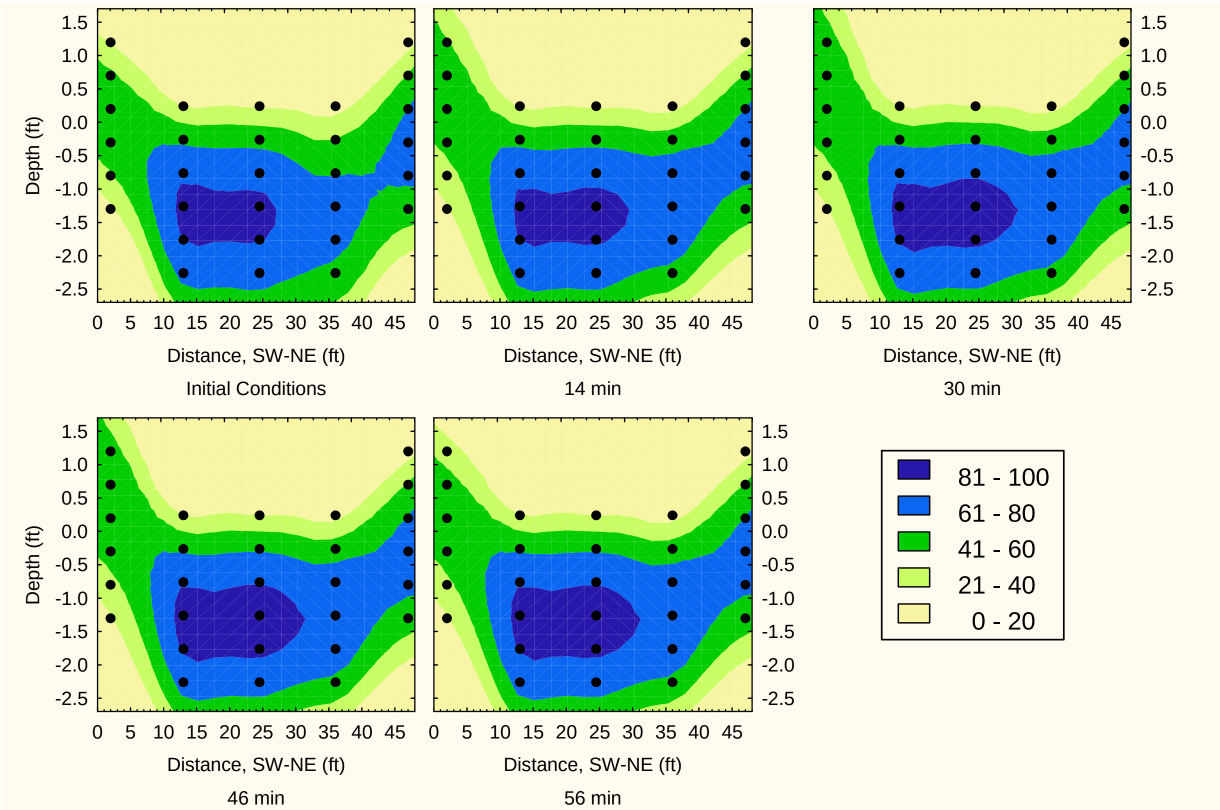

Figure 4-28. Southwest-to-northeast soil moisture profile from January 8, 2008, DVD test at the Stillwater bioretention cell.

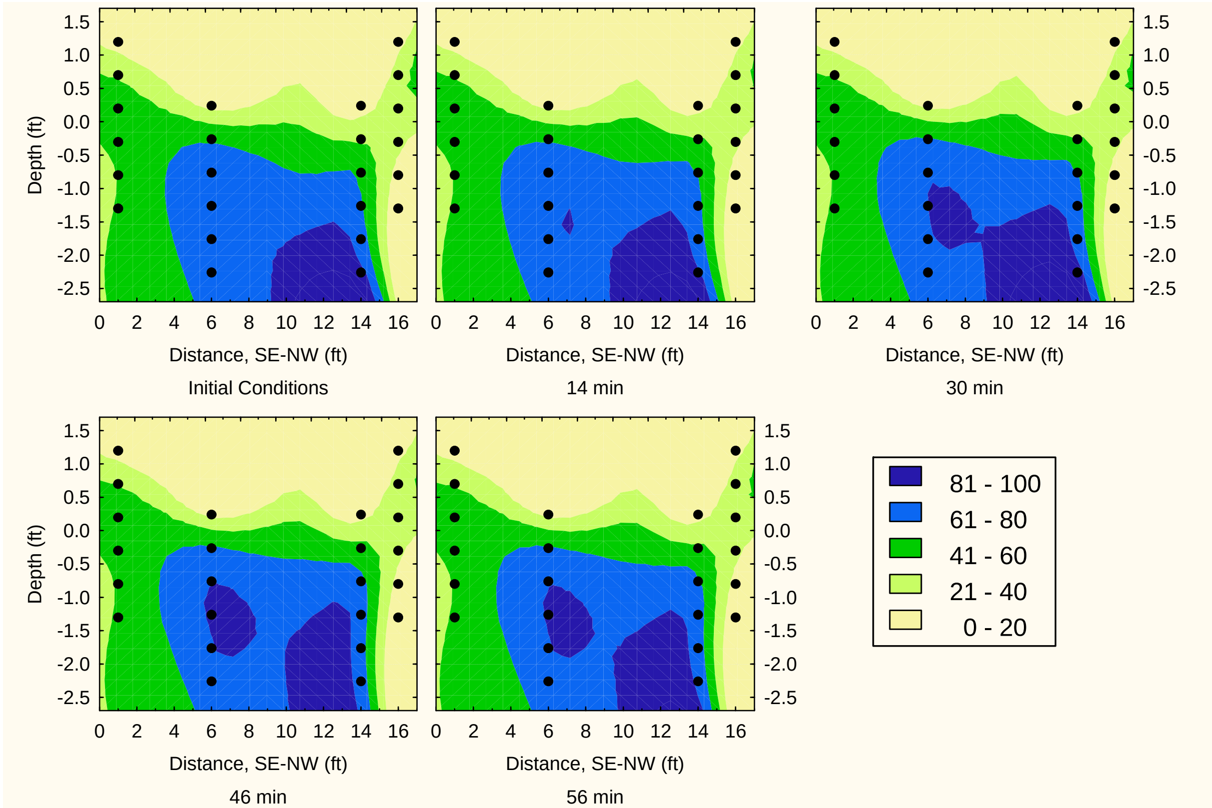

Figure 4-29. Southeast-to-northwest soil moisture profile from January 8, 2008, DVD test at the Stillwater bioretention cell.

The Stillwater site performed the worst mostly due to poor soils including clays and fine organics. Even under conditions without soil frost, infiltration was poor. This system would clearly provide greater function if high-quality amended soils were used and an under-drain was installed above the in-situ clay soils, such as was done at the Thompson Lake bioretention cell.

4.6. Analysis of DVD Tests at All Sites Combined

Study data show a wide range of observed infiltration rates (0.15 – 18.9 in/hr), but indicate that bioretention does work in cold climates.

Overall, 33 DVD tests were conducted at four bioretention cells throughout the greater Twin Cities, MN, area. A single test was added at a fifth site (RWMWD) to determine how it fit into the range of values seen at the four regular test sites. In some cases extremely high infiltration rates were obtained (e.g., 18.9 in/hr) and in other cases, very low infiltration rates were obtained (e.g., 0.15 in/hr). Excluding the Stillwater bioretention cell where clay soils precluded both warm and cold season infiltration, hydrologic performance is sustained throughout the winter season. However, where concrete frost forms, infiltration is very limited, at least under the test water volume and time constraints of this research.

These results are consistent with Muthanna et al. (2008), who conducted a study of two 26-cubic foot bioretention cells at Risvollan Urban Hydrological Research Station in Trondheim, Norway. In her study, Muthanna was able to measure hydraulic detention, storm lag time and peak flow reduction. The study illustrated a clear decreasing trend in lag time between rain events (117 min.), rain-on-snow events (47 min.) and snowmelt events (30 min). In addition, the winter resulted in a lower hydraulic detention time than in the summer which was measured by the total weekly inflow divided by the outflow. The peak flow reduction for 44 storms during the entire study period was 42%. In the winter peak flow reduction was reduced to 27%. It appears that overall, hydrologic function was reduced in the winter, but it is still effective. Likewise, at the WERF sites, hydrologic function was maintained except in the case where concrete frost formed or soils were initially poor.

Table 4-9 illustrates the generally poor correlations (R-squared values) between antecedent conditions and infiltration rates for all 33 DVD tests. Figure 4-31 through Figure 4-34 illustrate in more detail the main trends found from the correlation analysis regarding the driving forces behind cold climate bioretention performance. Note, however, that the major causative relationship is described by a combination of site characteristics.

Table 4-9 Correlations (R-squared values) between infiltration rates and various site characteristics from 33 DVD tests at four bioretention cells.

Site Characteristic		**R^2-value for All Sites**
Soil Temperature (Avg 3-d Daily High)	Surface	0.02 (+)
	0.5 m	0.28 (+)
	1 m	0.34 (+)
Frost Depth		0.20 (-)
Test Water Temperature		0.14 (+)
Snow Cover		0.06 (+)
Soil Water Content (3-d Average)	6-inch	0.01 (-)
	12-inch	0.03 (-)
Chloride Concentration		0.01 (+)
Air Temp (Avg 3-d Daily High)		0.00

Infiltration rates as a function of air temperature are plotted for all 33 DVD tests in Figure 4-30. As identified throughout the analysis of individual study sites, air temperature does not appear to correlate with hydrologic performance. Certainly air temperature ultimately drives soil temperature and, therefore, frost, but average daily high temperatures are not the driving factor. Average daily lows combined with a duration of time could possibly correlate with infiltration rates.

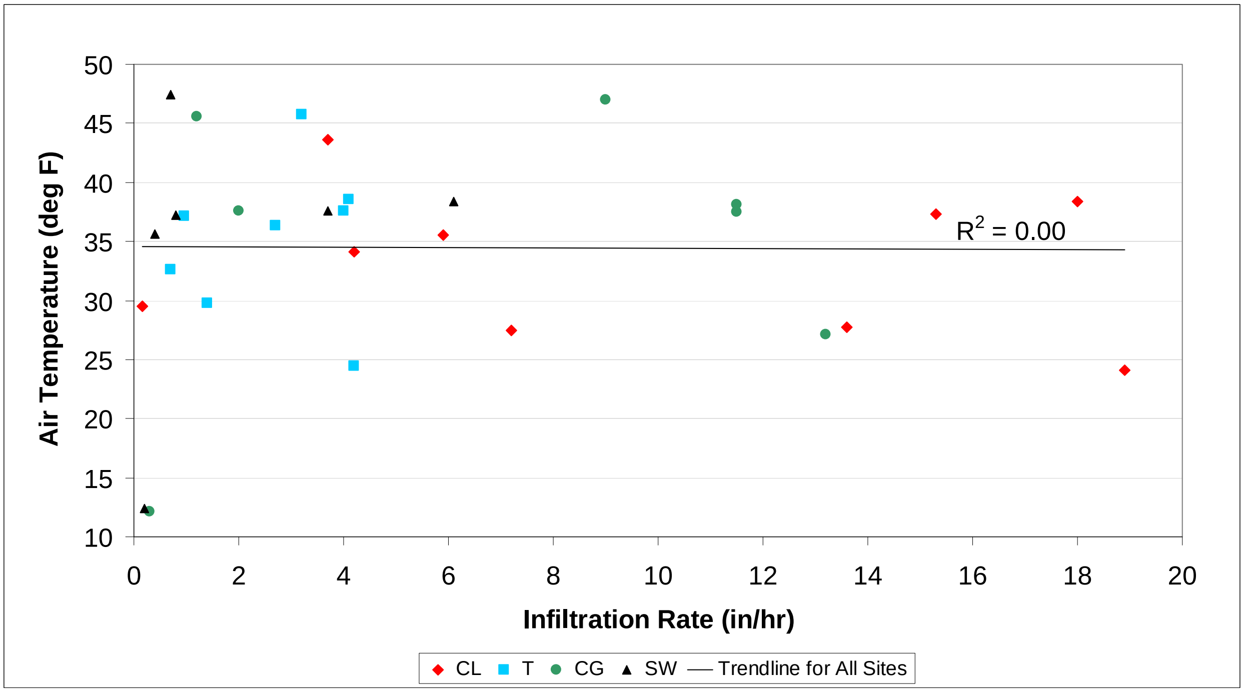

Figure 4-30 Trend between three-day average daily high air temperatures and infiltration rate among 33 DVD tests at four bioretention cells.

Snow cover also illustrated little to no correlation with infiltration rates. Xiuqing and Flerchinger (2001) found that insulation provided by snow cover and amount of soil moisture can dictate the shape of infiltration curves for cold climate bioretention. Anecdotal evidence of unfrozen soils beneath un-compacted snow and frozen soils beneath compacted snow was documented in some of the field notes at the WERF sites. If a data component of duration of cover at certain depths of snow had been collected, snow cover possibly could have correlated with hydrologic performance.

Chloride concentrations had no apparent correlation to infiltration rates. This is strong evidence that while water quality and vegetation may be threatened by chloride in bioretention cells, the hydrologic performance of a bioretention cell is unaffected under the limits of this study. In the long term, soil structure might break down from repeated chloride doses.

Infiltration test water temperature shows a very slight positive correlation (0.14) overall with infiltration rates. Intuitively, warm test water has the capacity to melt ice layers in the soil. Xiuqing and Flerchinger (2001) proved this to be true through a cold climate bioretention study, but it took 80 to 90 minutes of exposure to infiltration water at 48 deg F. The range of water temperature used for the Xiuqing and Flerchinger (2001) study was 39 to 48 deg F, comparable to studies of this type. Test water for the WERF study was generally within this range with occasional temperatures in the 50s. A slight correlation is reasonable based on the literature and our test water temperature. The low correlation and the reality that snowmelt temperature likely has a small range, indicates that there are other factors that have greater influence on cold climate bioretention performance.

Frost depth and soil temperature (at 0.5 and 1 m) have the highest correlation to infiltration rates of all the antecedent conditions analyzed (Table 4-9), but are still relatively minor. They are obviously interrelated. Infiltration rate as a function of frost depth is illustrated in Figure 4-31 for all 33 DVD sites. Note that each site tends to fill out unique portions of the overall trend. For example, the Stillwater site, though exhibiting no high-range infiltration rates, follows the trend that where frost depth is deep, infiltration rates are low.

Figure 4-31 illustrates a second important trend. Crystal Lake has both the fastest observed infiltration rates as well as the slowest. The fast performance is likely due to the fact that Crystal Lake resulted in relatively low occurrences of deep frost and benefits from the free draining sands and gravel underlying the site. The slowest observed rate was likely due to the presence of concrete frost. The sandy soils of Cottage Grove exhibited more occurrences of frost greater than 1-m deep than the engineered soils of Crystal Lake (also very sandy, but in the presence of sandy loam). Contrastingly, poor clays and fine organics in at the Stillwater site precluded hydrologic performance and likely facilitated the occurrence of frozen soils by holding in moisture which ultimately froze with the onset of cold temperatures. Only one DVD test at Stillwater resulted in no soil frost. Caraco and Claytor (1997) found that for successful infiltration of snowmelt, infiltration rates need to be at least 0.5 in/hr and clay content less than 30%. The *Minnesota Stormwater Manual* (MN Stormwater Steering Committee, 2007) recommends that bioretention soil mixes contain less than 5% clay, preferably zero. The importance of good soils during the growing season is widely understood. While the benefits of good soils may be different in cold climates, good soils are equally, if not more, important under cold conditions.

Asleson (2007) studied nine bioretention cells in the greater Twin Cities region. Three of the cells studied were the Crystal Lake, Thompson Lake and Cottage Grove bioretention cells from this WERF study. She collected soil samples and identified bulk densities (g/cm^3) for the soil matrix of each cell. In increasing order, they were 1.096±0.175 (signifying loams and clays) for Thompson Lake, 1.128± 0.218 (silty sands or sandy loams) for Crystal Lake and 1.573±0.076 (sands) for Cottage Grove. Generally, soils with the highest bulk density produce the highest infiltration rates. This trend was found to be true; however, the Cottage Grove bioretention cell, though having the highest bulk density, was out-performed by the Crystal Lake cell. Xiuqing and Flerchinger (2001) found a similar deviation from the typical relationship of bulk density and infiltration. Deep ploughing treatments enabled higher infiltration for soils with low bulk densities than those with high bulk densities. Xiuqing and Flerchinger (2001) also found that as frost depth increased, soil bulk density became a minor factor compared to the effects of water content and frost depth.

The vegetation at the Crystal Lake site and the Stillwater site also starkly contrasted. Crystal Lake includes a matrix of deep-rooted native vegetation including both herbaceous and woody plants. Alternatively, the Stillwater site includes mainly three species of woody plants. Soils are certainly the dominating factor relating to hydrologic performance. However, plants can be a key component in hydrologic performance through both evapotranspiration and creation of preferential flow paths along roots. Plants are also a key element in water quality treatment including nutrient update and phyto-remediation of heavy metals (Muthanna, 2007).

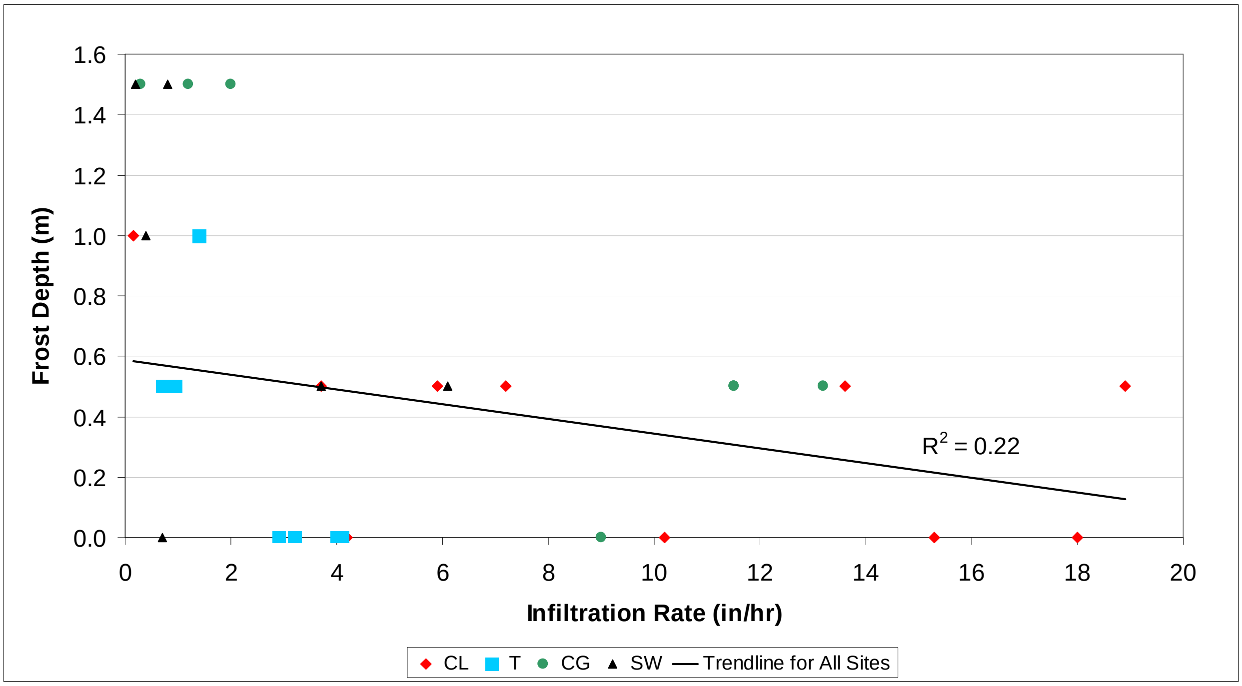

Figure 4-31 Limited correlation of frost depth with infiltration rate among 33 DVD tests at four bioretention cells.

Infiltration rates increase as soil temperatures increases. The trend is illustrated in Figure 4-32. Surface soils temperatures that are more temporally variable, demonstrate less of a trend. This relates to the important component of the duration of soil temperatures rather than just the magnitude. More stable 0.5-m and 1-m temperatures demonstrate increasing correlation with infiltration rates (0.28 and 0.34, respectively).

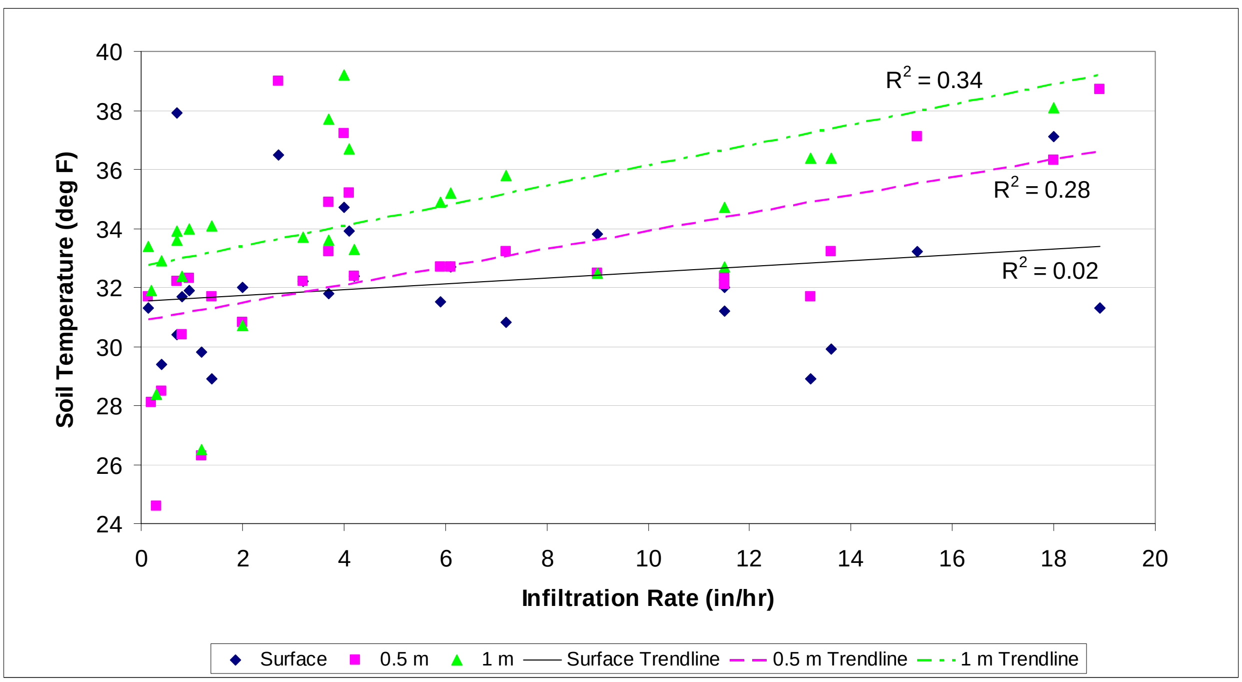

Figure 4-32 Increasing infiltration rates with increasing soil temperature among 33 DVD tests at four bioretention cells.

It is surprising that soil water content at the 6-in and 12-in depth had extremely low R-squared values of 0.01 and 0.03, respectively (see Figure 4-33), since frost depths and characteristics are so directly related to soil water content prior to the onset of freezing soil temperatures (Muthanna, 2007). Muthanna et al. (2008) studied two 26-cubic foot bioretention cells for a 10-week winter period and found that the key parameters to hydrologic performance were inter-event period (dry out) and seasonal air temperatures. Figure 4-34 illustrates the combined effect of soil temperature and soil water content on infiltration rates at the WERF sites, and the trend is clear. When saturated soils meet freezing soil temperatures (the definition of concrete frost), infiltration is severely inhibited (e.g. Stillwater DVD test at over 60% soil water content). Contrastingly, when soils are dry and temperatures are high (relative to a cold climate condition) infiltration rates can be very high. 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 (Muthanna, 2007; Stoecker and Weitzman, 1960). The 18.9 in/hr infiltration rate at Crystal Lake had soil frost to a depth of 0.5 m, likely indicative of the presence of porous frost possible in most of these cold climate DVD tests.

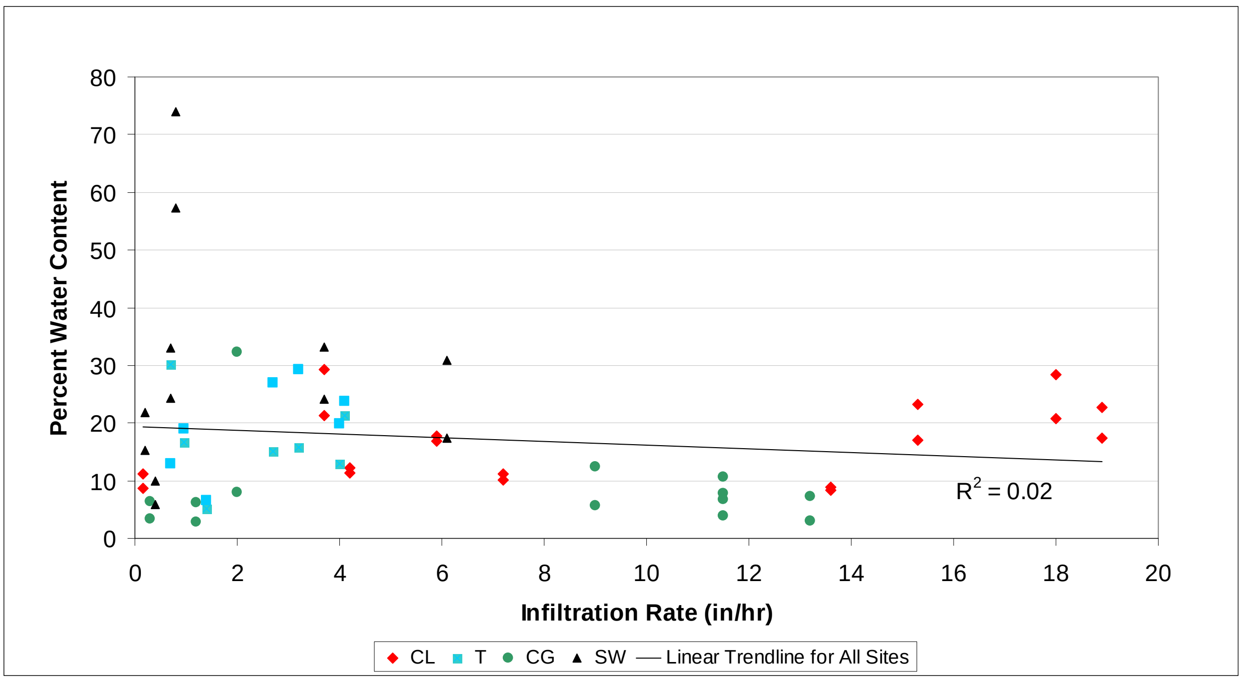

Figure 4-33 Little to no trend between infiltration rates and three-day average percent water content among 33 DVD tests at four bioretention cells.

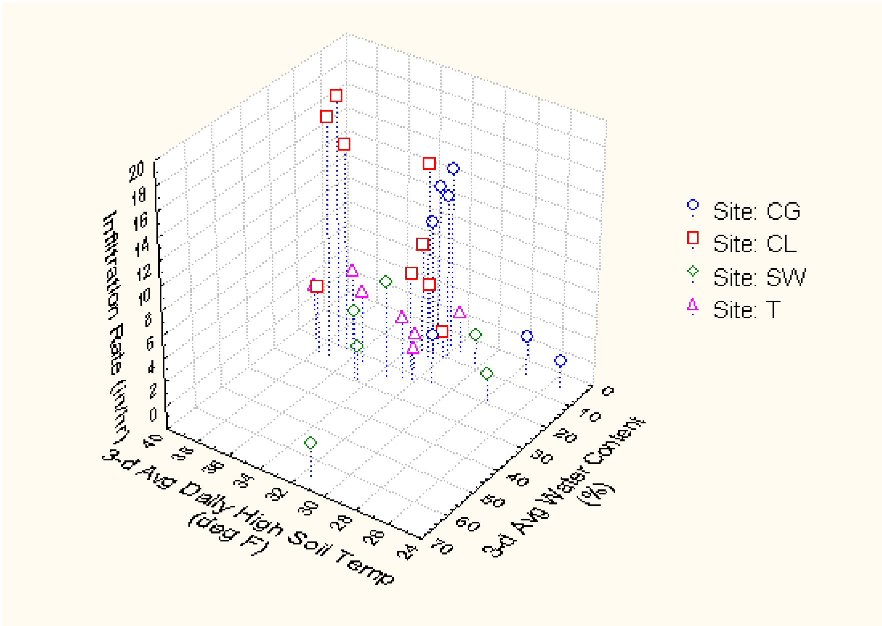

Figure 4-34 Combined effect of soil temperature and water content on infiltration rates among DVD tests at four bioretention cells.

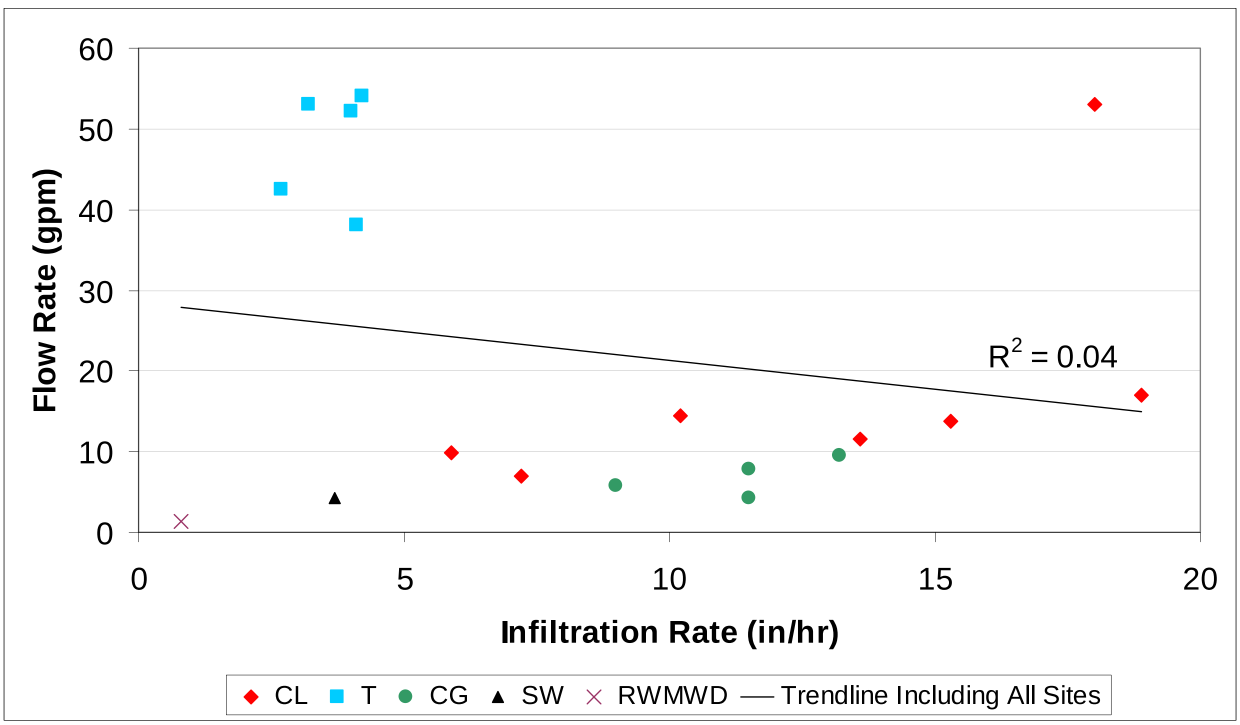

Figure 4-35 Calculated inflow rates compared to flow rates among DVD tests where complete drawdown occurred at four bioretention cells.

Calculated inflow rates in Figure 4-35 were calculated based on the known inflow volume and the time elapsed from the beginning of test water application to complete drawdown. This number differs from the *observed infiltration rate* (inches per hour from the time the test water application stopped) and is measured in gallons per minute (gpm) as the time to empty all added water out of the cell. The Thompson Lake bioretention cell experienced the highest flow rates even though it has the largest ratio of drainage area to bioretention cell area of all the four sites (approximately 53:1 if only the northern wetted test area is considered; 19:1 including the entire cell even areas that only came into contact with the test water once during the study). That is, even though low infiltration rates (less than 5 in/hr) were experienced by the Thompson Lake bioretention cell, the cell is capable of treating large flows (approximately 40 to 55 gpm). The reasons for this are the large size of the cell and the amount of test water added amounted to only 0.15 inches over the entire watershed (45% impervious) draining to the cell. This volume covered only 1,300 of the cell's 3,600 SF, or approximately one-third of its area. In other words, when designed to hold a suitable design volume of runoff water (for example, one inch of runoff), even a system with a low to moderate infiltration rate can infiltrate/filter a fair amount of runoff under cold conditions.

4.7. Ramsey-Washington Metro Watershed District (RWMWD) Bioretention Cell (Supplemental Test)

On February 5, 2008, a single DVD test was conducted on a 320 SF bioretention cell located at the RWMWD offices. This fifth site was added late in the study (Season 3) after construction and establishment were complete in order to test whether the findings from the four study sites were consistent with this site. This system was specifically designed to treat adjacent street runoff. The system has been monitored by the RWMWD and internal annual reports find it to be highly effective in reducing the impact of street runoff. Figure 4-36 shows that 400 gallons of test water infiltrated within about 6 hours at a steady infiltration rate of 0.8 in/hr and an approximate flow rate of 1.3 gpm. During this DVD test, the basin had an unknown depth of snow and chloride was added at a concentration of 100 mg/l. Near-complete drawdown occurs in this bioretention cell with engineered soils. Based on antecedent soil temperatures from the nearest two study sites (Thompson Lake and Stillwater), the RWMWD bioretention cell is likely to have had at least a 0.5 m frost depth during this DVD test (see Appendix B). Infiltration is active and steady. As in the case of Crystal Lake, engineered soils appear to be capable of infiltration even in the presence of frost.

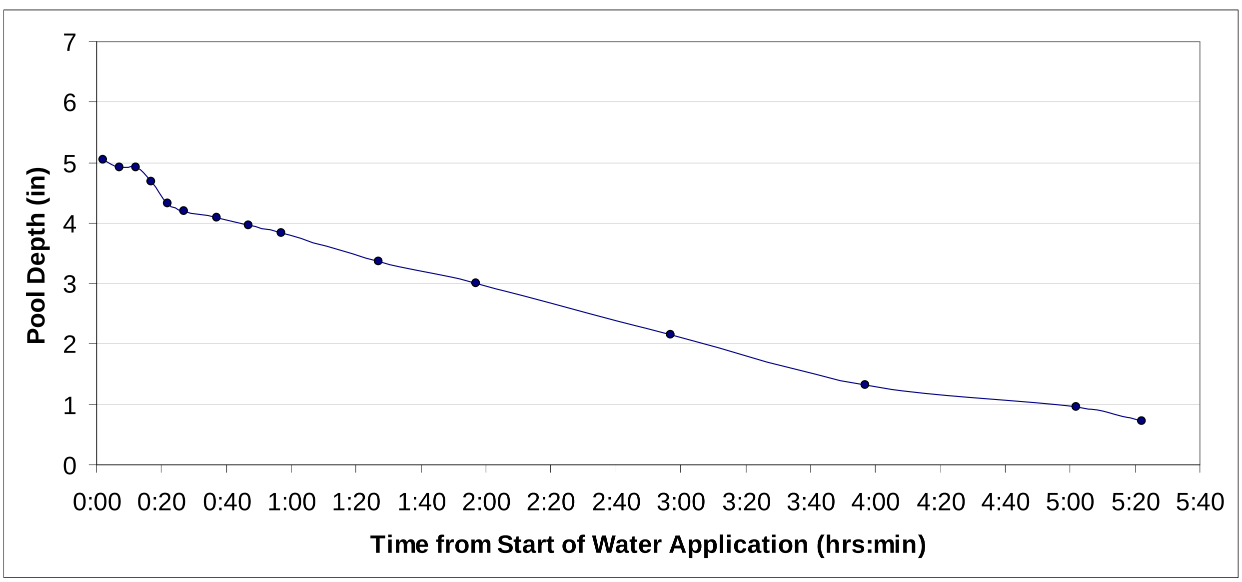

Figure 4-36. Drawdown of the February 5, 2008, DVD test at the RWMWD bioretention cell exhibiting an infiltration rate of 0.8 in/hr.

4.8. Results from Season 1 Double-Ring Infiltrometer Tests

Though double-ring infiltrometer testing was not effective in the long term due to freezing and preferential thawing, some findings resulted from the brief period of use (Season 1 only). Winter 2005-06 sampling typically showed good results from first, maybe even second, tests, but then a dramatic decrease in infiltration rates due to freezing as shown in Table 4-10 results from the Thompson site. Table 4-10 also shows that though the soil at the centrally located ('main') infiltrometer froze, the satellite test site (slightly up-gradient of the main site) continued to drain successfully and was operable during the entire season at over 14 in/hr. This may be an indicator that somewhat drier upland areas have a lower tendency to freeze and are hence more receptive to infiltration as the season progresses. Infiltrometer test results from the Stillwater cell never showed good infiltration rates, corresponding to results from the DVD tests. However, the Cottage Grove bioretention cell peaked at 3.09 in/hr which is much less than that of some of the DVDs tests. This may be an indicator of the spatial variability in infiltration rates as found by Asleson (2007) in the summer months at the same sites. Asleson (2007) tested nine bioretention cells in the greater Twin Cities region including three of the four WERF cells: Crystal Lake, Thompson Lake and Cottage Grove.

Table 4-10. Initial results of double-ring infiltrometer testing at the Thompson Lake bioretention cell during Season 1 (winter 2005-2006).

Date	Main	Satellite
1/11/2006	14.4 in/hr	14.4 in/hr
1/26/2006	7.9 in/hr	20.2 in/hr
2/14/2006	0.0 in/hr	16.8 in/hr
3/1/2006	ICE	16.6 in/hr

While freezing was an issue with infiltrometer testing, so was artificial heating as described in Chapter 3. Different techniques are required if infiltrometer testing is a preferred method. At the outset of their double-ring infiltrometer tests, Xiuqing and Flerchinger (2001) were aware of the micro-climate created by the instruments. Before the testing season, they installed enough rings to use an unused infiltrometer for each test throughout the winter. However, the WERF bioretention cells did not allow space for this approach. As in the WERF study, Xiuqing and Flerchinger (2001) found at the location of metal infiltrometers both freezing of saturated soils and due to the sun reflecting off the side walls, preferentially thawed soil.

CHAPTER 5.0

CONCLUSIONS

5.1. Cold Climate Hydrologic Performance Findings

The results of evaluating three years of cold climate performance data from the four existing bioretention systems produced the hydrologic performance findings discussed below.

5.1.1. Crystal Lake Performance Findings

Observed Infiltration Rates

- The 10 DVD observed infiltration rates varied from 18.9 inches/hour to 0.15 inches/hour.
- Of the 2008 observed infiltration rates, the fastest rates occurred early in the testing season and clearly showed a decreasing trend toward spring.
- The average observed infiltration rate was 9.7 inches/hour.
- Five observed infiltration rates were faster than the average and five were slower.
- One observed infiltration rate was remarkably slow, suggesting concrete frost may have been a factor.

Calculated Inflow Rates

- The DVD test water volume was absorbed into the cell within the one hour test period in seven out of 10 tests. (70%)
- Of the seven completed DVD tests, the calculated inflow rate varied from 53 gallons/minute to 7.0 gallons/minute.
- The average calculated inflow rate was 18 gallons/minute.
- The average calculated inflow rate per square foot was 0.045 gpm/SF.

5.1.2. Thompson Lake Performance Findings

Observed Infiltration Rates

- The eight DVD observed infiltration rates varied from 4.2 inches/hour to 0.70 inches/hour.
- Of the 2008 observed infiltration rates, the fastest rates occurred in early winter during the testing season and clearly showed a decreasing trend and then rose sharply in the spring.
- The average observed infiltration rate was 2.7 inches/hour.
- Five observed infiltration rates were faster than the average and three were slower.
- Two observed infiltration rates were remarkably slow, suggesting concrete frost may have been a factor.

Calculated Inflow Rates

- The DVD test water volume was absorbed into the cell within the one hour test period in five out of eight tests. (63%)
- Of the five completed DVD tests, the calculated inflow rate varied from 54 gallons/minute to 38 gallons/minute.
- The average calculated inflow rate was 48 gallons/minute.
- The average calculated inflow rate per square foot was 0.037 gpm/SF.

5.1.3. Cottage Grove Performance Findings

Observed Infiltration Rates

- The seven DVD observed infiltration rates varied from 13.2 inches/hour to 0.30 inches/hour.
- Of the 2008 observed infiltration rates, the fastest rates occurred in early winter during the testing season and clearly showed a decreasing trend and then rose sharply in the spring.
- The average observed infiltration rate was 6.9 inches/hour.
- Four observed infiltration rates were faster than the average and three were slower.
- One observed infiltration rate was remarkably slow, suggesting concrete frost may have been a factor.

Calculated Inflow Rates

- The DVD test water volume was absorbed into the cell within the one hour test period in four out of seven tests. (57%)
- Of the four completed DVD tests, the calculated inflow rate varied from 9.6 gallons/minute to 4.2 gallons/minute.
- The average calculated inflow rate was 6.7 gallons/minute.
- The average calculated inflow rate per square foot was 0.017 gpm/SF.

5.1.4. Stillwater Performance Findings

Observed Infiltration Rates

- The seven DVD observed infiltration rates varied from 3.7 inches/hour to 0.20 inches/hour.
- Of the 2008 observed infiltration rates, the fastest occurred in early winter and showed a decreasing trend toward spring.
- The average observed infiltration rate was 1.1 inches/hour.
- Two observed infiltration rates were faster than the average and five were slower.
- Five observed infiltration rates were remarkably slow, suggesting concrete frost may have been a factor.

Calculated Inflow Rates

- The DVD test water volume was absorbed into the cell within the one hour test period in only one out of seven tests. (14%)
- Of the one completed DVD test, the calculated inflow rate was 4.9 gallons/minute.
- The calculated inflow rate per square foot was 0.007 gpm/SF.

5.2. Conclusions

This study was structured to explore the movement of water into and through the soil profile of four existing bioretention cells during cold climate conditions. The study completed its objective to monitor and quantify the individual performance responses of each of the studied cells under full scale winter conditions.

In the largest sense, the observed performance responses of the bioretention cells were products of the natural cold climate conditions and the soil conditions encountered during the study. Winter conditions consist of an ever changing variety of unpredictable weather events that set into motion a complex, interactive relationship between the various factors that drive the hydrologic functions within the bioretention cells. While the overall study data clearly showed the wide range of observed performance was reflective of the wide range of climate driven influences, the data did not show strong correlations between hydrologic performance and individually measured factors.

The data clearly showed the following conclusions:

- Three of the four studied bioretention cells remained hydrologically active during cold climate conditions most of the time. The fourth cell, although infiltrating some water, appeared limited in both warm and cold weather due to its poor draining soils.
- The observed infiltration rates within each cell varied widely during the testing season.
- The bioretention cells that performed well under warm conditions were observed to perform well under cold conditions; and the cell that did not perform well in warm conditions, did not perform well under cold conditions.

This study addressed four main questions.

1. Are bioretention systems hydrologically functional in the winter?

A qualified yes. With the exception of the Stillwater cell, which has inherently poor soils, the data indicated the hydrologic performance of the studied cells was characteristically reliable throughout the study. At the Crystal, Thompson and Cottage Grove cells, the entire amount of Direct Volume Discharge (DVD) test water was absorbed into the cell within the test period 16 out of 25 tests (64%) clearly indicating these cells were capable of infiltrating water during cold climate conditions most of the time. The Stillwater cell only absorbed the test water volume within the test period 1 out of 7 tests (14%) indicating limited performance most of the time.

The Stillwater cell infiltrated very slowly (if at all) under cold climate conditions. However it was noted the Stillwater cell was observed to have poor hydrologic performance during warm climate conditions as well. The Crystal Lake, Thompson Lake and the Cottage Grove cells were all observed to have good hydrologic performance during warm climate conditions.

2. What range of hydrologic performance is likely during cold climate conditions?

The range of observed infiltration rates spanned from very fast to virtually zero depending on the influencing factors. The Crystal Lake cell recorded the widest range of observed infiltration rates (18.9 to 0.15 in/hr), followed by the Cottage Grove cell (13.2 to 0.30 in/hr), the Thompson Lake cell (4.2 to 1.4 in/hr) and the Stillwater cell (3.7 to 0.20 in/hr). Characteristically, the fastest rates occurred early winter in the testing season and progressively slowed as the tests were completed later in the season toward spring. The data also showed the fastest infiltration rates occurred when the soils were warm and dry; the infiltration rates decreased as the soils became colder and wetter. The data indicated that each bioretention cell operated within its own performance range unique to its specific location.

3. Which factors most affect winter hydrologic performance?

Within each bioretention cell, the influencing factors of soil temperature, soil texture and soil moisture combined to affect the observed infiltration rate dramatically. Of the monitored factors, the data indicated that soil temperature had the strongest correlation to performance and soil moisture the weakest. Overall, the data suggested that hydrologic performance was most strongly influenced by the sum of the combined factors. Due to the complex and interrelated nature of those factors, this study was not able to further define or quantify the individual relationship ratios of these factors tied to hydrologic performance; and many questions remain.

Anecdotal observations indicated a key component linking these factors is soil texture and the permeability of frost. For example, a combination of cold, wet, and fine textured soils at the Stillwater cell seemed to be more susceptible to concrete frost than are corresponding cold, wet and coarse textured soils at the Crystal cell. The combination of soil moisture and soil temperature was the leading antecedent condition that drove the presence and type of frost. Where cold temperatures met wet soils, concrete frost was most likely to develop. Where soils were frost-free, independent conditions at varying degrees drove hydrologic performance. For instance, bioretention cells with wet soils prior to a simulated runoff event did not perform as well as a cell with antecedent dry soils.

4. Can systems be designed to optimize cold climate performance?

Yes. The Crystal, Thompson and Cottage Grove cells had the fastest observed infiltration rates and clearly demonstrated successful operations under cold climate conditions. While the factors which most influenced that success were not well defined by this study, it was apparent these three functioning cells shared common characteristics such as free draining granular soils that were observed to perform well under warm climate conditions. Field observations concluded that expanding on the design components that optimize warm climate performance would likely optimize cold climate performance.

5.3. Recommendations for Future Studies

DVD Tests: Tests worked well.

DVD tests were found to be highly effective in understanding cold climate bioretention performance. Findings from this study can improve the design and scope of future studies. Due to time and budget constraints, some DVD test measurements did not continue through complete drawdown of the bioretention cell.

DVD Tests: Continue Measurements through Complete Cell Drawndown

A future study could benefit from pool depth and soil moisture probe measurements through complete cell drawdown. DVD tests and corresponding infiltration rate and soil moisture measurements provide substantial information on the performance of cold climate bioretention. Future studies could attempt a higher quantity of DVD tests for a stronger development of trends.

Test Water Quality

Since effective quantitative cold climate bioretention testing (via DVD tests) has been established at the WERF study sites, water quality testing and measurement could be effectively incorporated at these sites by sampling the inflow and outflow to compare pollutant loads.

DVD Tests: Use More Test Water

In the DVD tests, the amount of water added varied, but in all cases was less than 0.25 inches over the contributing area. The logistics of transporting or pumping water into the cells in such a way as to not disturb the cell dictated a certain volume of water. Similarly, in all cases, very little of the storage capacity of the bioretention cell was used for holding the added volume. Future DVD tests should utilize a volume of test water sufficiently large to reach the full extents of the bioretention cell and, where possible, closer to the equivalent of one inch of runoff from the drainage area.

Refine Monitoring and Test Procedures for Frozen Conditions

An effective monitoring system does not freeze-up during the cold season. Double-ring infiltrometers tend to freeze solid due to cold season testing. They are useful if enough are installed prior to the winter such that no infiltrometer is used more than once throughout the testing season. This requires a test cell large enough to handle multiple infiltrometers. Frost tubes can be effective but tended to freeze-up and prevent data collection. A secondary or supporting frost depth measurement system (e.g., soil temperature) is recommended.

Characterize Soil Frost

Field notes on bioretention cell conditions prior to DVD tests could be benefitted by a characterization of the soil frost, when frost is present, before every test. On the spot, soil excavation would be compared with soil temperature readings and antecedent soil moisture content. In fact, a study could be orchestrated that establishes for a single bioretention cell, different types of frost for different DVD tests. Under this controlled environment, the mechanisms of infiltration of each frost type could be better analyzed.

Conduct Year-Round Testing

The scope of this study was limited to measuring cold climate performance. Future studies would benefit by conducting year-round testing of a series of bioretention cells to compare cold climate performance with warm climate performance.

CHAPTER 6.0

DESIGN RECOMMENDATIONS

6.1. Introduction

The purpose of this chapter is to translate the conclusions of the study into practical recommendations and technical guidance that can be applied by stormwater professionals who design, construct and maintain bioretention systems operating under cold climate conditions. These recommendations are not meant to replace the design criteria already in use for warm climates, but rather used to supplement those existing criteria with the knowledge gained through the study to optimize designs for operating in cold climate conditions. The study found that:

> *The bioretention cells that performed well under warm conditions were observed to perform well under cold conditions; and the cell that did not perform well in warm conditions, did not perform well under cold conditions.*

This simple finding suggests the best way to optimize performance for cold climate operations is to design, construct and maintain well performing warm climate systems. Further study effort was made to identify the design elements and functional characteristics of the three cells that functioned well.

In comparing the design, construction, maintenance, and functional characteristics of the three Crystal, Thompson and Cottage Grove cells, a pattern of common characteristics developed that established the core of the cold climate recommendations provided in this study. In contrast, the fourth cell, Stillwater did not share these characteristics.

1. All three cells had sufficient surface area to accommodate its entire design runoff treatment volume within a surface pool less than one foot deep.
2. All three cells were observed to have adequate capacity to infiltrate the volume of runoff received during the interim snowmelt events within a working pool depth between 0.3 feet to 0.6 feet. During the large spring melt event, the cells filled to capacity and bypassed the high flows.

3. Highly permeable, well-draining coarse granular materials, (void of fine silts and clays), decreased the duration time of soil saturation to minimize freezing and to restore soil capacity to accommodate future melt events.
4. Investigation of installation methods indicated that efforts were made during the installations to protect the infiltration capacity of the soils, both under and within, the cells to avoid soil compaction, smearing and damage from construction sediment.
5. Regular maintenance was provided in the years following their installations to remove sediment buildup at the inlets, remove debris/weeds and sustain the health of the vegetation within the cells.

Based on field observations, an operational theory of the basic manner in which the bioretention cells operate in cold climate was developed (see Figure 6-1). The graphic represents hydrologic performance phases during cold climate operations and describes the changing factors thought to most influence hydrologic performance. Over the three year study, the Crystal, Thompson and Cottage Grove cells operated within the active phase, at various observed infiltration rates, approximately 84% of the time during the cold climate season. All three cells became occasionally hydrologically restricted during extended periods of air temperatures well below freezing; and all were flooded beyond capacity for brief time periods during large spring snowmelt events.

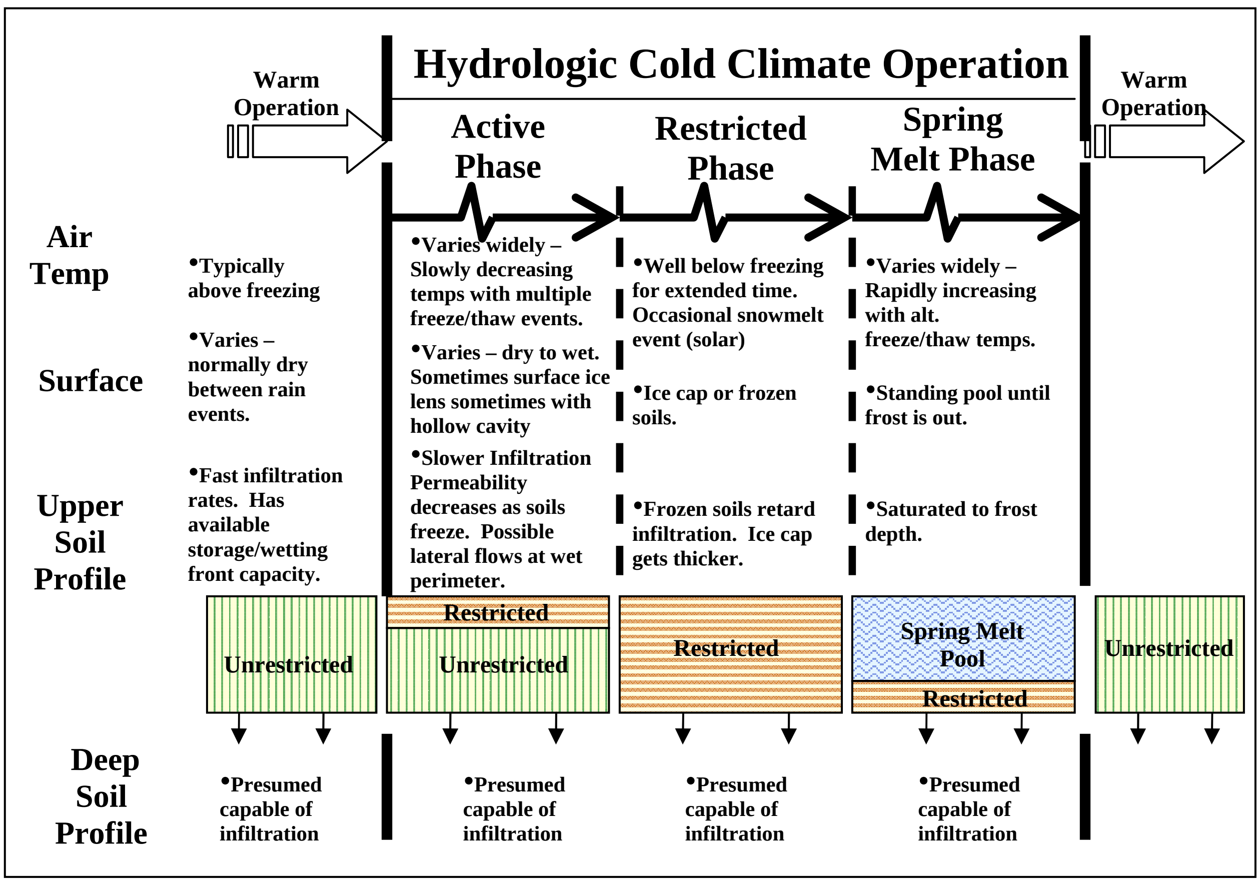

Figure 6-1 Cold climate bioretention operation theory based on observations.

6.2. Study Recommendations to Optimize Cold Climate Performance

Accompanying this report is the guidance document *Recommendations to Optimize Hydrologic Bioretention Performance for Cold Climates (October 2008).* Completed as part of this study, the guidance document provides practical recommendations and technical information that can be applied by stormwater professionals who design, construct and maintain bioretention systems operating under cold climate conditions.

The list of recommendations within the guidance document are not all inclusive and many other best management practices many be applicable that also may improve performance. The recommendations within the guidance document are not meant to replace the design criteria already in use for warm climates, but rather to supplement those existing criteria with the knowledge gained by the cold climate study to optimize designs for operating in cold climate conditions.

The guidance document presumes the design professionals utilizing the recommendations are proficient in hydrology, stormwater management, water quality issues and are current with low impact development technologies and concepts without further explanation. Therefore, the information supporting each recommendation is presented in a format that only lists brief self-evident statements which spotlight key criteria and design elements in terms easily recognizable by stormwater professionals.

The guidance document does not duplicate available published information or provide detailed explanation of warm climate bioretention design or operations. The user of the document is advised to refer to Chapter 12-6 Bioretention of the *Minnesota Stormwater Manual (2007)* for that information. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

The study recommendations are briefly summarized below. The user is advised to refer to the guidance document *Recommendations to Optimize Hydrologic Bioretention Performance for Cold Climates (October 2008)* for further information.

Study Recommendation No. 1:

Bioretention cells operating in cold climates should be designed to have sufficient surface area to accommodate its entire designed water quality treatment volume within a surface pool less than one foot deep.

- Bioretention cells should be designed for low flow water quality treatment for runoff resulting from small events. Bioretention cells are not a high flow rate control devices and pool depth should be limited to less than 1 foot.
- Bioretention cells must be sized in compliance with regulatory criteria to treat various applicable water quality treatment requirements.

Study Recommendation No. 2:

Design infiltration rates should not be applied to predict cold climate hydrologic performance. Under cold climate conditions bioretention cells operate within a wide range of infiltration rates that are unpredictable and may reduce to near zero at any time during cold climate conditions.

- The range of observed infiltration rates varied from very fast to nearly zero depending on very unpredictable site conditions.
- Very high rates of infiltration were observed during some tests, but could not be relied upon for consistency all winter.

Study Recommendation No. 3:

Using engineered soils with known permeability and performance characteristics is recommended for cold climate operations. Highl**y** permeable, free draining soil similar to Mix B: Enhanced Filtration Blend performed well (*Minnesota Stormwater Manual;* http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html). The use of existing onsite (in-situ) soils or topsoil blends should only be considered if controlled testing certifies the permeability and performance of those soils is equal to or greater than Mix B engineered soils.

- The use of soils with unknown performance should be avoided. Only a very small percentage of fines or clay has the potential to severely reduce soil performance and increase susceptibility to freezing.
- Engineered soils consisting of coarse wash sand and compost worked well. The *Minnesota Stormwater Manual* went to great lengths to research soil mixes necessary for successful bioretention operation (MN Stormwater Steering Committee, 2007). The following recommendation resulted from that research:

  Mix B Enhanced Filtration Blend**:** *A well blended, homogenous mixture of 20-70% construction sand: and 30-50% organic leaf compost is necessary to provide a soil medium with a high infiltration/filtration capacity.*
  Sand: *Provide clean construction sand, free of deleterious materials. AASHTO M-6 or ASTM C-33 with grain size of 0.02"- 0.04"*
  Organic Leaf Compost: *Mn/DOT Grade 2*

  Note: Mix A: Water Quality Blend is not recommended since its specification allows topsoil with a maximum of 5% clay (based on an ideal of zero clay content) to be used (MN Stormwater Steering Committee, 2007). In reality topsoil of that quality is not available and the field verification of the specification for clay content is difficult.

Study Recommendation No. 4:

Avoid use of fine textured soils containing silt or clay particles within the cell; they infiltrate slowly increasing their susceptibility to freezing. Over-excavation to remove slow draining soils and replacement with engineered soils is advised.

Study Recommendation No. 5:

Cell design should be off-line to bypass high flows. Design pool depths should be less than 1 foot deep and recede within 12 hours or less to minimize potential for freezing.

- Cells that utilize the same entrance and exit flow path upon reaching pooling capacity are considered to be an off-line cell design.
- Cells should be off-line designs that only allow low flow to enter the cell. The low flow volume of runoff during interim snowmelt events created a working pool

depth between 0.3 feet and 0.6 feet deep that effectively infiltrated into the soils before freezing.

- During the large spring melt event, the off-line cells filled to overflow capacity and bypassed the high flows. High flows should not cross the cell.
- Curb-cuts need to be a least five feet wide and gutter pans sloped at least three inches to avoid run by. Adjacent curb inlet casting should be raised at least one inch higher than the gutter flow lines.
- Easily maintained grass turf at curb-cuts is preferred to filter sediment.
- The top of sod should be two inches below the lowest point of the curb-cut to minimize ice and debris blockage.
- Reinforce the down-slope inflow path all the way to the lowest point in the cell to minimize erosion.
- Plant materials should be nursery grown plug or pots. (Do not seed cells)

Study Recommendation No. 6:

The installation of an under-drain system with an accessible cap or valve at its outlet is recommended to allow the option of operating the bioretention cell as either an infiltration system (valve closed) or a filtration system (valve open). Residence time for water quality treatment can be managed by adjusting a partially open valve.

- Opening the subdrain valve may allow early-fall drawn down in preparation for freezing weather.
- It is better to open the valve to have a functional filtration system then a non-functional (frozen) infiltration system.

Study Recommendation No. 7:

Avoid reducing the infiltration capability of the underlying soils during installation by avoiding compaction, smearing and damage from construction sediment.

- Installation should only be done during periods of dry weather.
- All stormwater during construction must be diverted until all disturbed soils up gradient of the cell have been stabilized and impervious surfaces cleared of all construction sediments.
- Construction equipment should not be allowed into the basin area; except that a tracked skid loader may be used for spreading the enhanced soil mixture after the first 1.5 feet of enhanced filtration blend soil has been placed in the excavated bottom.
- Excavate with a backhoe equipped with a toothed bucket to avoid compacting or smearing the underlying soils.
- Underlying soils in the excavated bottom and side slope soils should be ripped 18 to 24 inches deep to remove compaction.

- The bottom of the excavated cell should be flat and level (not parabolic and sloped)
- Care must be taken to avoid contamination of enhanced filtration soils during excavation and backfilling operations.

Study Recommendation No. 8:

Regular maintenance is needed provided to remove sediment buildup, remove debris/weeds and sustain the health of the vegetation within the cells.

- Cell should be kept off-line until the vegetation within the cell is well established.
- Plant materials should be deep rooted native species. The dense matrix of deep roots provided by native vegetation creates long downward flow paths as roots decay. All plants used should be salt tolerant because of the likelihood of street, road and parking lot runoff having high salt concentrations. Lists of salt tolerant vegetation are available in most states. A representative list and additional references are available in Appendix E of the *Minnesota Stormwater Manual* (MN Stormwater Steering Committee, 2007).
- Ongoing maintenance should be provided to include watering plants during dry weather periods, controlling weed growth, replacing/enhancing mulch, pruning, thinning and replacing unhealthy plants, and removal of accumulated sediment, trash and other debris.
- Frequent street sweeping is recommended to minimize the sediment load into the cell.
- Biological permeability driven by biological functions such as plant bio-mass, worm/mouse activity, plant density/root penetration should be promoted.

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APPENDIX A

SOIL MOISTURE PROFILES

Table A-1. Site conditions and infiltration rates for DVD tests at the Crystal Lake bioretention cell.

DVD Test Date (season number)	Infiltration Rate from End of Water Application (in/hr)	Inflow Rate from Start of Water Application (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in test water (mg/l; ppm)	DVD Volume (gal)	Field Notes/Anecdotes
3/6/2006* (1)	5.9	9.9	31.5	32.7	34.9	16.9	17.8	0.5	35.5	50.5	1.2	0	425	
1/2/2007 (2)	18	53	37.1	36.3	38.1	28.3	20.8	0	38.4	47.2	3	0	425	
2/27/2007 (2)	0.15	N/A**	31.3	31.7	33.4	11.1	8.7	1	29.5	41.4	13.2	0	425^	
12/13/2007 (3)	10.2	14.5	N/A	N/A	N/A	N/A	N/A	0	N/A	56	9	0	425	
12/18/2007 (3)	18.9	17	31.3	38.7	41.9	22.7	17.4	0.5	24.1	50	9.6	127	425	1/2-in frozen layer near double-ring infiltrometer but thawed underneath; also thawed where snow is uncompacted.
1/8/2008 (3)	15.3	13.7	33.2	37.1	40.1	23.2	17.1	0	37.3	47	10.8	1,184	425	Currently calm and foggy; snow areas frozen where compacted based on excavation; not frozen where uncompacted.
2/5/2008 (3)	13.6	11.5	29.9	33.2	36.4	8.9	8.4	0.5	27.7	41.2	12	592	425	1 - 2 inches of snow yesterday; frozen soils throughout basin based on excavation.
3/4/2008 (3)	7.2	7.0	30.8	33.2	35.8	10.1	11.1	0.5	27.5	40.8	18	592	425	Dry; ground frozen based on excavation.
3/18/2008 (3)	4.2	N/A**	32.4	32.4	33.3	11.4	12.3	0	34.1	46.7	33	592	425	3 inches of snow last night; 2 inches standing water cell; cell still semi-frozen following DVD test, possible surface frost.
4/1/2008 (3)	3.7	N/A**	46.6	33.2	33.6	29.3	21.2	0.5	43.6	38.5	6.6	254	425	6 inches of snow last night; half thawed-half frozen basin bottom based on excavation; some water standing in bottom of garden upon arrival; surface frost.

* No soil moisture data.

Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

** Not able to be determined because of standing water at end of test period.

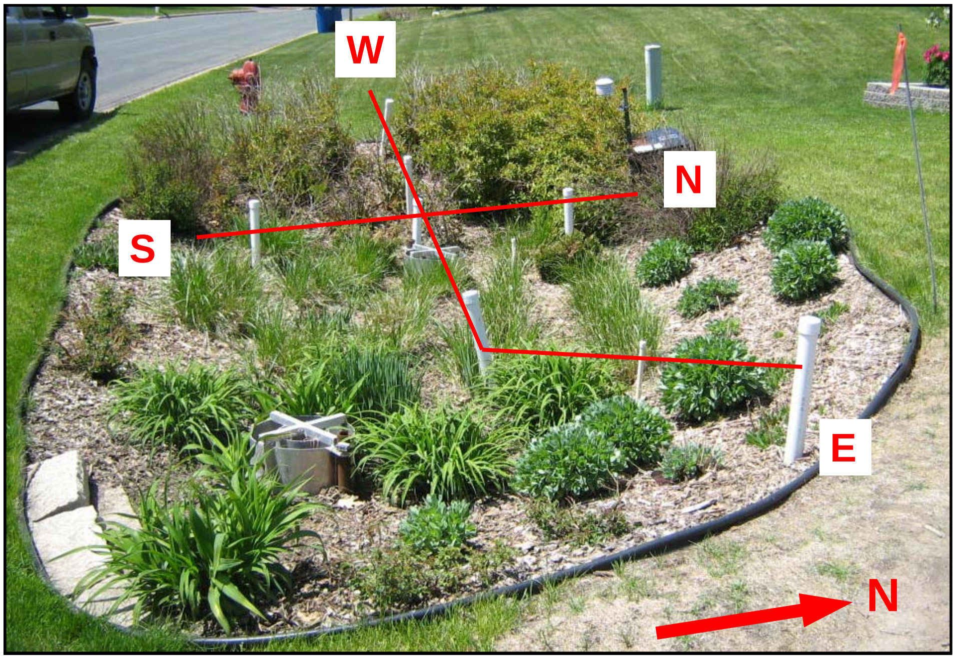

Figure A-1. Soil moisture probe transects for the Crystal Lake bioretention cell.

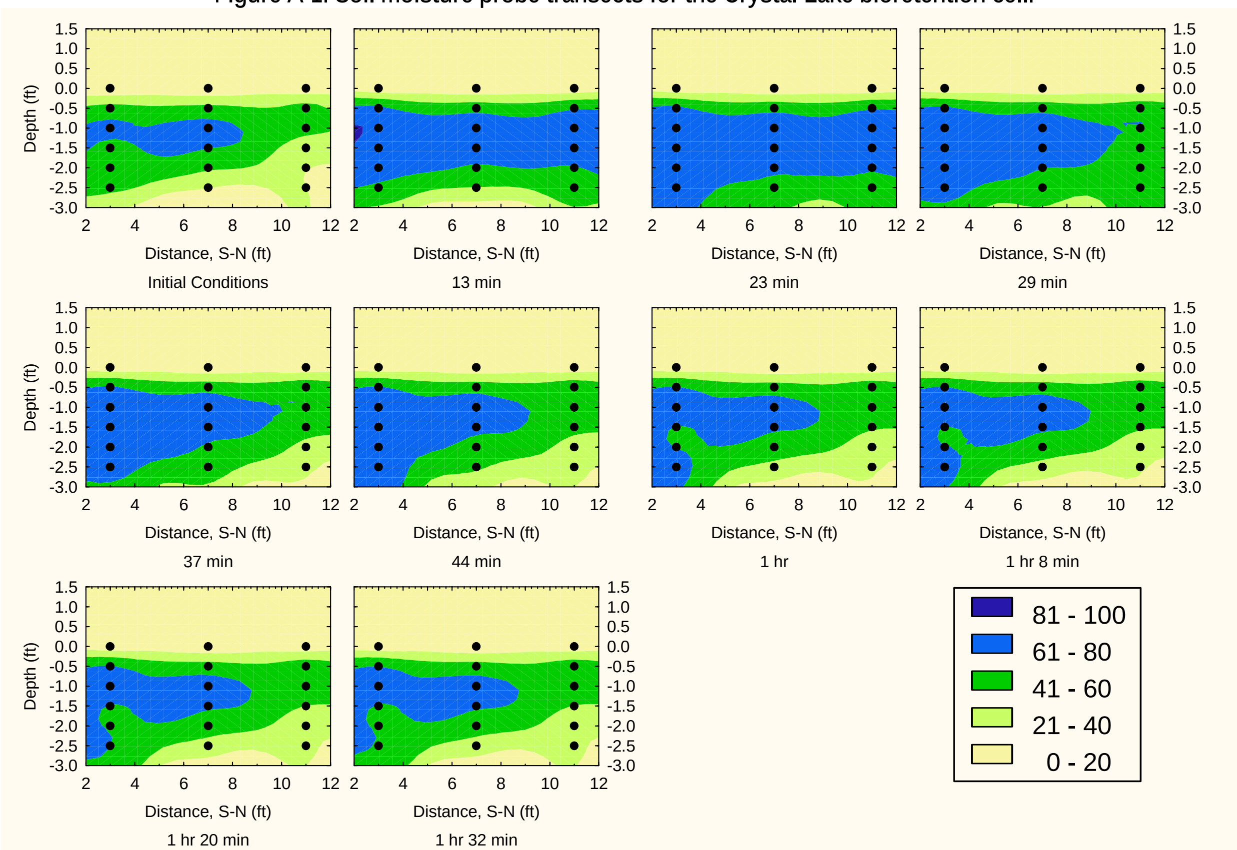

Figure A-2. South to north soil moisture profile from January 2, 2007, DVD test at the Crystal Lake bioretention cell.

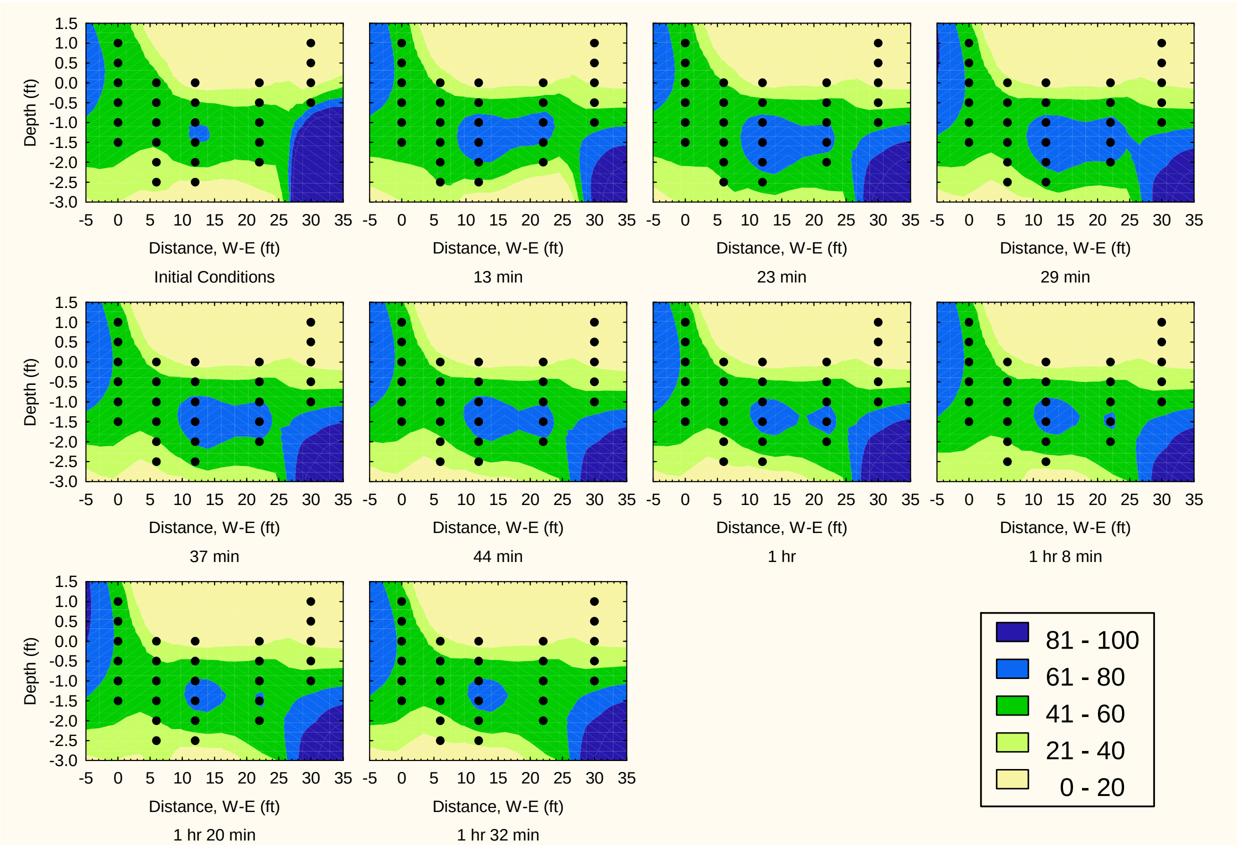

Figure A-3. West to east soil moisture profile from January 2, 2007, DVD test at the Crystal Lake bioretention cell.

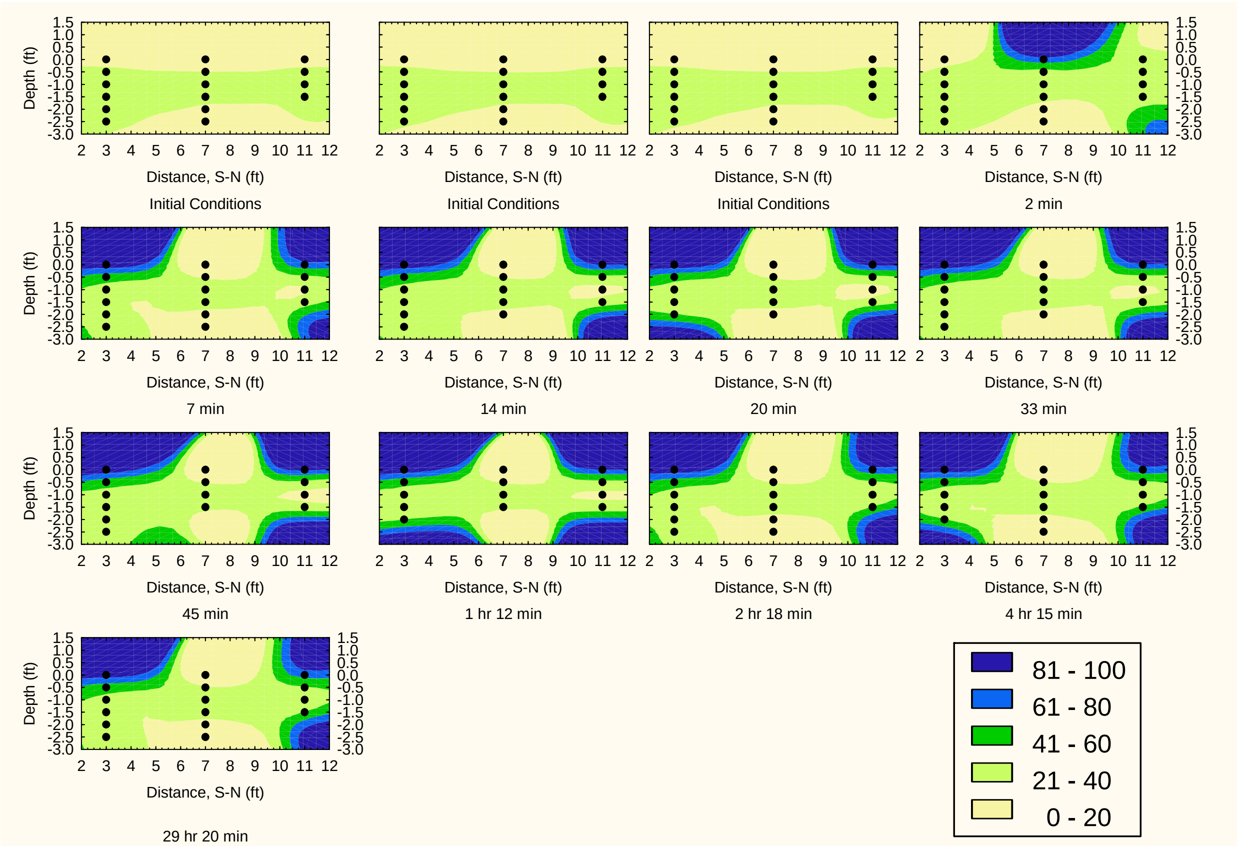

Figure A-4. South to north soil moisture profile from February 27, 2007, DVD test at the Crystal Lake bioretention cell.

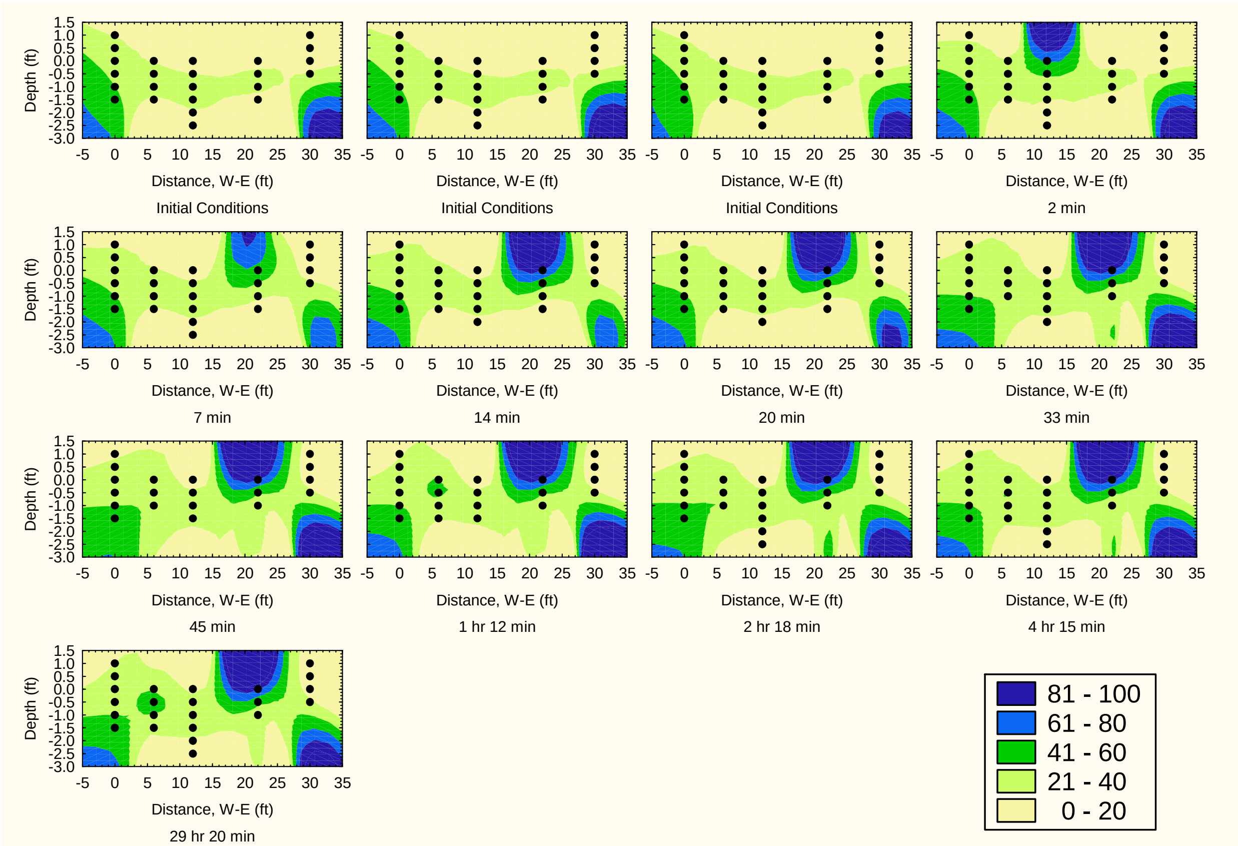

Figure A-5. West to east soil moisture profile from February 27, 2007, DVD test at the Crystal Lake bioretention cell.

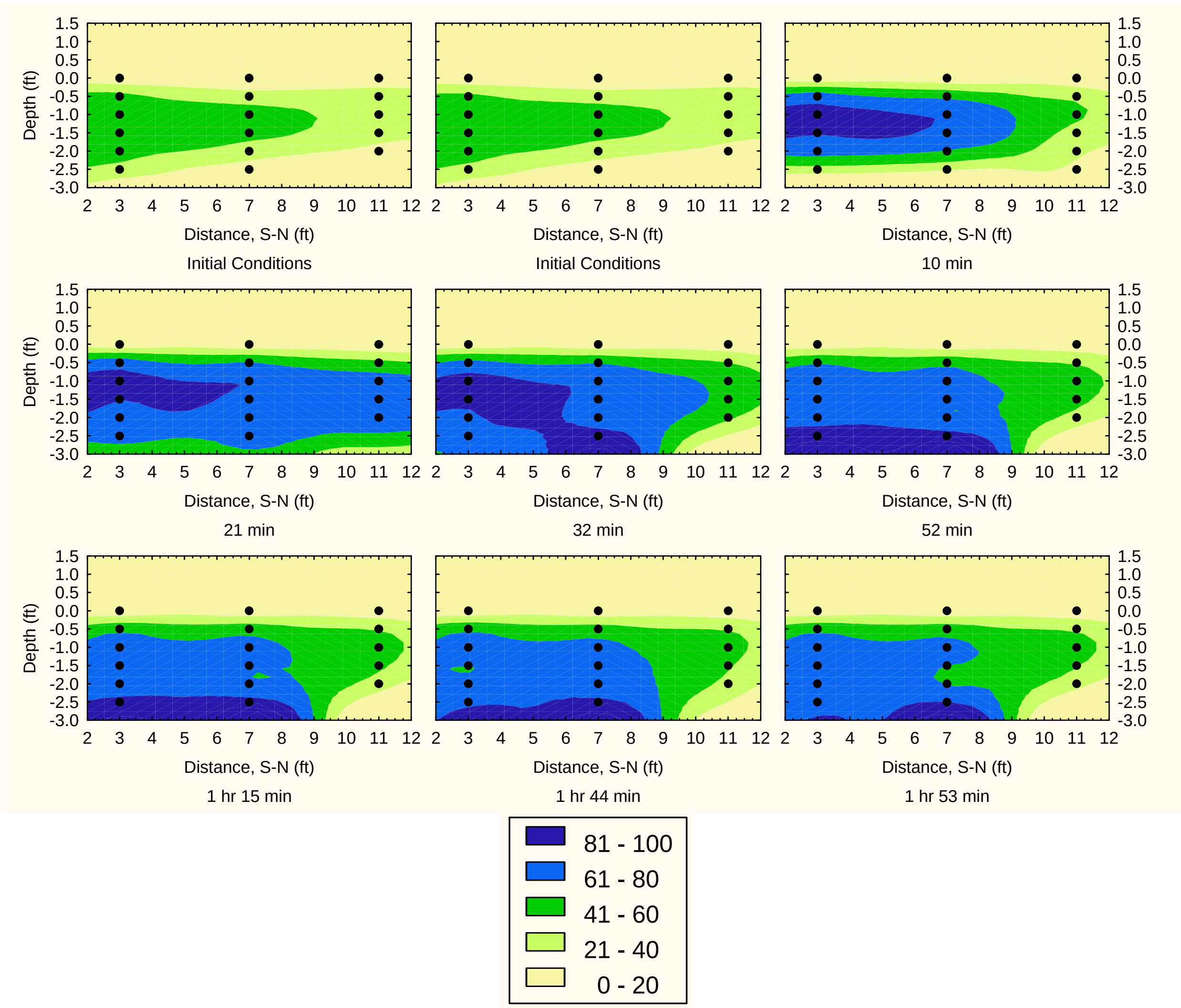

Figure A-6. South to north soil moisture profile from December 13, 2007, DVD test at the Crystal Lake bioretention cell.

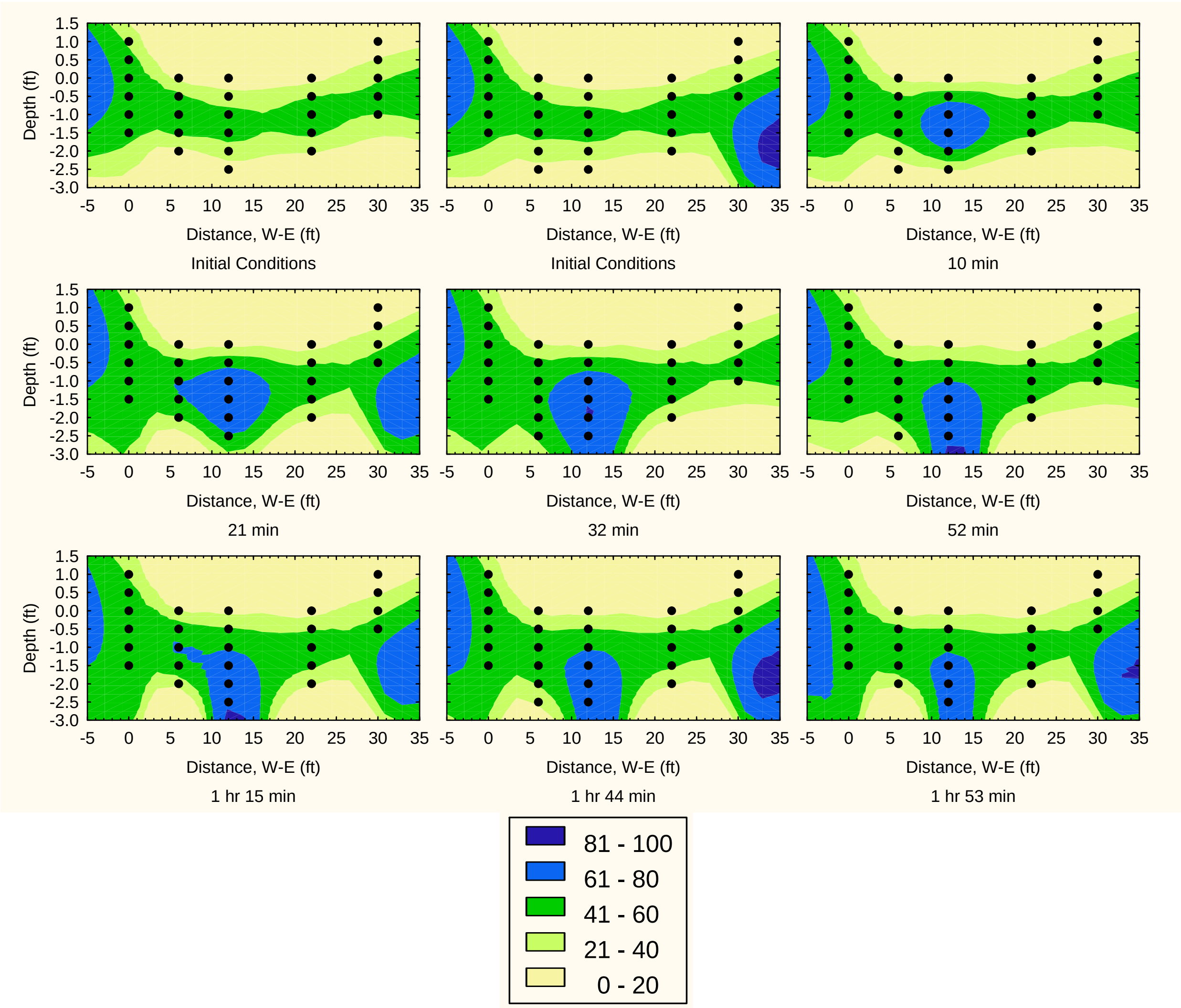

Figure A-7. West to east soil moisture profile from December 13, 2007, DVD test at the Crystal Lake bioretention cell.

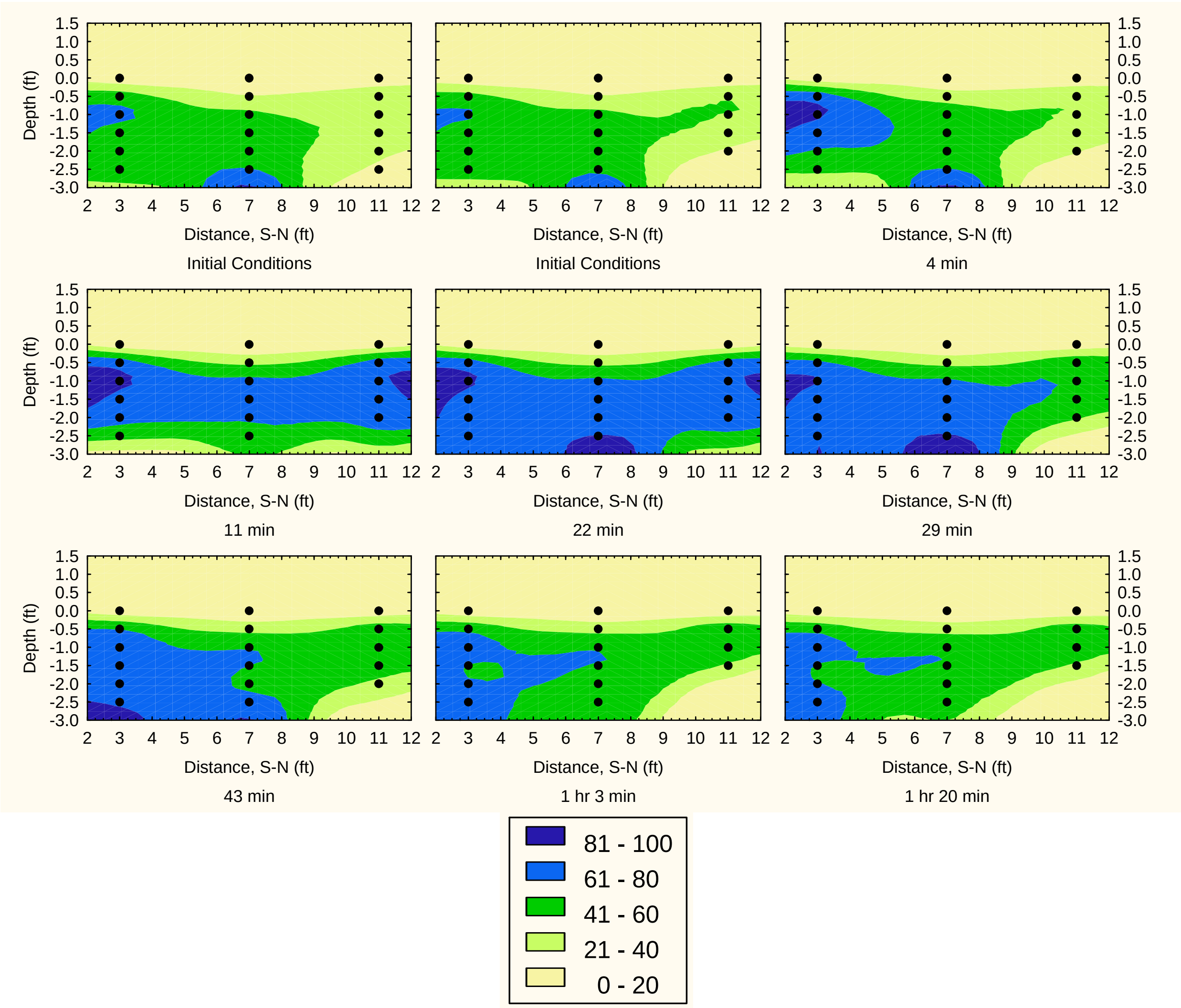

Figure A-8. South to north soil moisture profile from December 18, 2007, DVD test at the Crystal Lake bioretention cell.

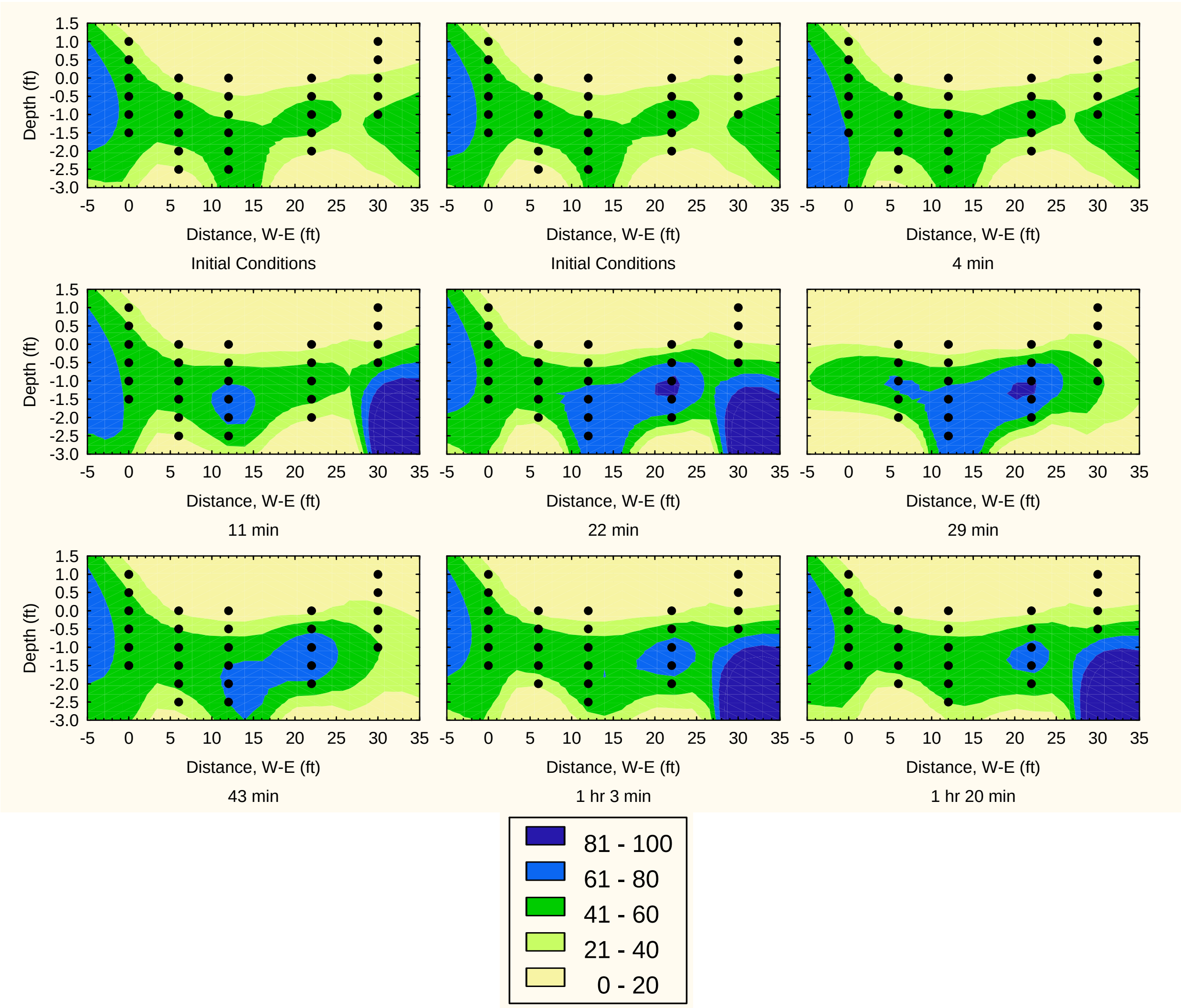

Figure A-9. West to east soil moisture profile from December 18, 2007, DVD test at the Crystal Lake bioretention cell.

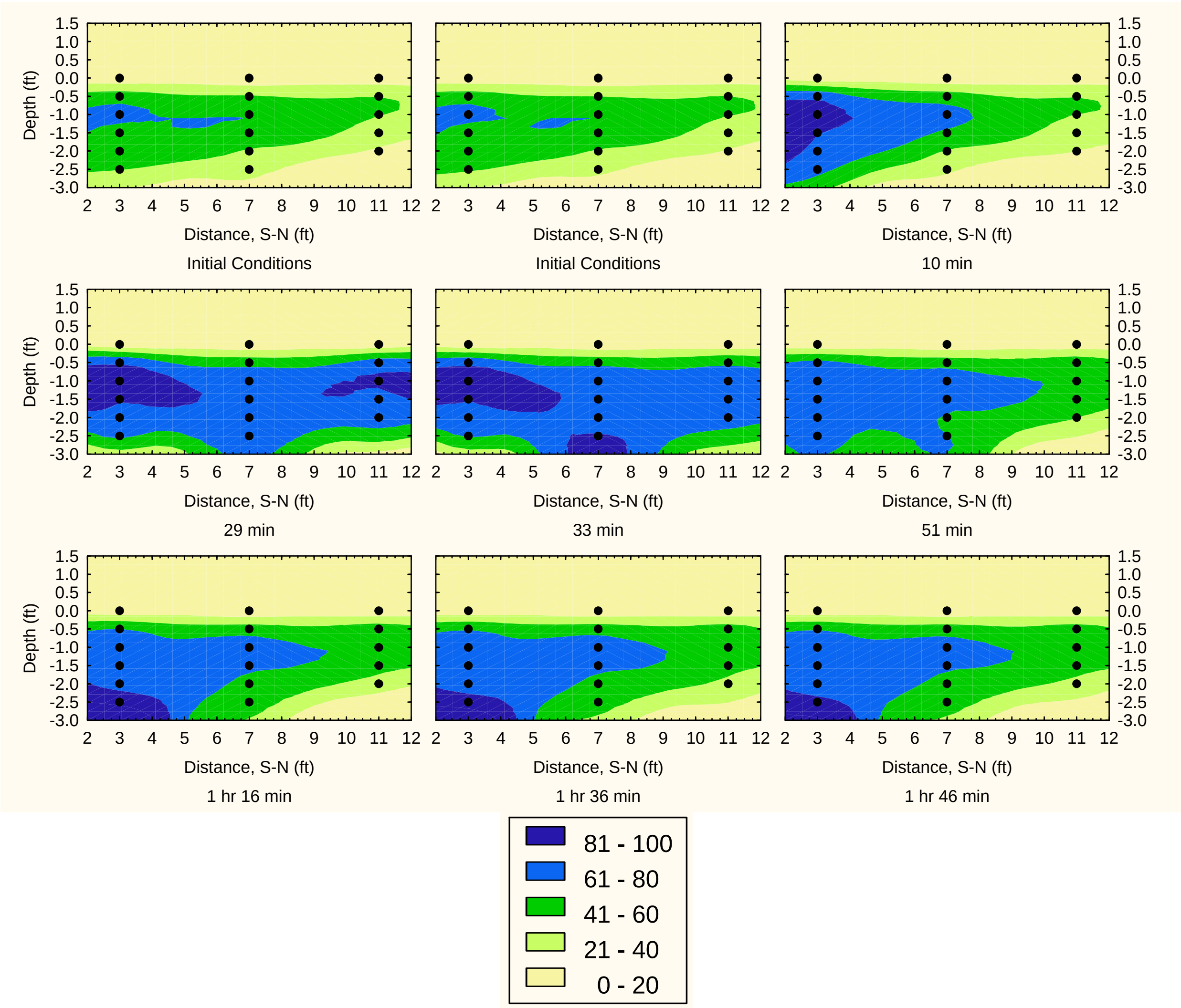

Figure A-10. South to north soil moisture profile from January 8, 2008, DVD test at the Crystal Lake bioretention cell.

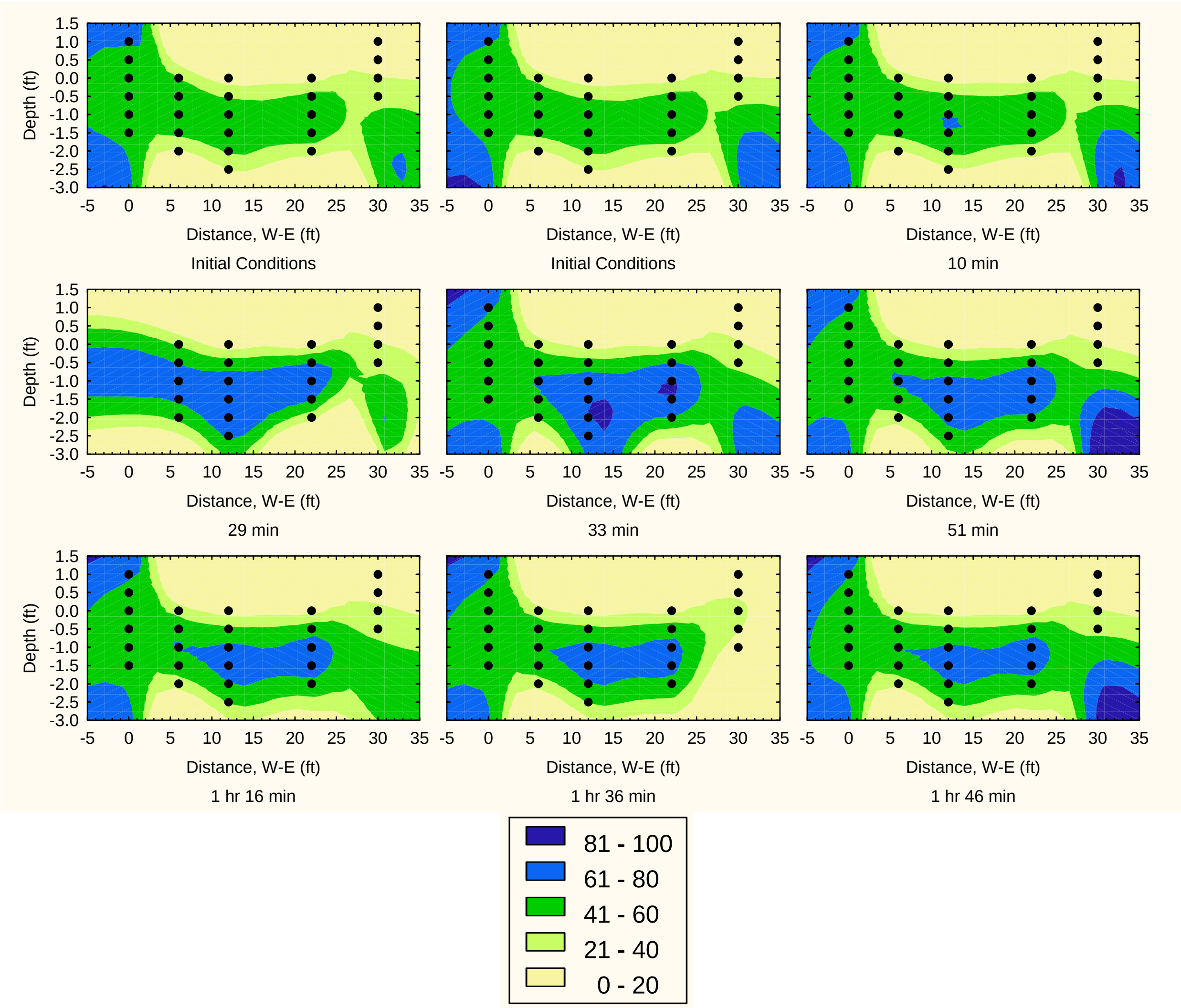

Figure A-11. West to east soil moisture profile from January 8, 2008, DVD test at the Crystal Lake bioretention cell.

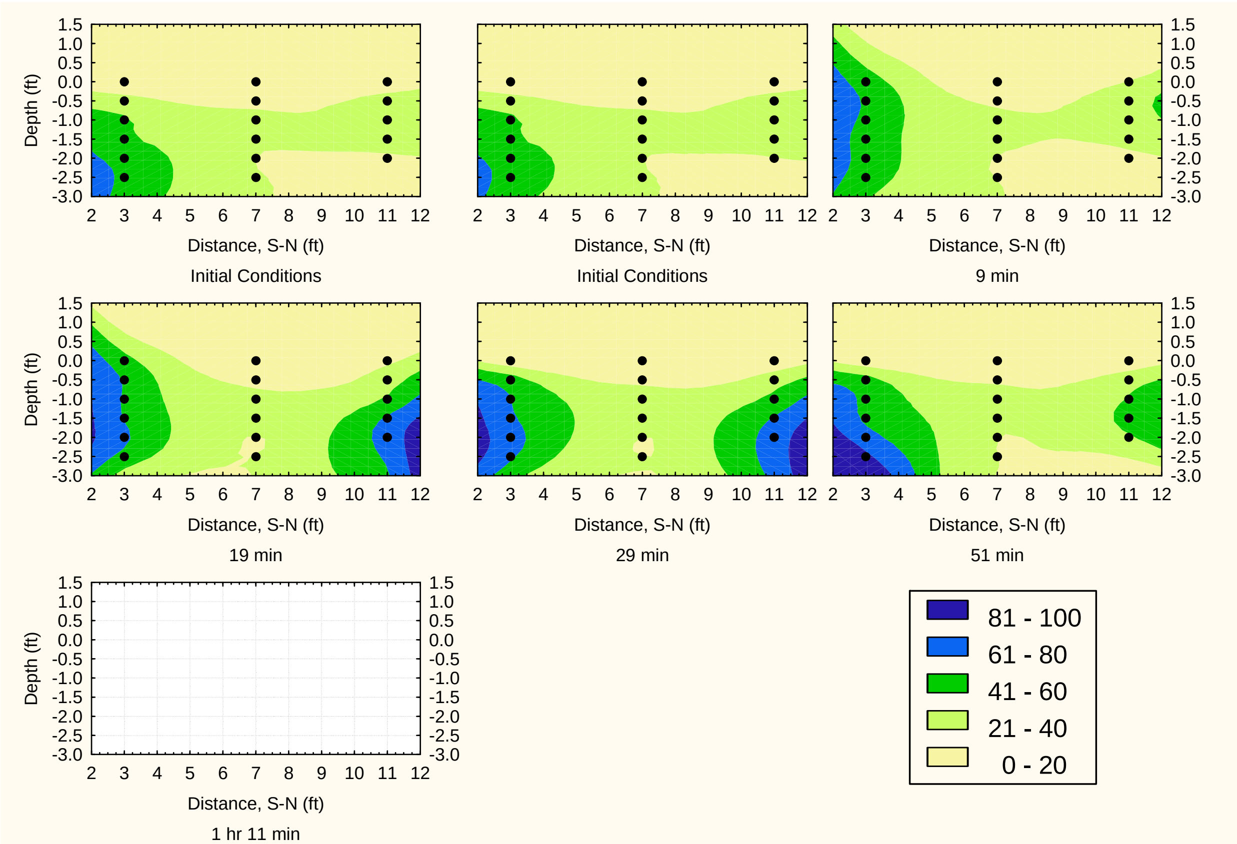

Figure A-12. South to north soil moisture profile from February 5, 2008, DVD test at the Crystal Lake bioretention cell.

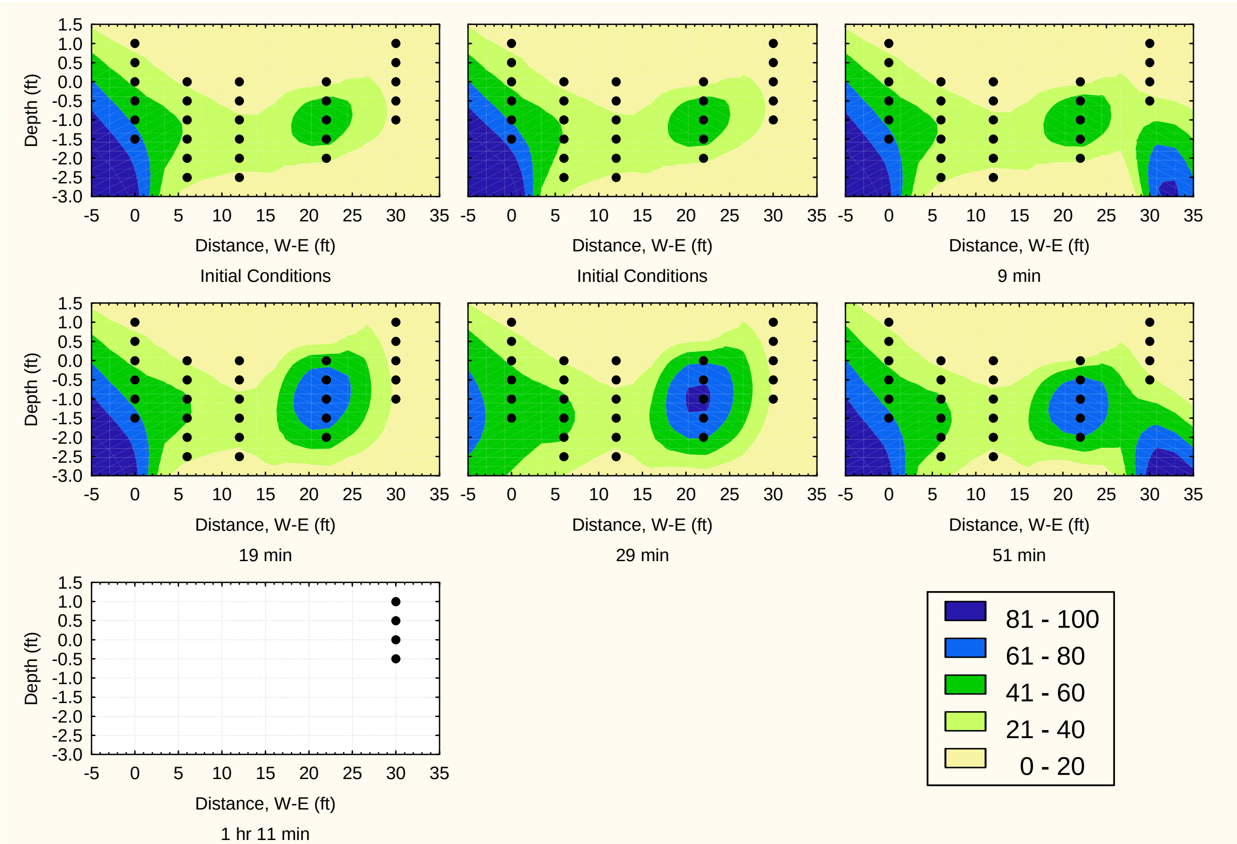

Figure A-13. West to east soil moisture profile from February 5, 2008, DVD test at the Crystal Lake bioretention cell.

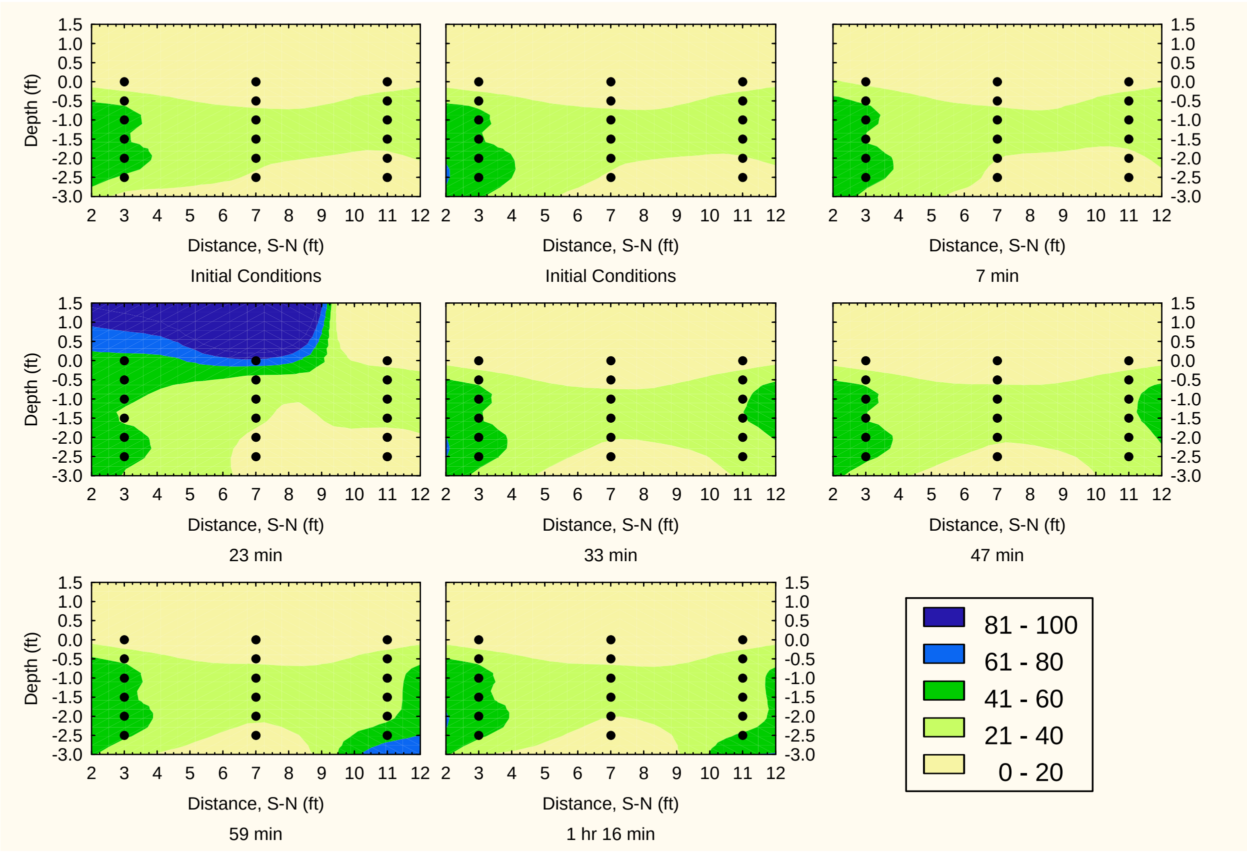

Figure A-14. South to north soil moisture profile from March 4, 2008, DVD test at the Crystal Lake bioretention cell.

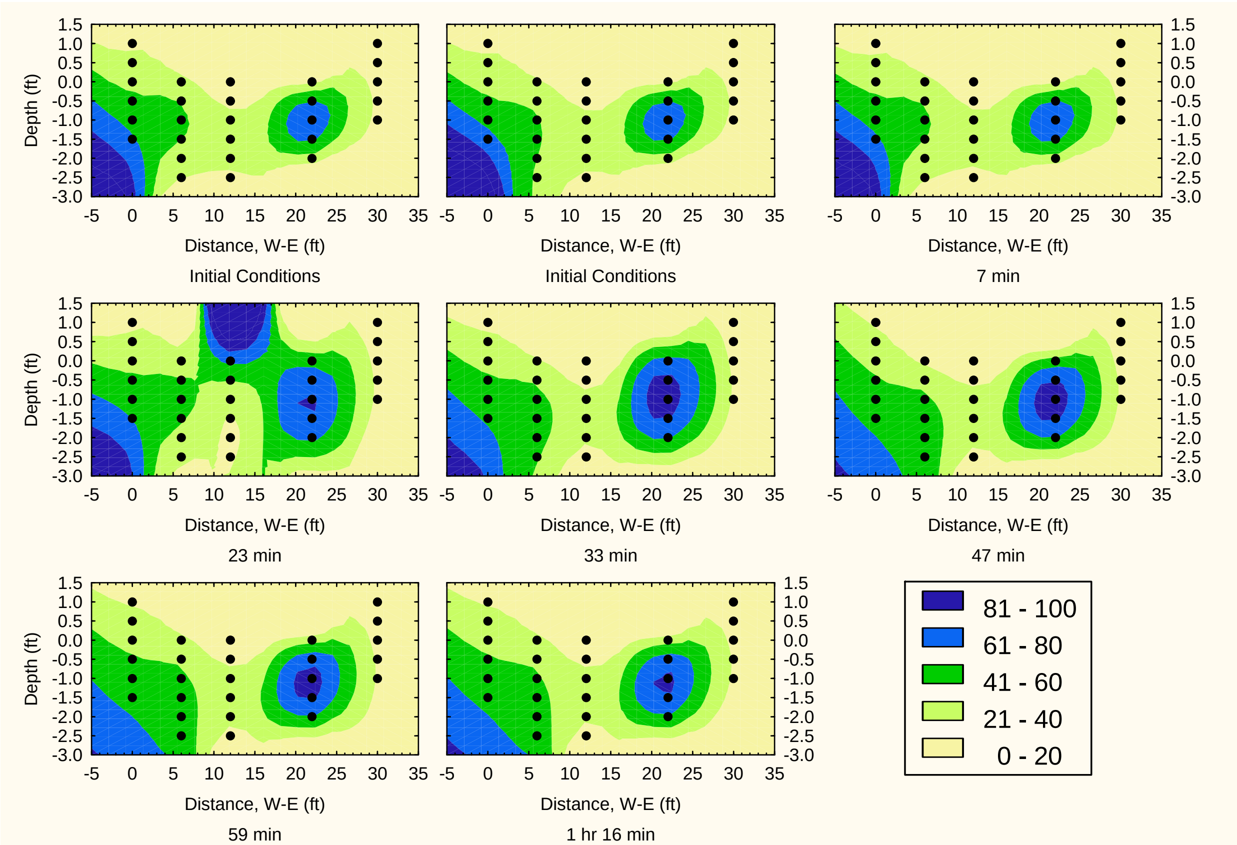

Figure A-15. West to east soil moisture profile from March 4, 2008, DVD test at the Crystal Lake bioretention cell.

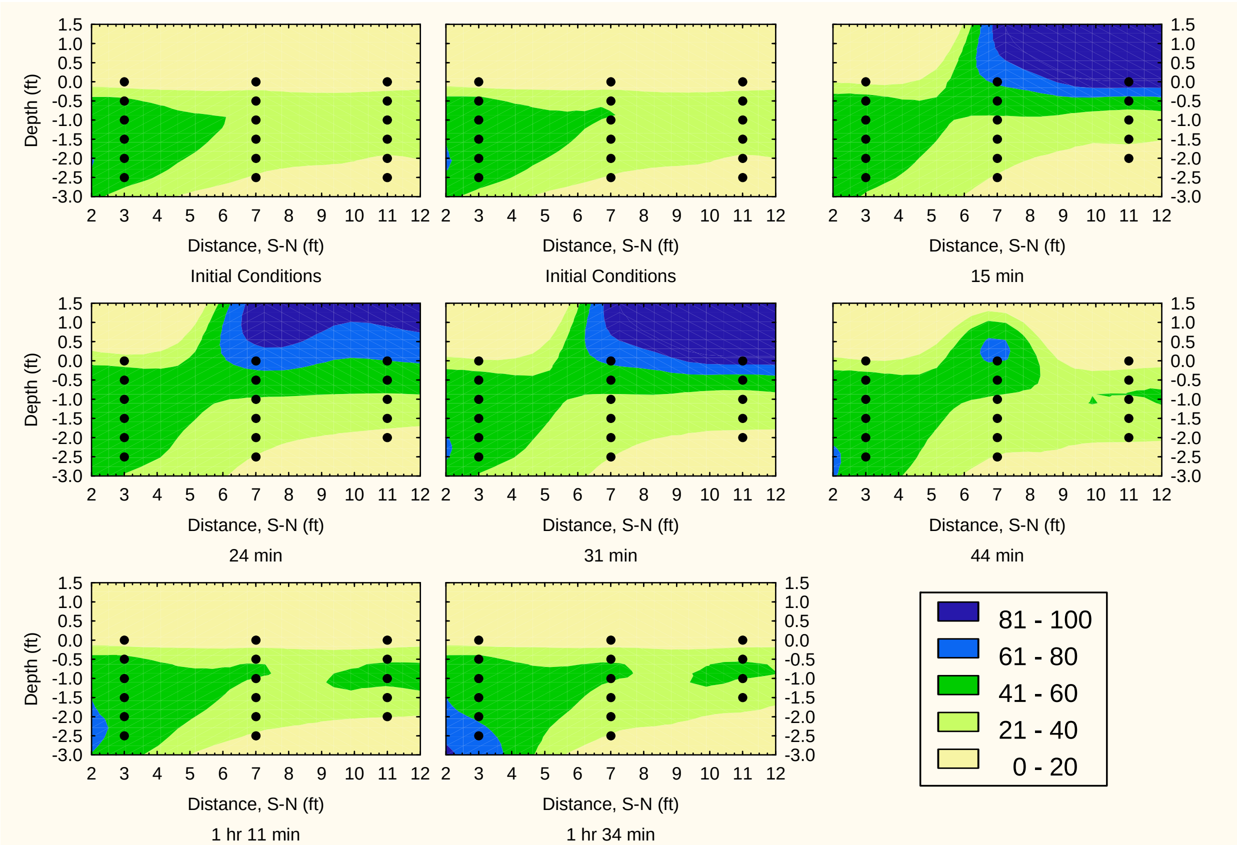

Figure A-16. South to north soil moisture profile from March 18, 2008, DVD test at the Crystal Lake bioretention cell.

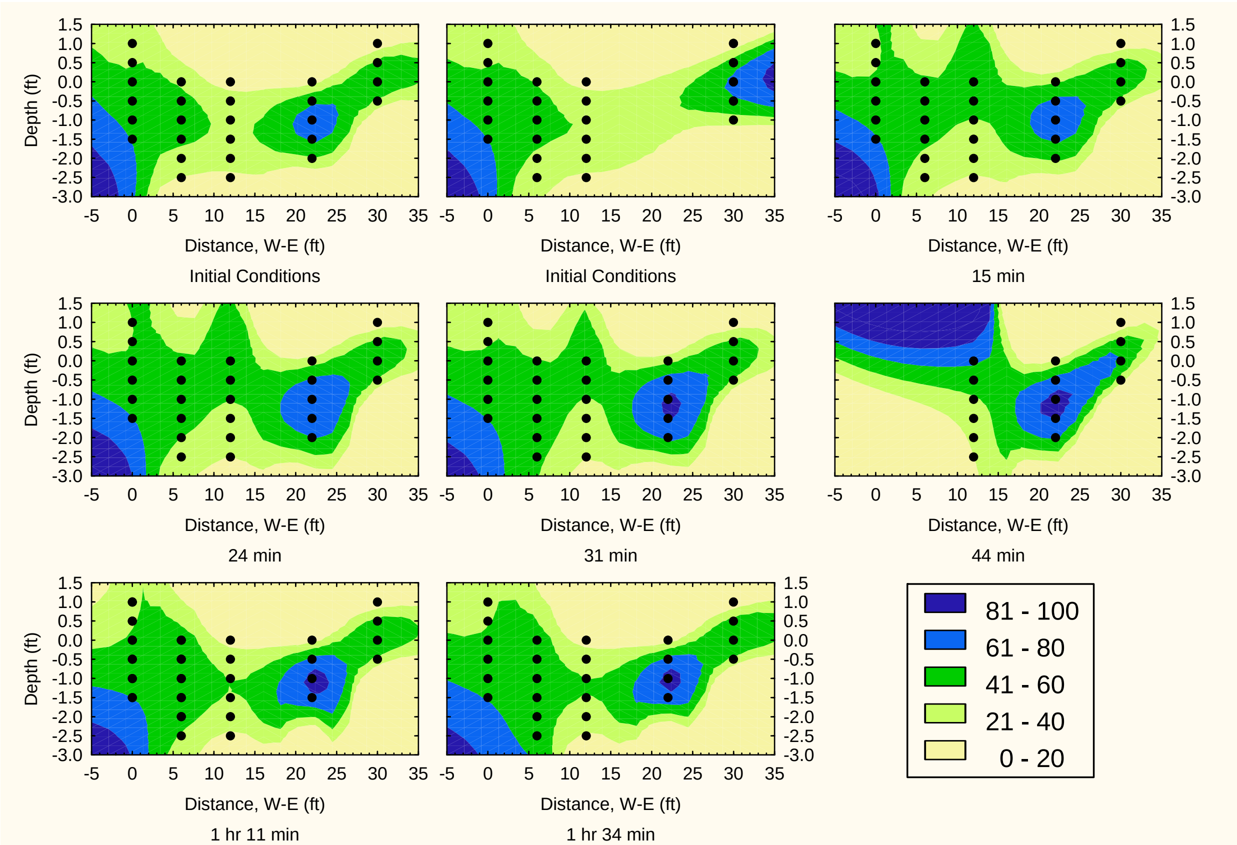

Figure A-17. West to east soil moisture profile from March 18, 2008, DVD test at the Crystal Lake bioretention cell.

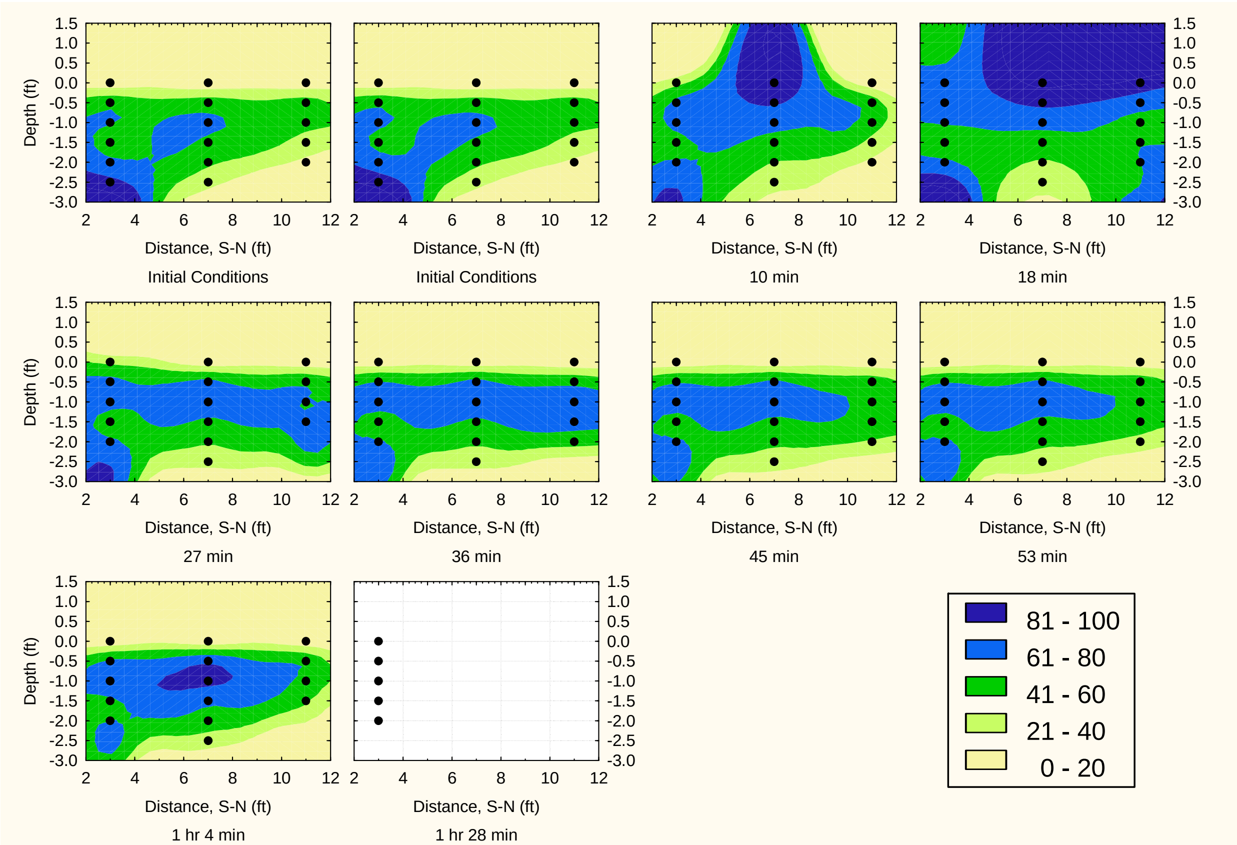

Figure A-18. South to north soil moisture profile from April 1, 2008, DVD test at the Crystal Lake bioretention cell.

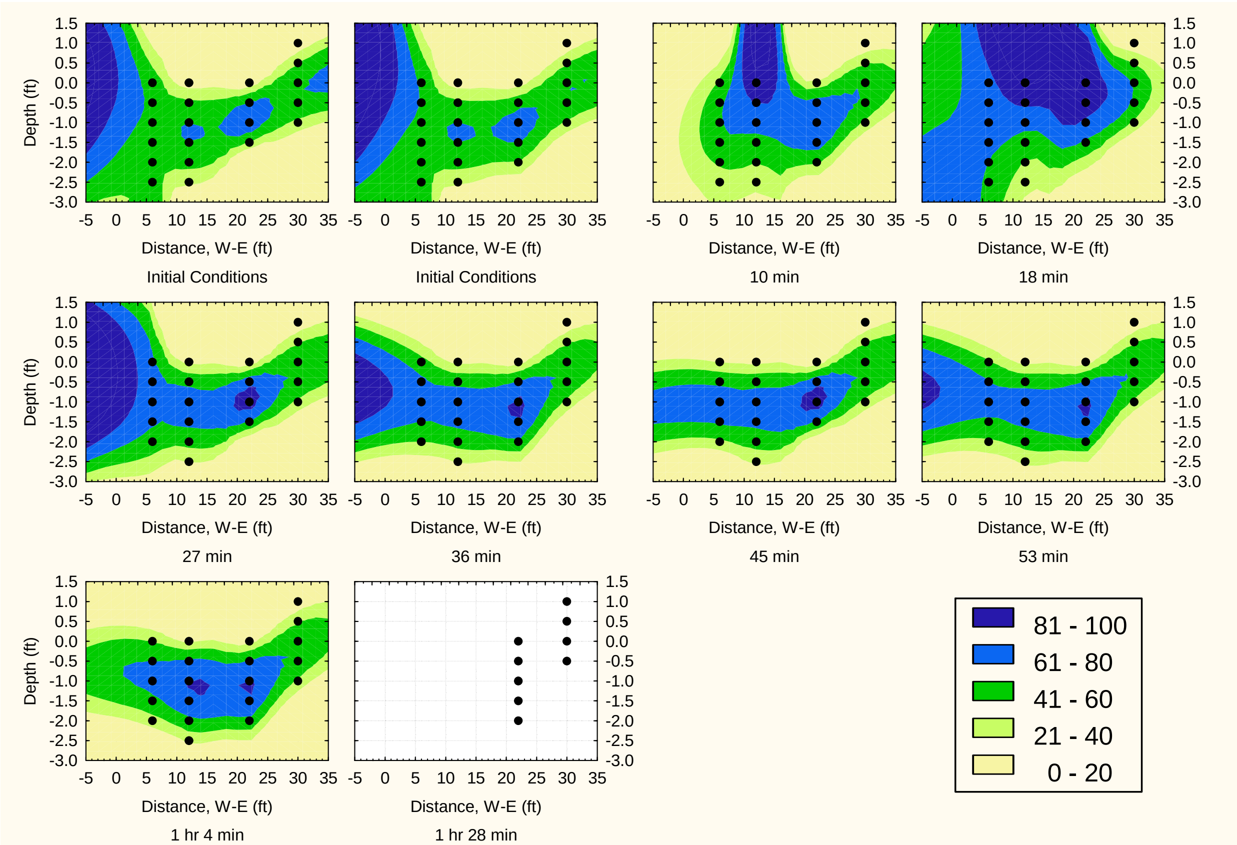

Figure A-19. West to east soil moisture profile from April 1, 2008, DVD test at the Crystal Lake bioretention cell.

Table A-2 Site conditions and infiltration rates for DVD tests at the Thompson Lake bioretention cell.

DVD Test Date (season number)	Infiltration Rate from End of Test Water Appli-cation (in/hr)	Inflow Rate from Start of Test Water Appl-ication (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth^Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/21/2006* (1)	4.1•	38	33.9	35.2	36.7	21.3	23.7	0	38.6	51.1	7.8	0	2,000^	Solid snow cover in basin; no standing water; 2.5 deg C (36.5 deg F) water temp at infiltrometer while still pouring out (slushy); capillary movement into snow observed; possible movement of water laterally, rather than into soil.
1/4/2007* (2)	2.9•	42.5	36.5	39.0	40.5	15.1	26.9	0	36.3	47.0	1.8	0	2,000	No standing water in cell.
12/18/2007 (3)	4.2	54	N/A	N/A	N/A	N/A	N/A	N/A	24.5	31.8#	7.2	100	5,000	Heard water rushing through drain system beneath bioretention cell after about 20 min of DVD test; wet surface area extended from row B to row E.
1/8/2008 (3)	4	52	34.7	37.2	39.2	12.9	19.8	0	37.6	34	6	1081	5,321	At about 13:40 saw extensive bubbling and sub-drains flowing.
2/5/2008 (3)	1.4	N/A**	28.9	31.7	34.1	5.1	6.6	1	29.8	30.8	9	479	6,000	Filled to within 1/2 inch of overflow; ground frozen based on excavation; little to no bubbling observed during fill; sub-drains not flowing at 1:57pm; running water heard in overflow sub-drain and catch basin; observed water running from discharge pipe into lake.
3/4/2008 (3)	0.7	N/A**	30.4	32.2	33.9	30.2	13.0	0.5	32.6	30.2	6	802	3,586	Stopped filling bioretention cell when water reached the top of the overflow pipe; ground frozen based on excavation; no bubbling during fill; no sub-drain flow from sub-drain at beginning or end of test.

* No soil moisture data.

^Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

• Average of 3 sites.

\# Average of temperatures from all other Thompson tests using lake water.

** Not able to be determined because of standing water at end of test period.

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DVD Test Date (season number)	Infiltration Rate from end of Test Water Appli-cation (in/hr)	Inflow Rate from Start of Test Water Appli-cation (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth[Δ] (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/18/2008 (3)	0.95	N/A**	31.9	32.3	34.0	16.6	18.9	0.5	37.1	31.9	3	518	5,547	Ground frozen except in flow-path of west curb-cut based on excavation; baseflow noted from west plug (none from east); bark leaf debris on top of overflow grate (evidence of full capacity?); bottom basin frozen (based on excavation) except near curb-cut inlets; only water standing at west curb-cut flow into basin.
4/1/2008 (3)	3.2	53	32.2	32.2	33.7	15.8	29.3	0	45.7	31.5	6	0	6,700	Ground thawed in spots to about 6-in deep based on excavation; small pool at curb- cuts; frost in spots; observed sub-drain flows from filling of bioretention cell.

* No soil moisture data.

[Δ] Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

• Average of 3 sites.

[#] Average of temperatures from all other Thompson tests using lake water.

** Not able to be determined because of standing water at end of test period.

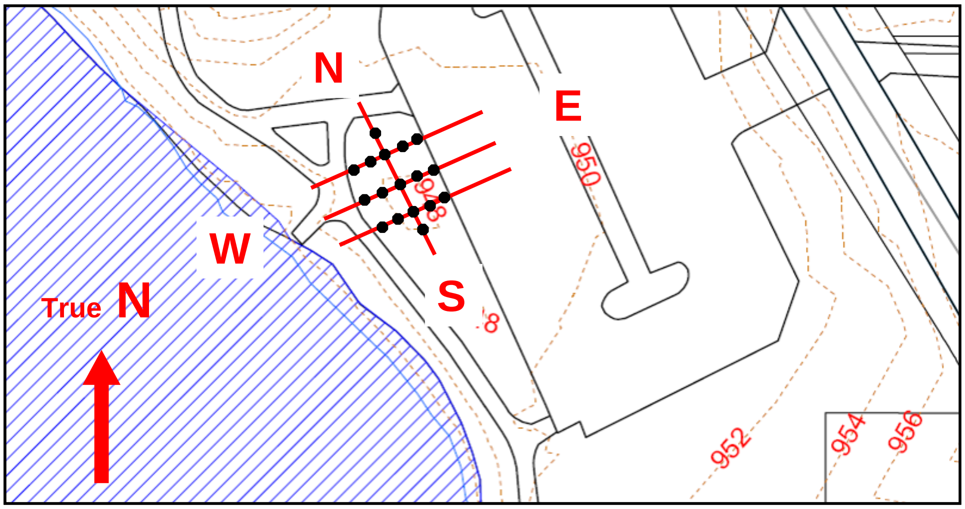

Figure A-20. Soil moisture probe transect locations for the Thompson Lake bioretention cell.

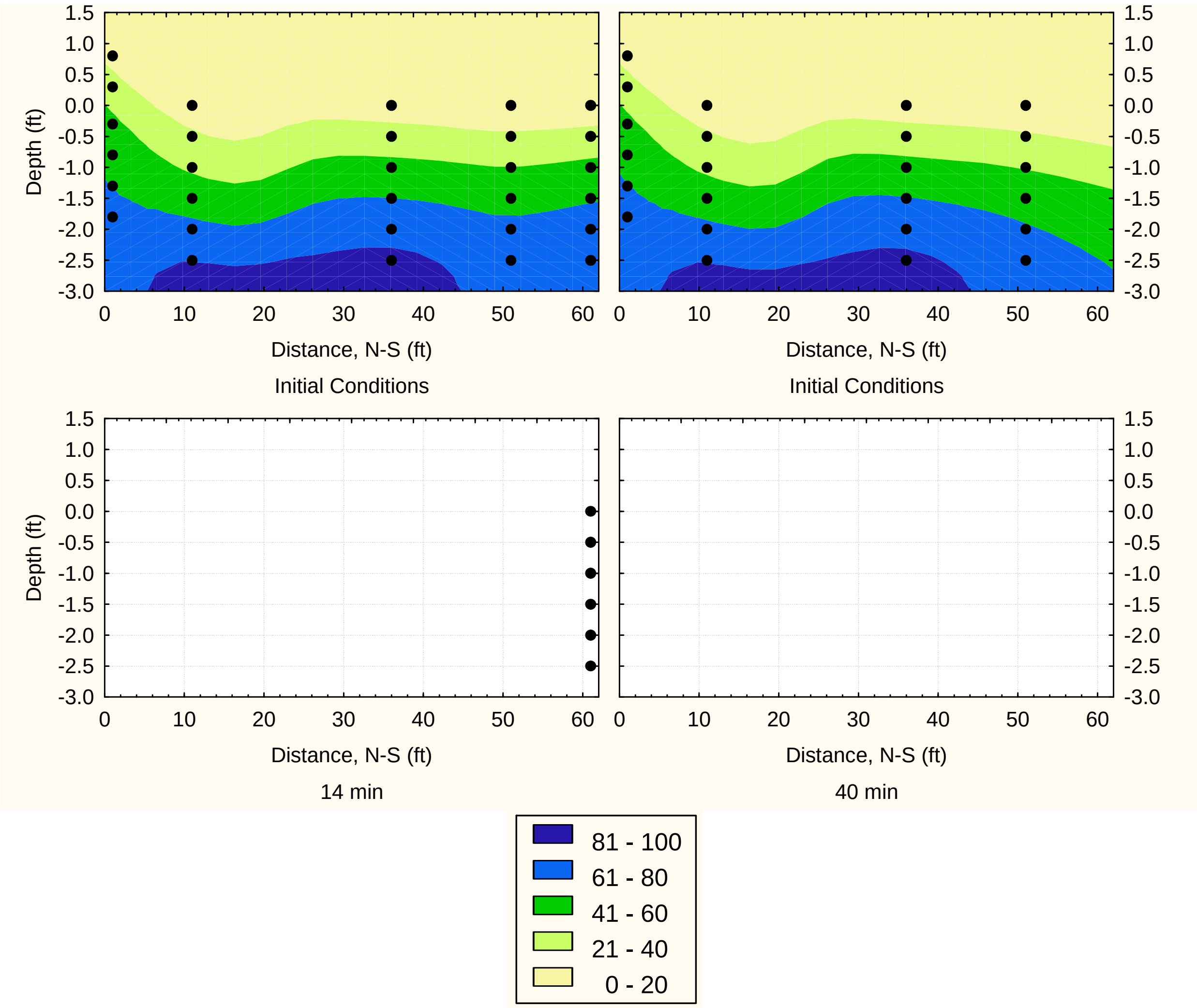

Figure A-21. North to south soil moisture profile from December 13, 2007, DVD test at the Thompson Lake bioretention cell.

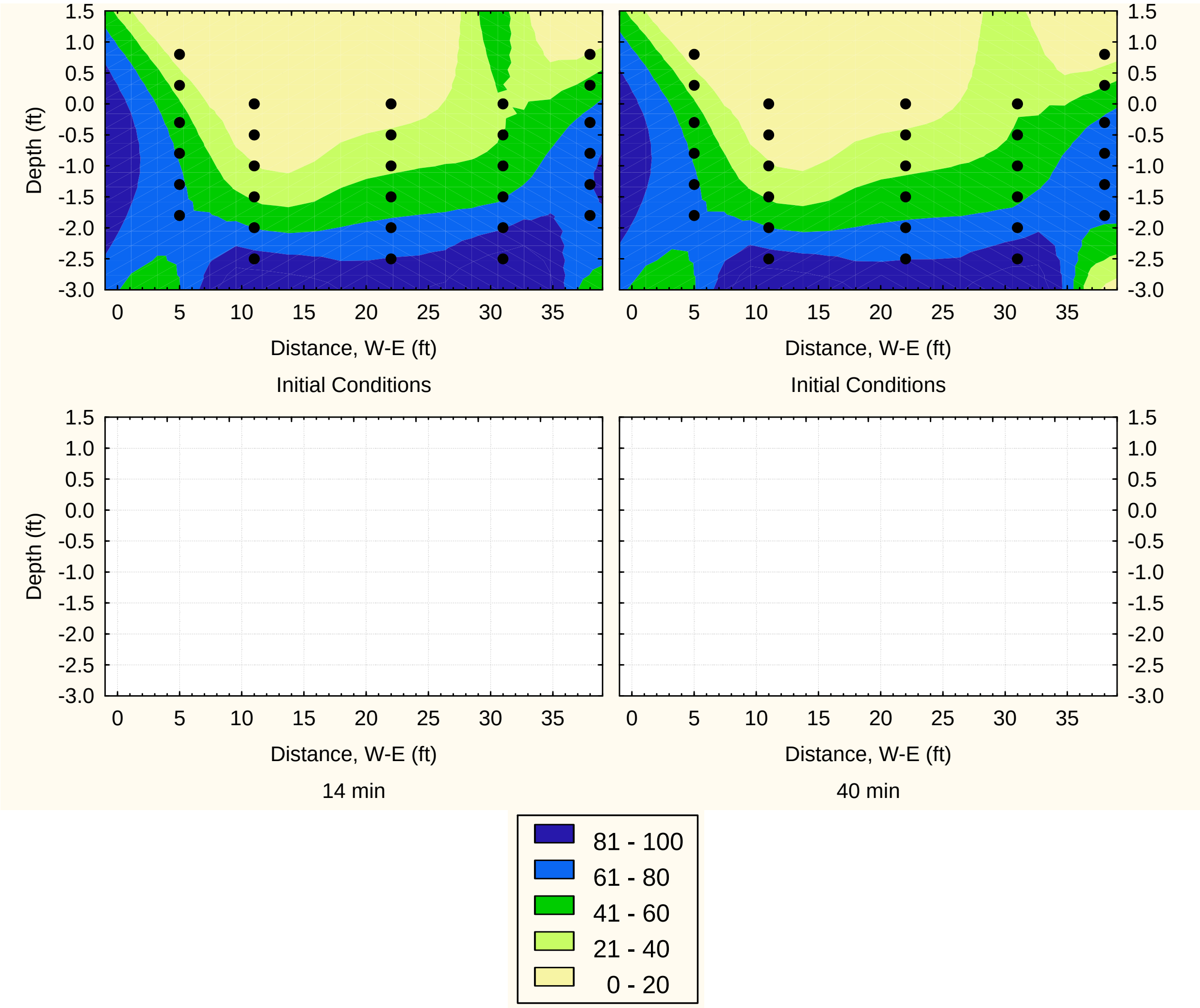

Figure A-22. West to east soil (north transect) moisture profile from December 13, 2007, DVD test at the Thompson Lake bioretention cell.

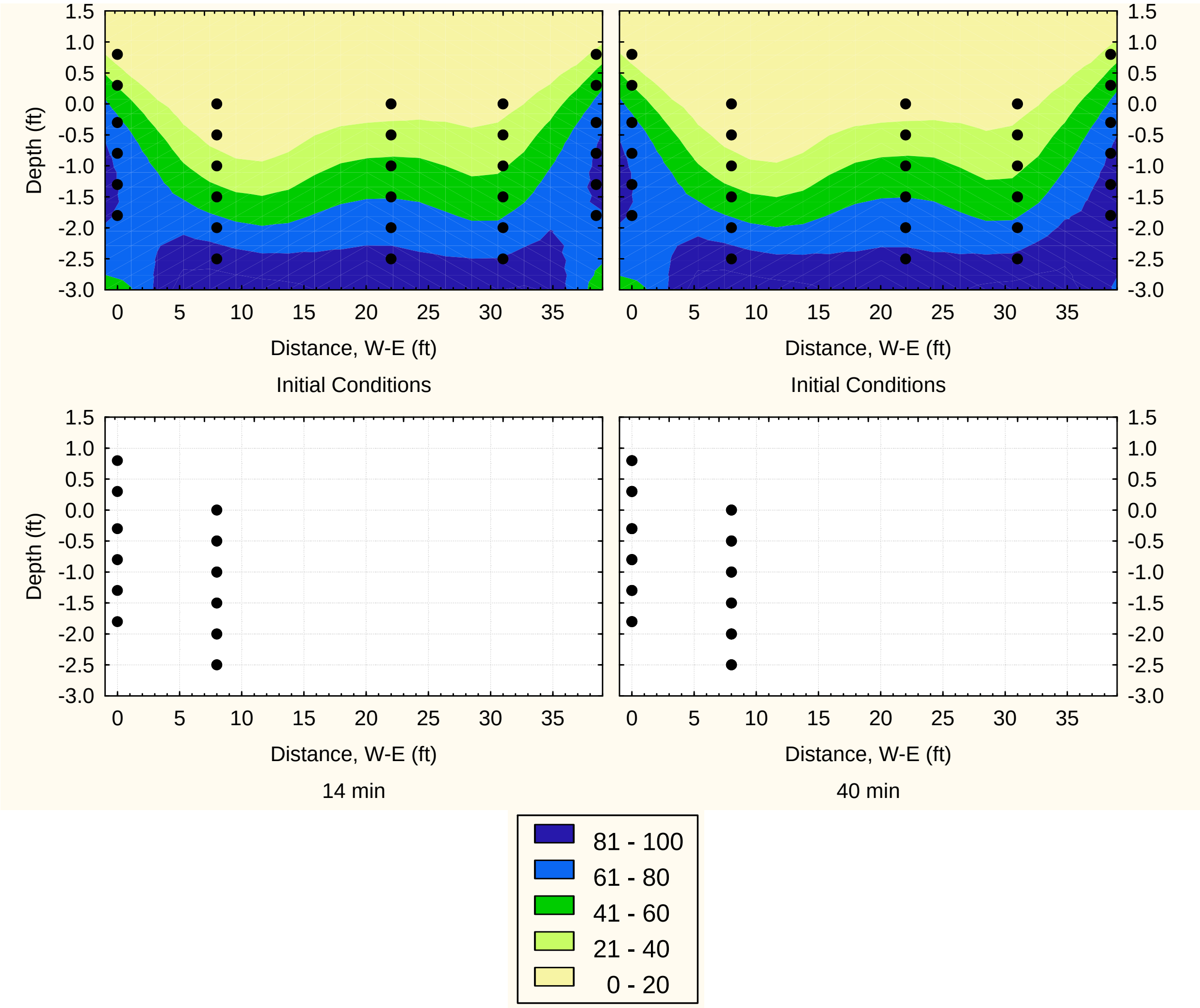

Figure A-23. West to east soil (middle transect) moisture profile from December 13, 2007, DVD test at the Thompson Lake bioretention cell.

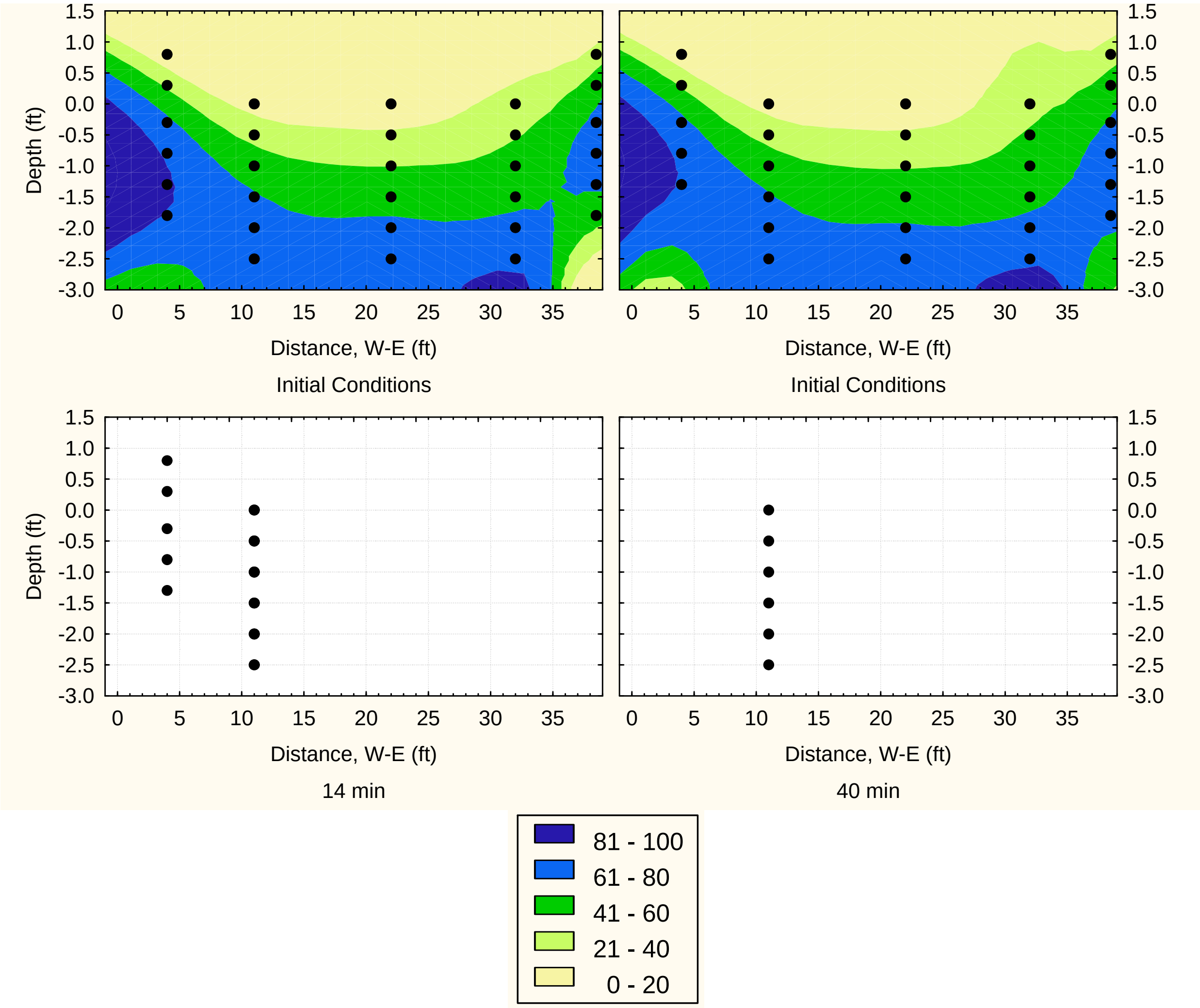

Figure A-24. West to east soil (south transect) moisture profile from December 13, 2007, DVD test at the Thompson Lake bioretention cell.

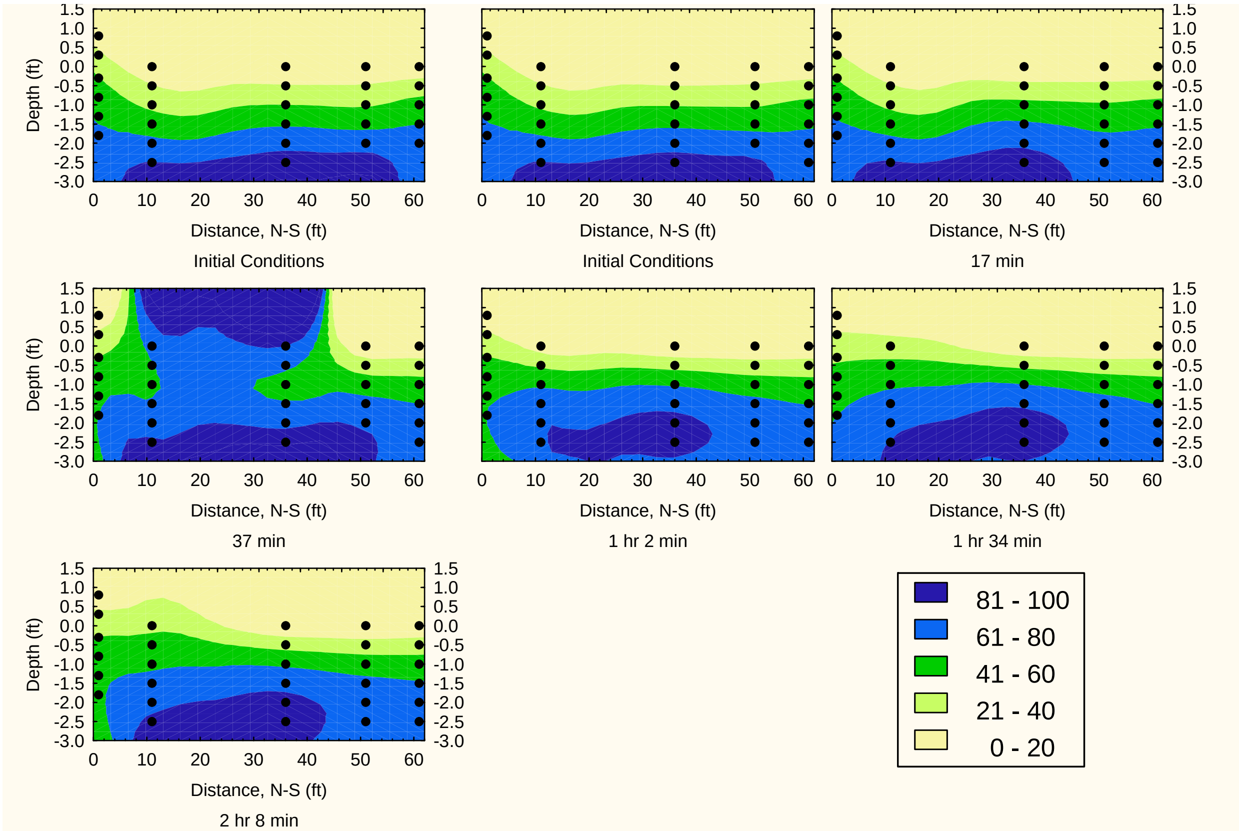

Figure A-25. South to north soil moisture profile from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

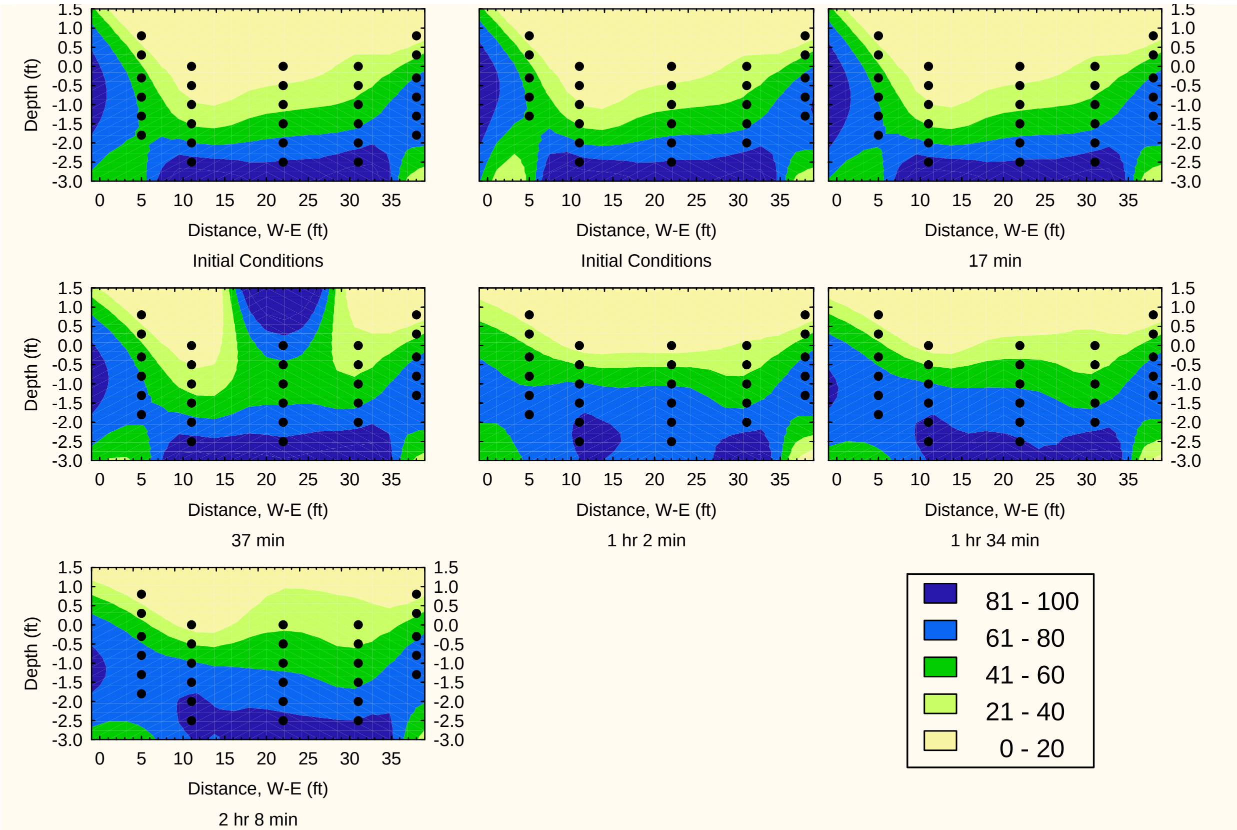

Figure A-26. West to east soil (north transect) moisture profile from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

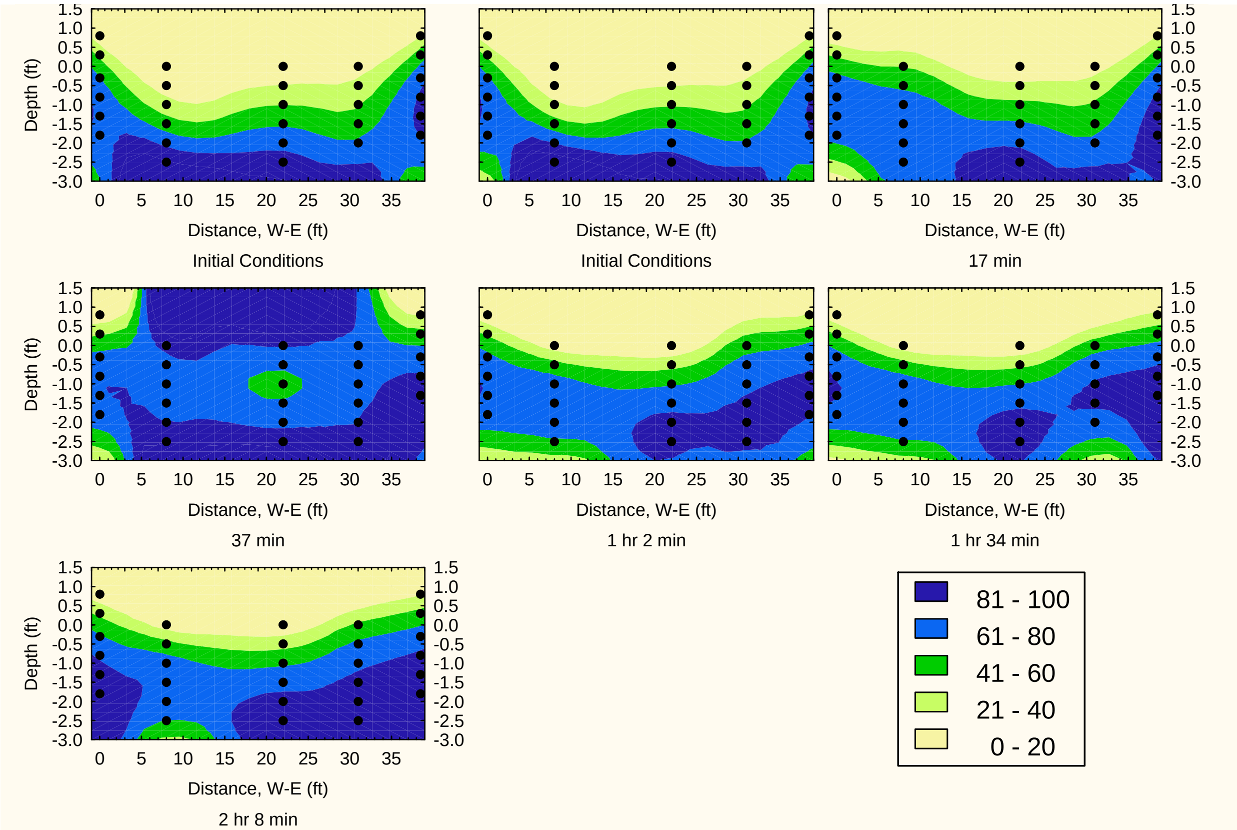

Figure A-27. West to east soil (middle transect) moisture profile from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

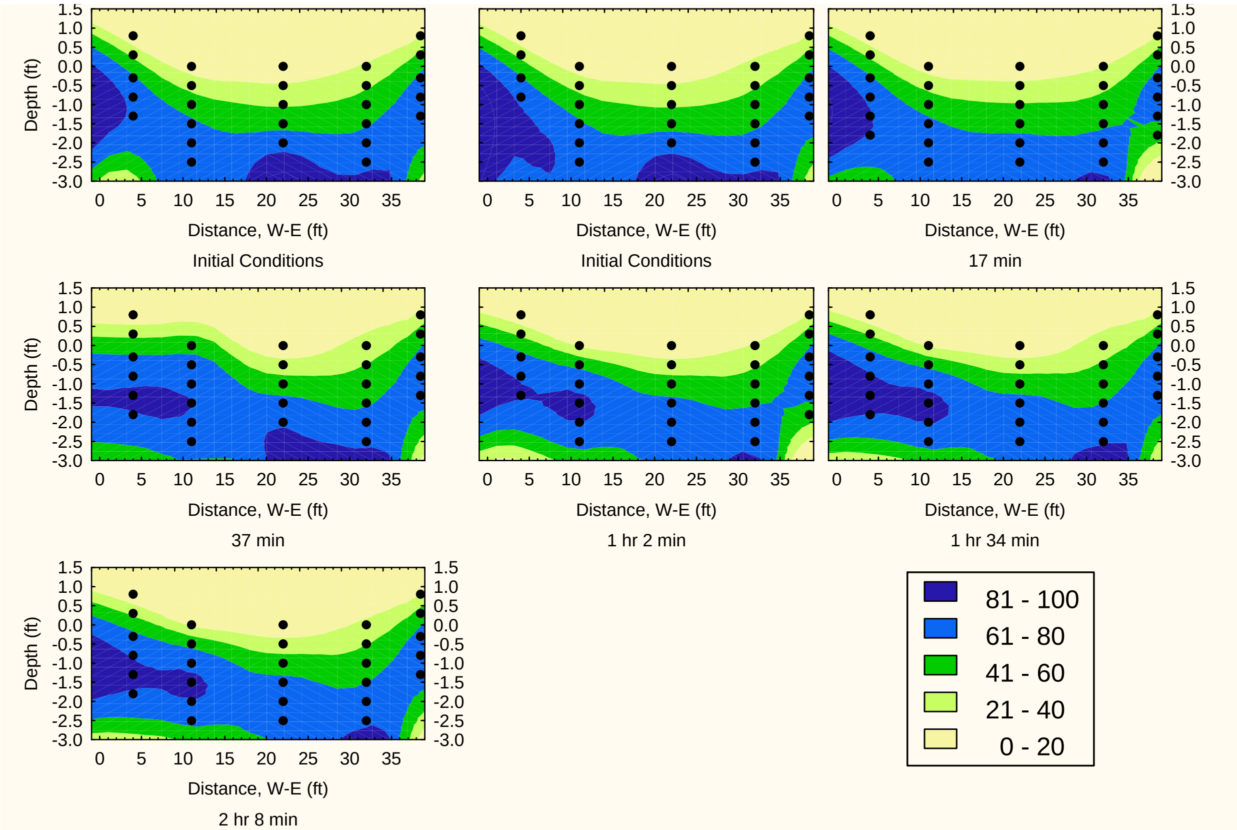

Figure A-28. West to east soil (south transect) moisture profile from December 18, 2007, DVD test at the Thompson Lake bioretention cell.

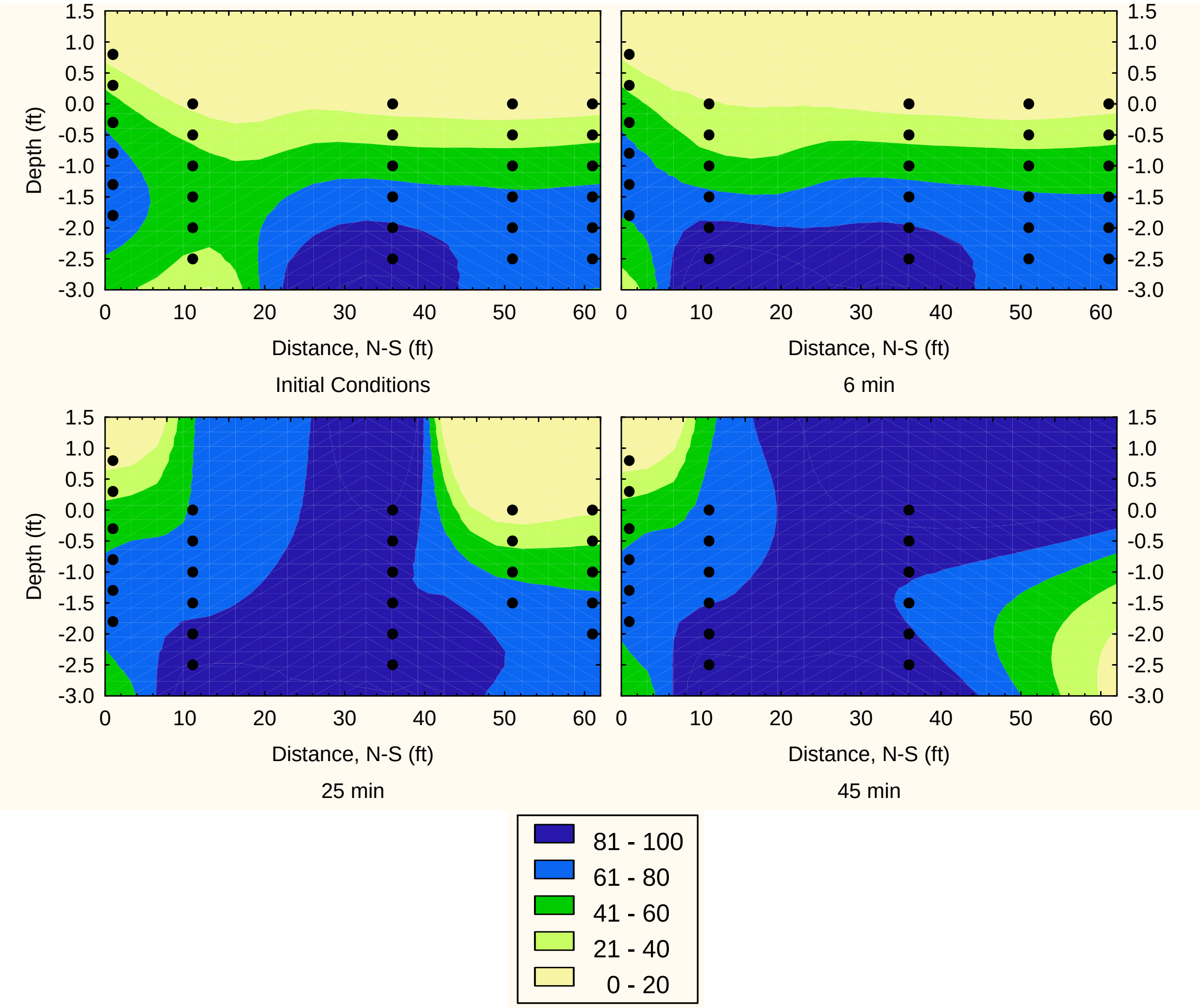

Figure A-29. North to south soil moisture profile from January 8, 2008, DVD test at the Thompson Lake bioretention cell.

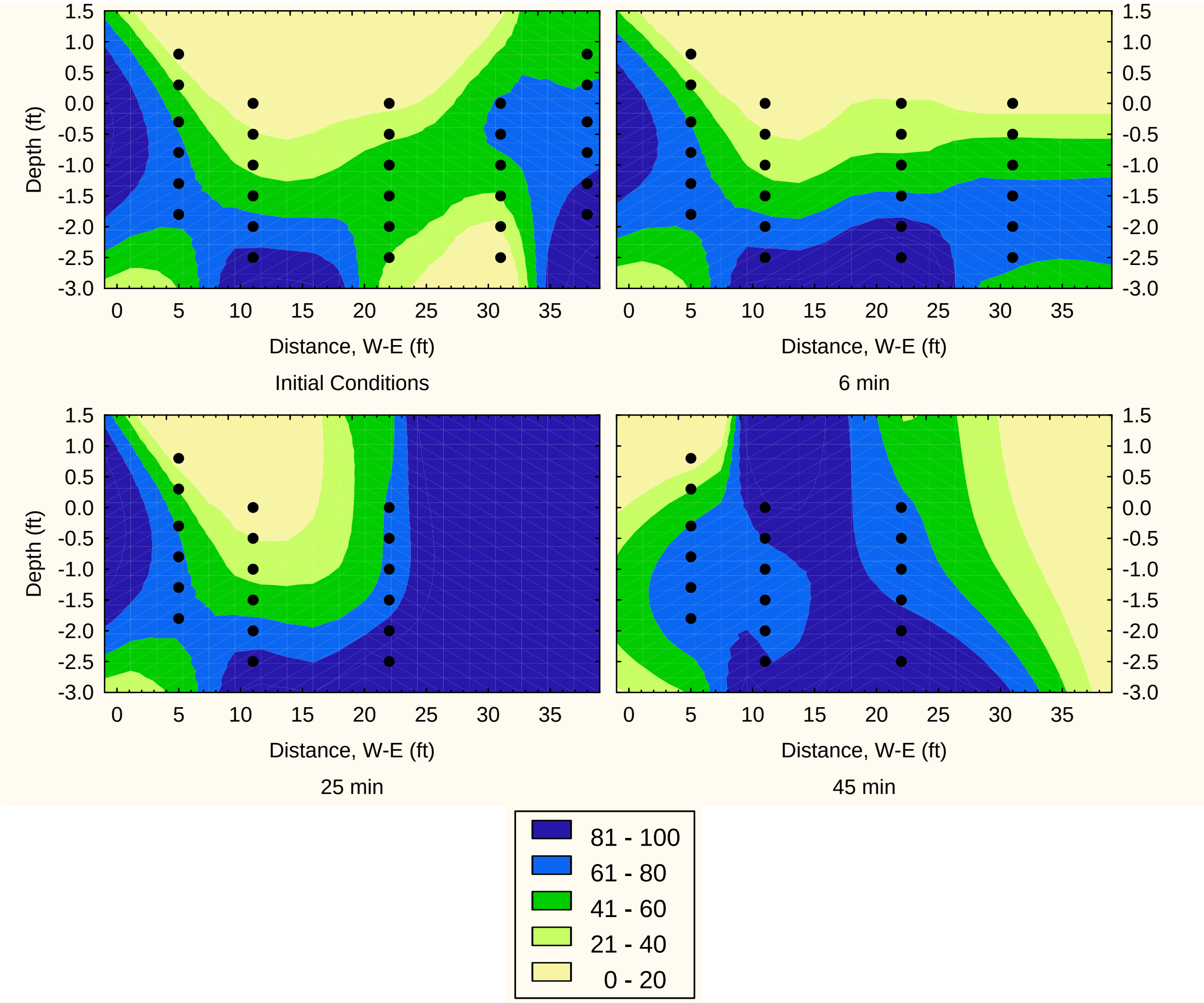

Figure A-30. West to east soil (north transect) moisture profile from January 8, 2008, DVD test at the Thompson Lake bioretention cell.

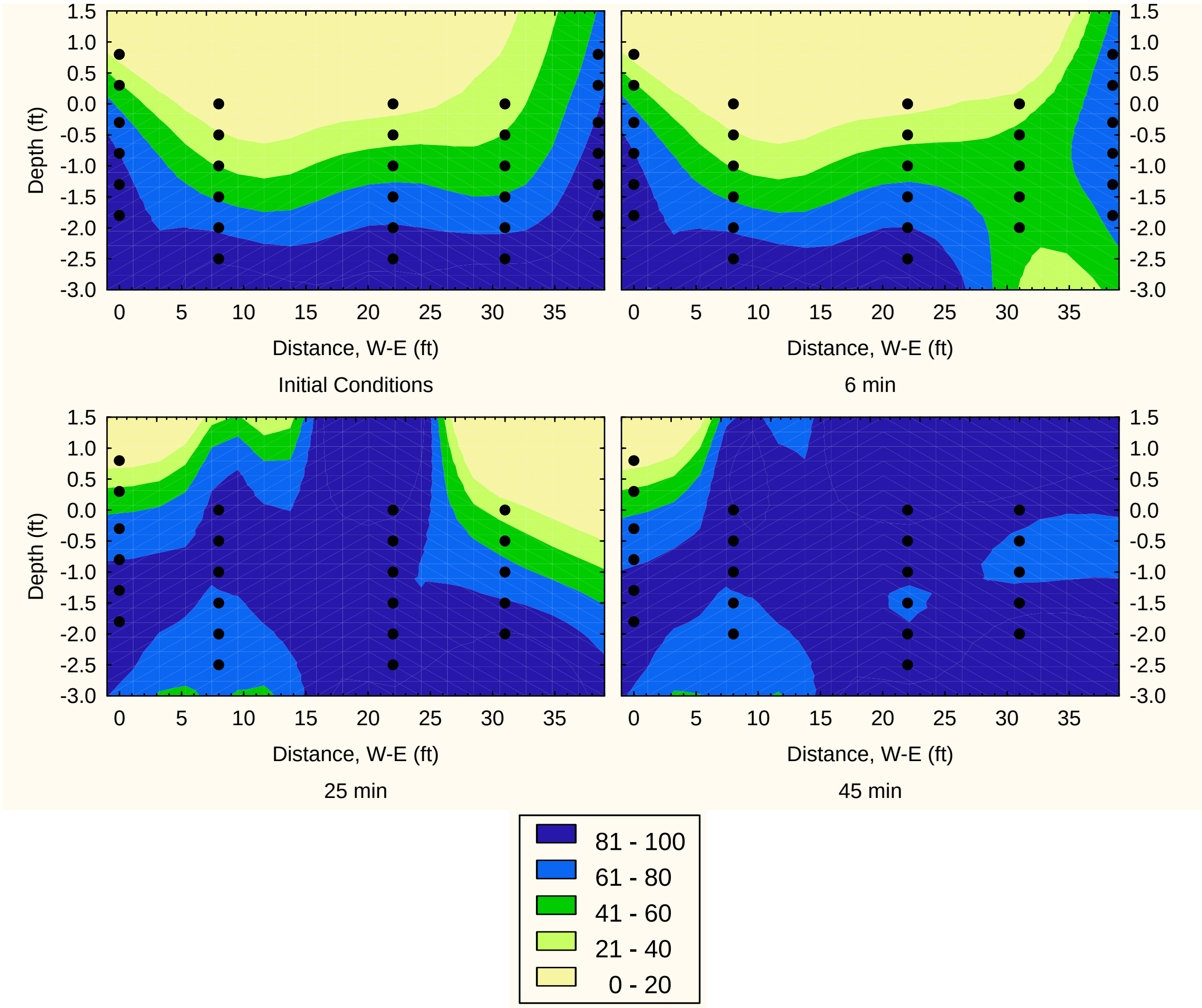

Figure A-31. West to east soil (middle transect) moisture profile from January 8, 2008, DVD test at the Thompson Lake bioretention cell.

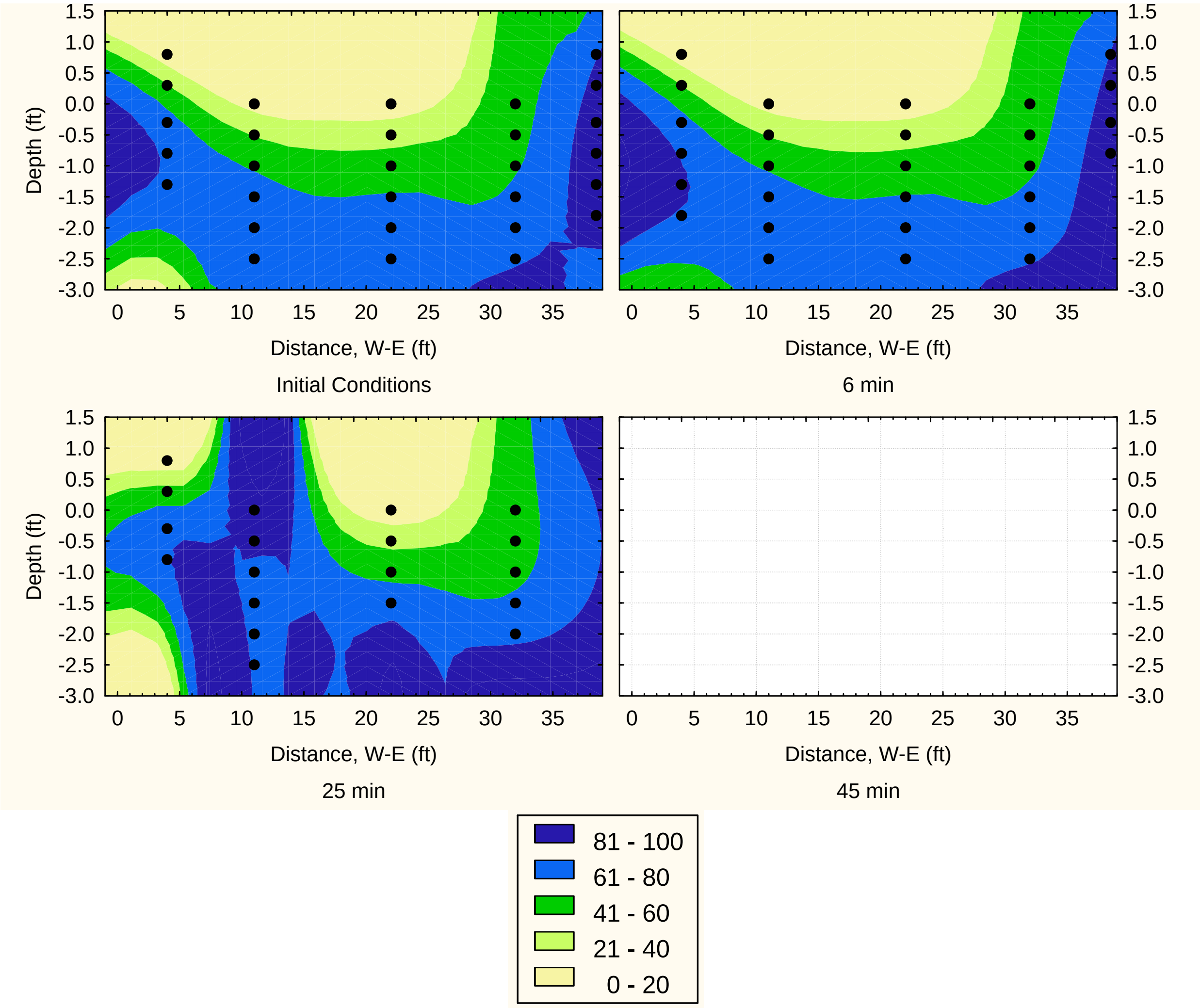

Figure A-32. West to east soil (south transect) moisture profile from January 8, 2008, DVD test at the Thompson Lake bioretention cell.

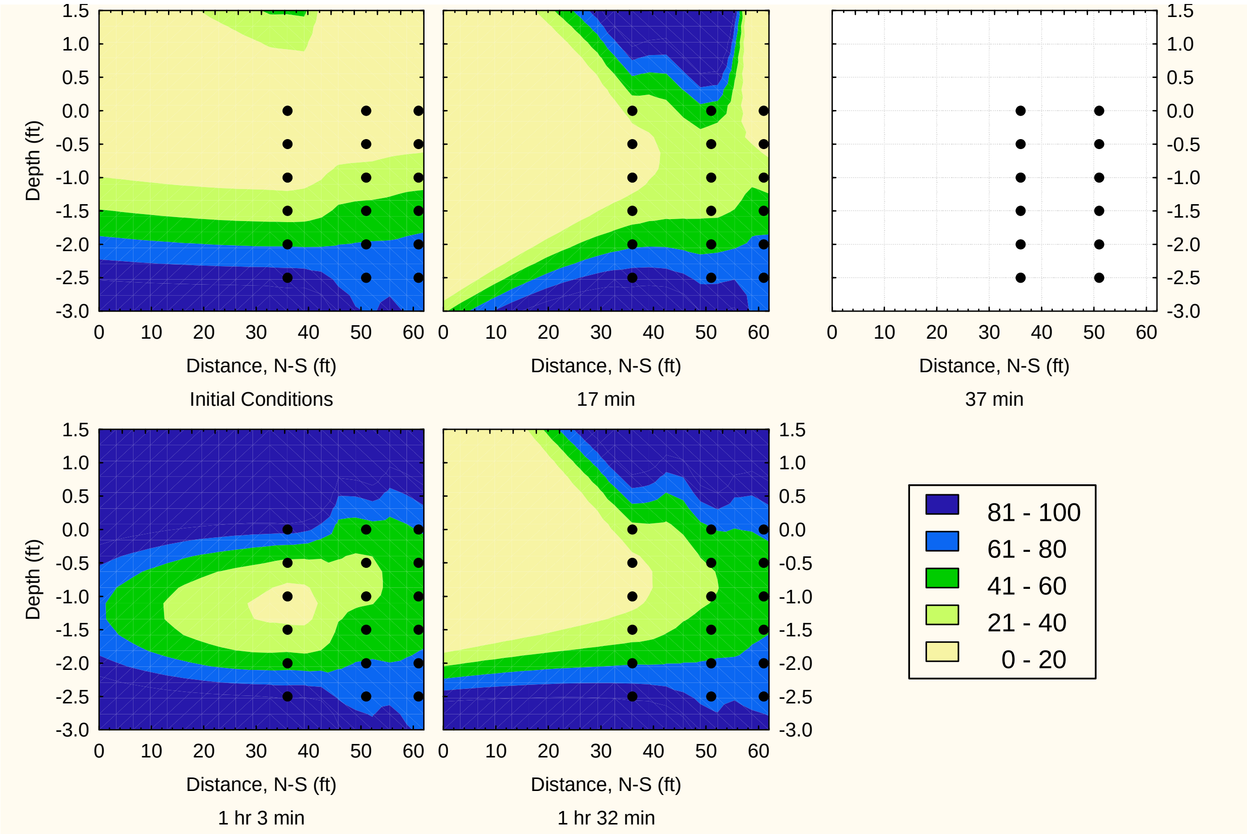

Figure A-33. North to south soil moisture profile from February 5, 2008, DVD test at the Thompson Lake bioretention cell.

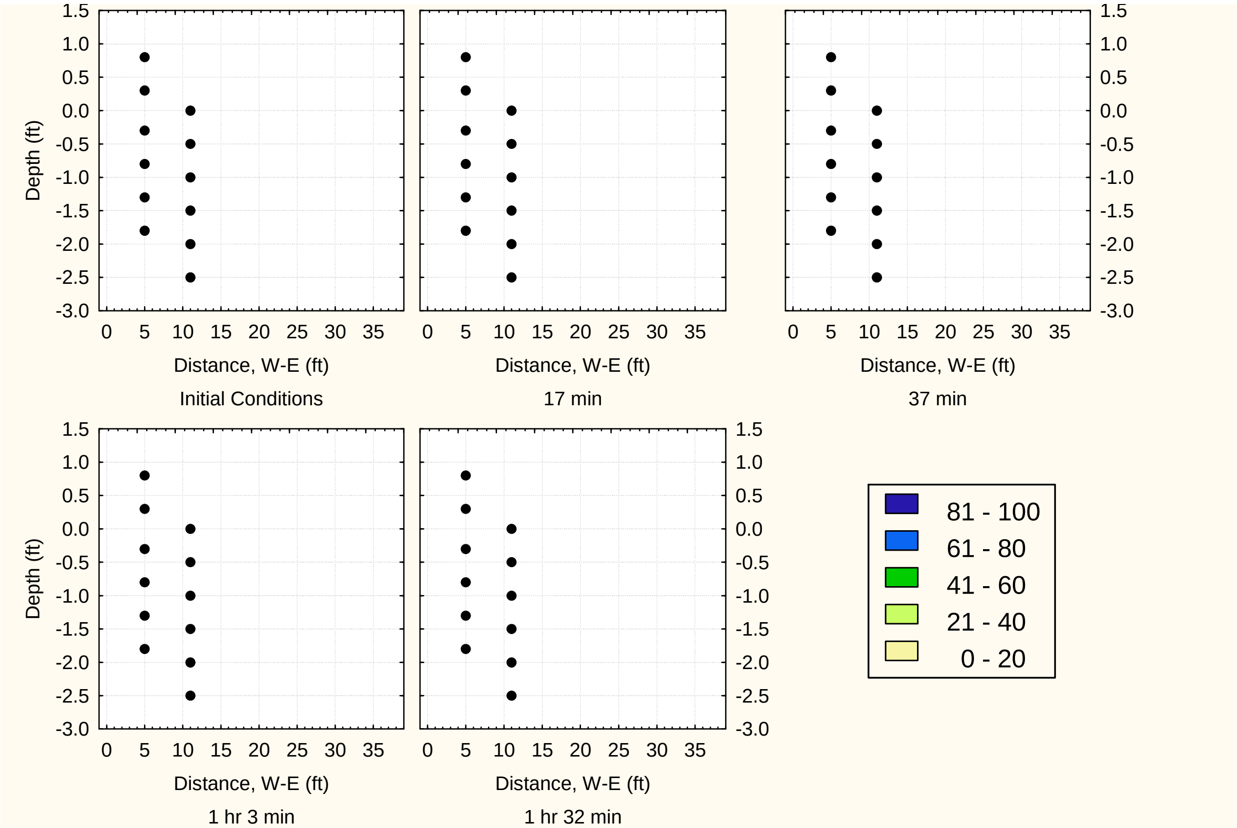

Figure A-34. West to east soil (north transect) moisture profile from February 5, 2008, DVD test at the Thompson Lake bioretention cell.

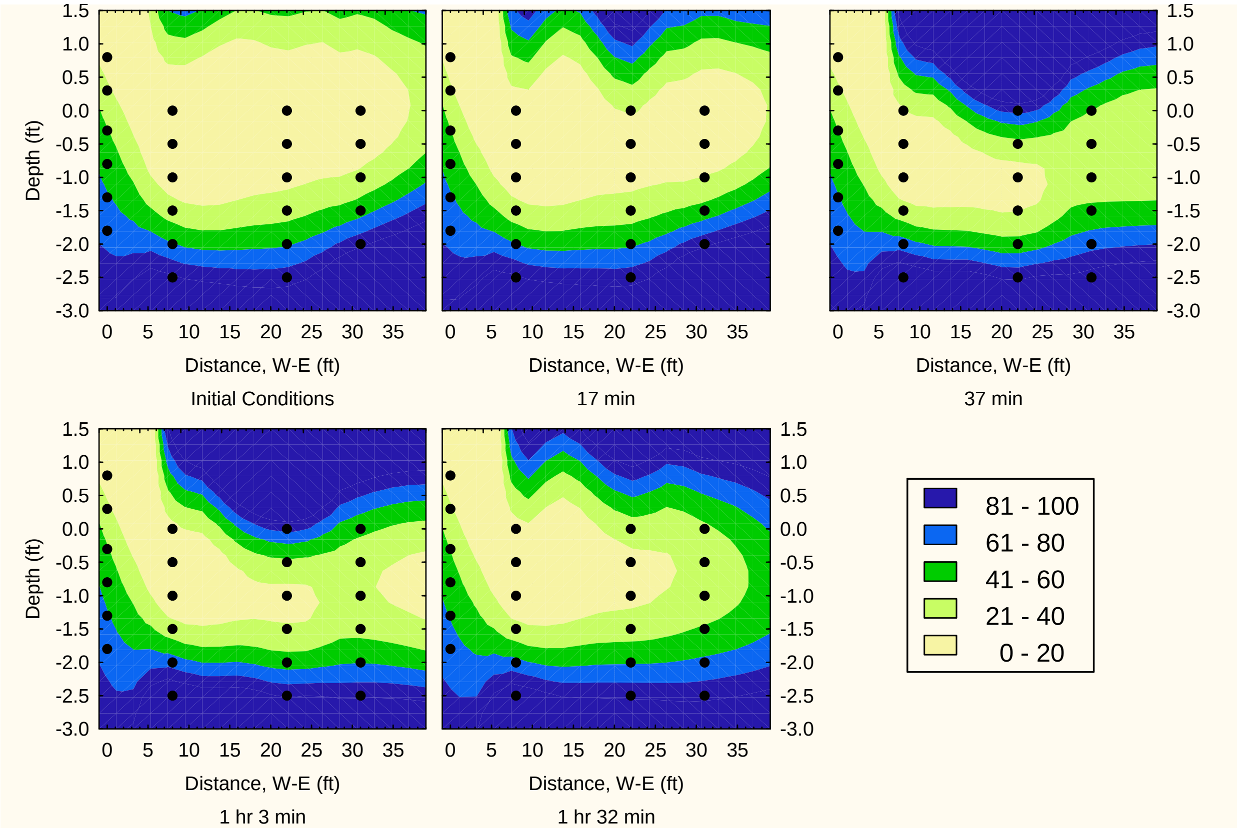

Figure A-35. West to east soil (middle transect) moisture profile from February 5, 2008, DVD test at the Thompson Lake bioretention cell.

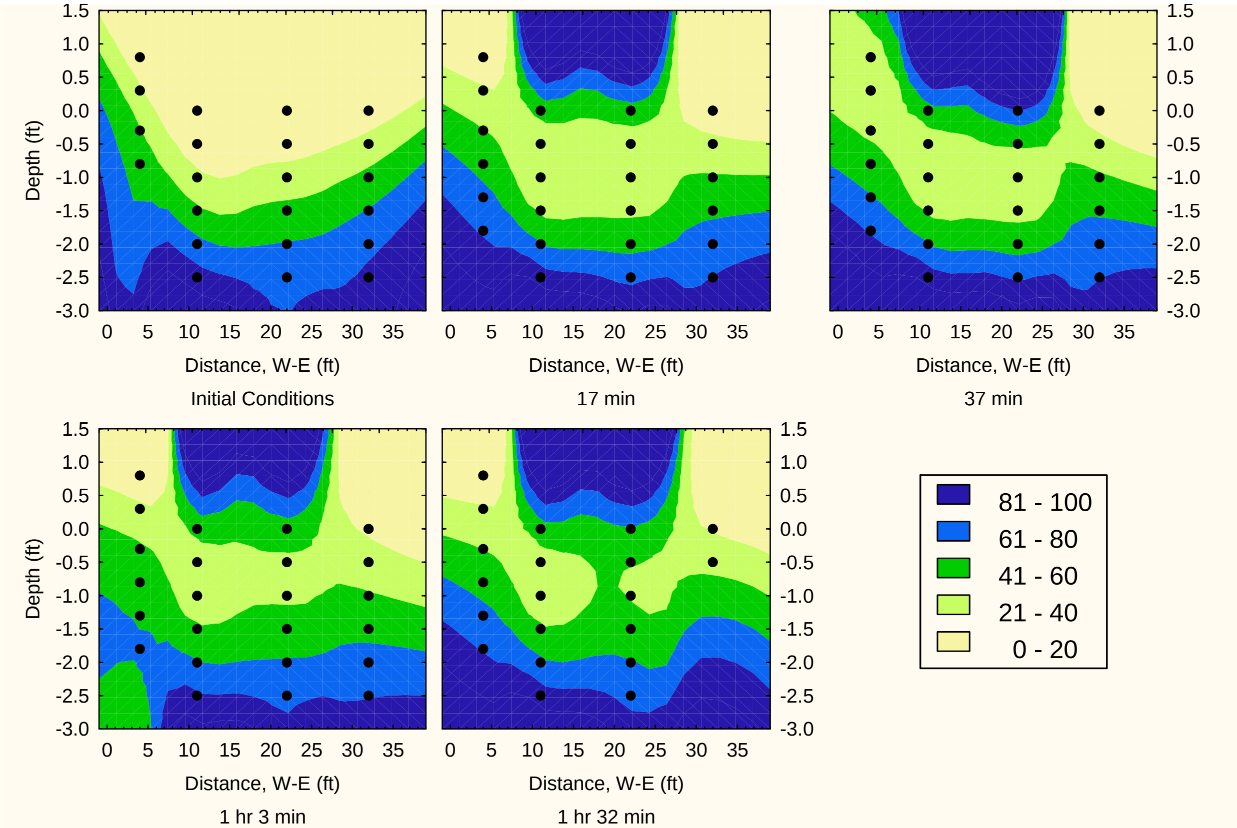

Figure A-36. West to east soil (south transect) moisture profile from February 5, 2008, DVD test at the Thompson Lake bioretention cell.

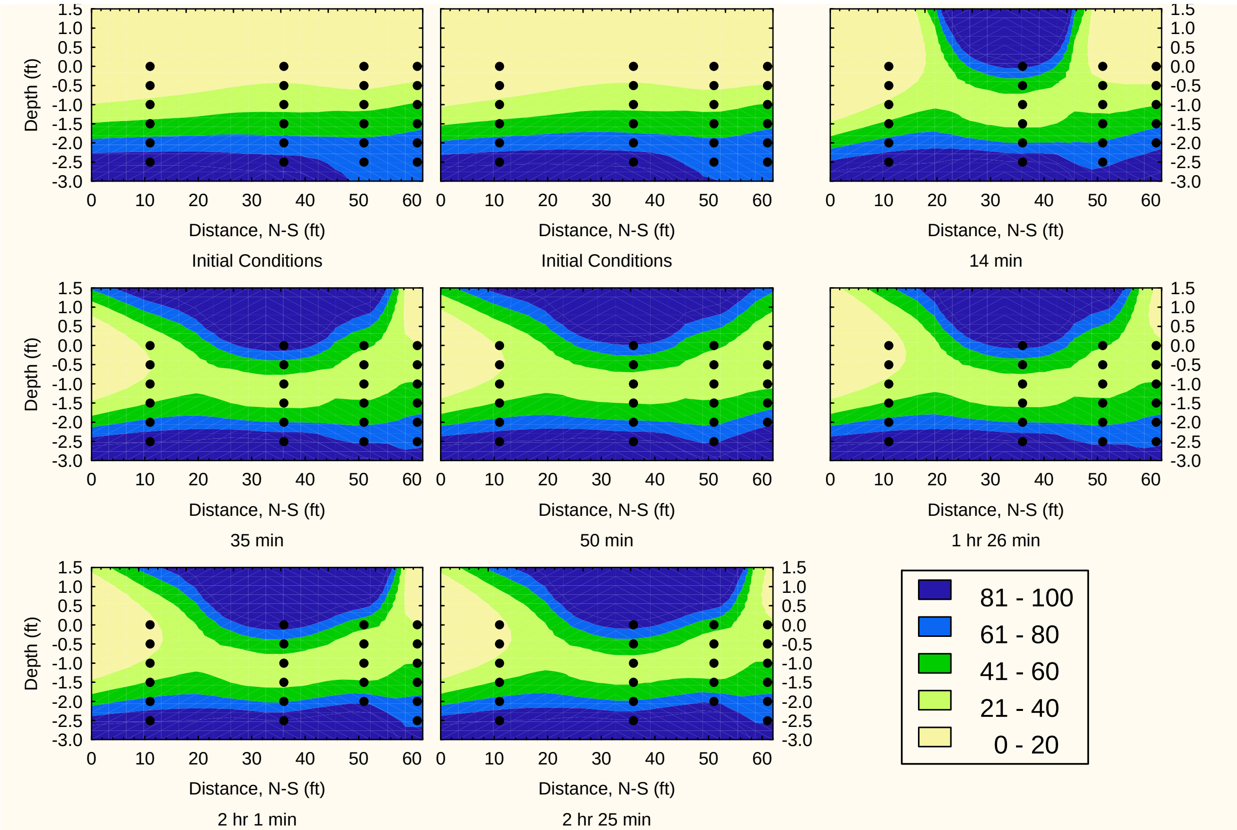

Figure A-37. North to south soil moisture profile from March 4, 2008, DVD test at the Thompson Lake bioretention cell.

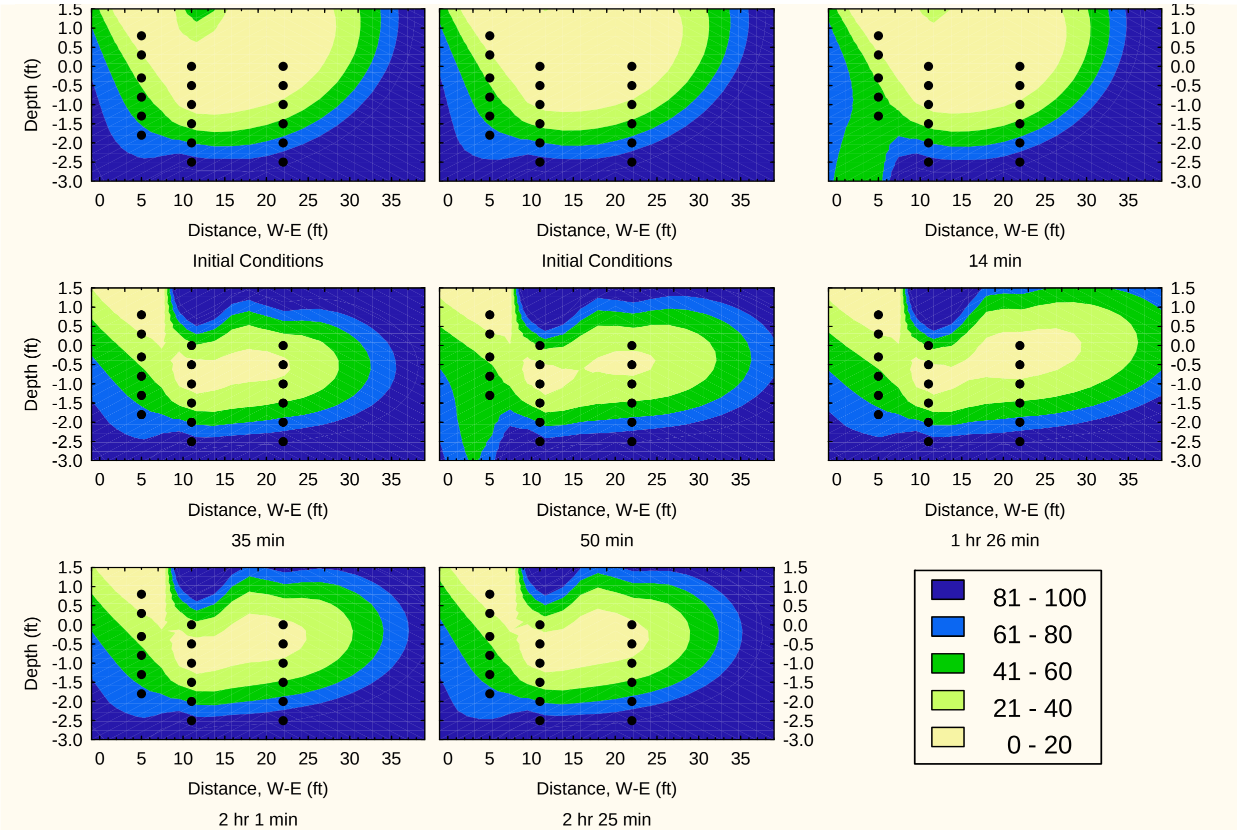

Figure A-38. West to east soil (north transect) moisture profile from March 4, 2008, DVD test at the Thompson Lake bioretention cell.

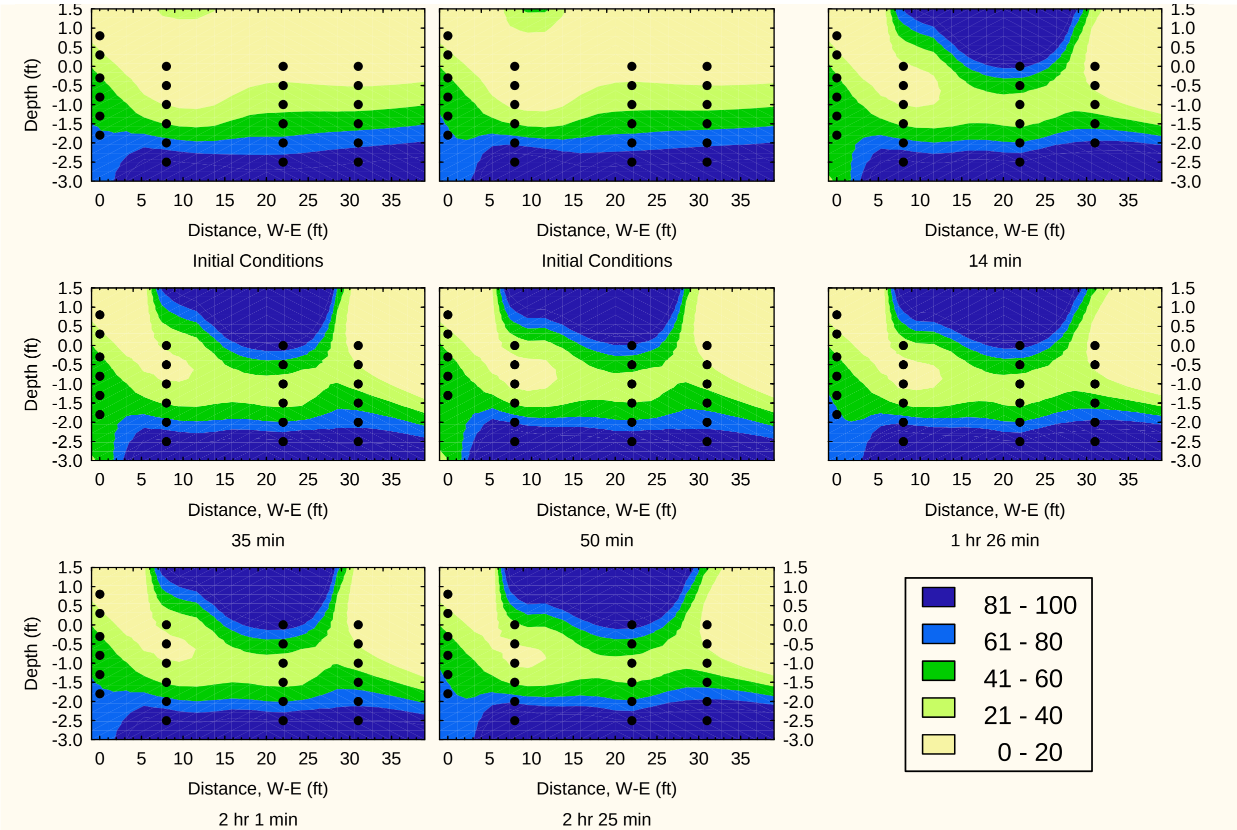

Figure A-39. West to east soil (middle transect) moisture profile from March 4, 2008, DVD test at the Thompson Lake bioretention cell.

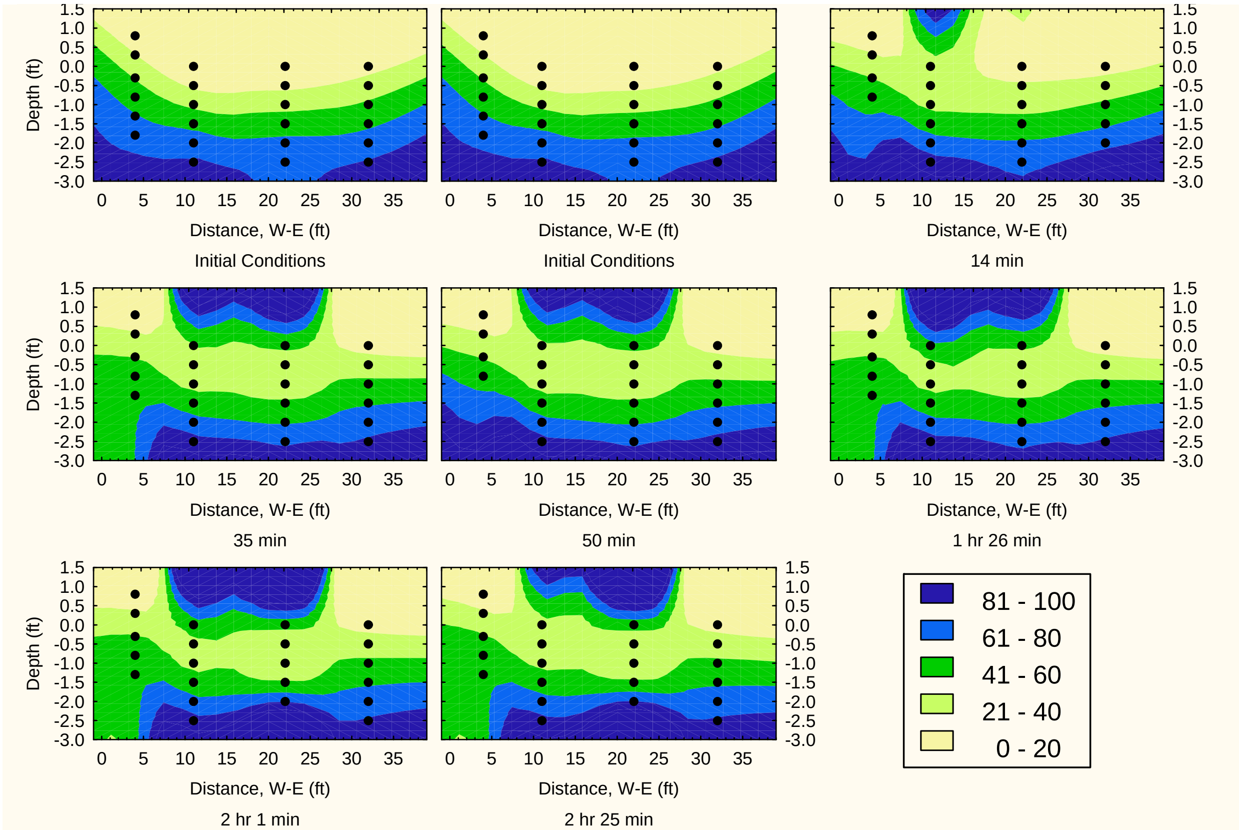

Figure A-40. West to east soil (south transect) moisture profile from March 4, 2008, DVD test at the Thompson Lake bioretention cell.

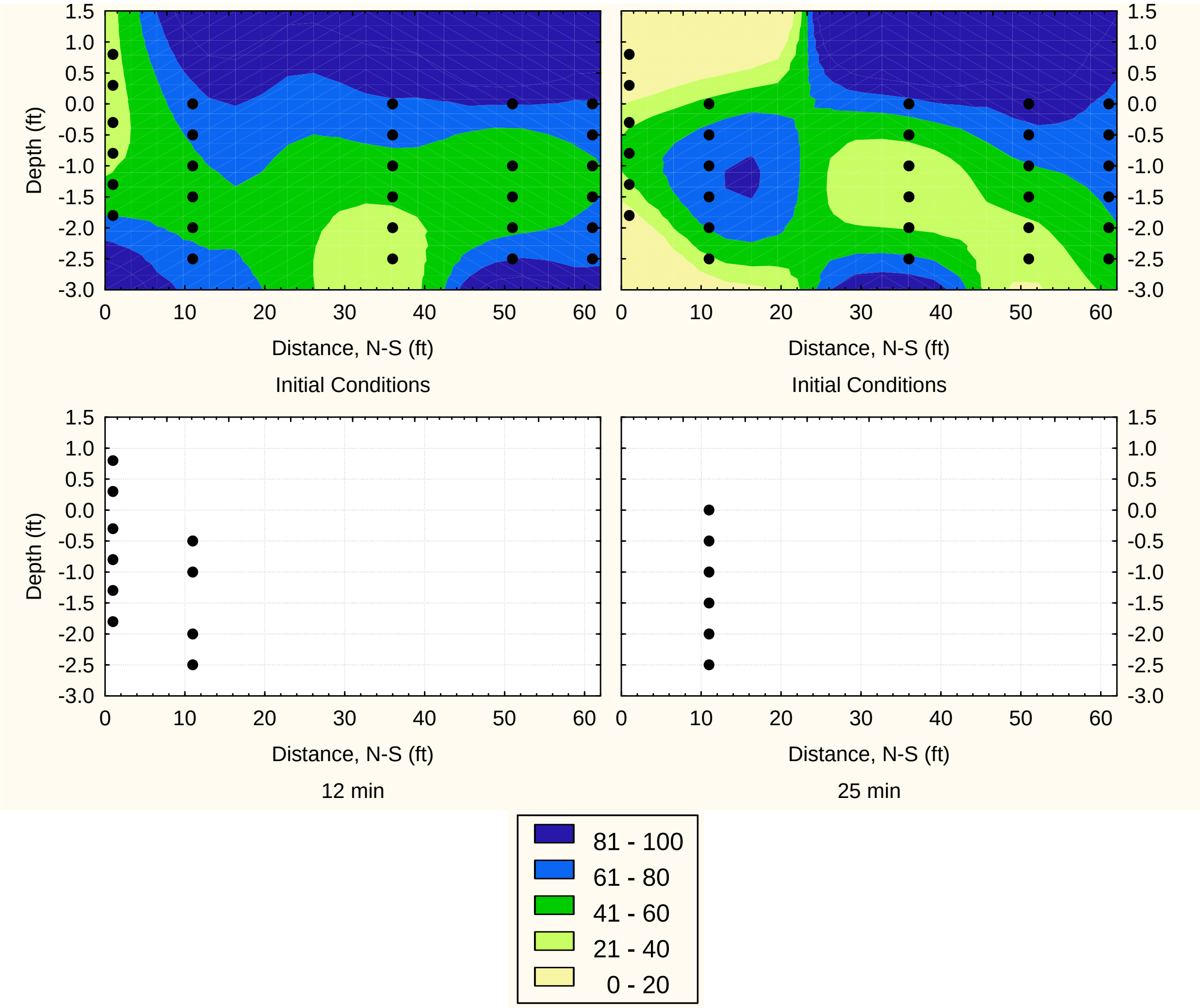

Figure A-41. North to south soil moisture profile from March 19, 2008, DVD test at the Thompson Lake bioretention cell.

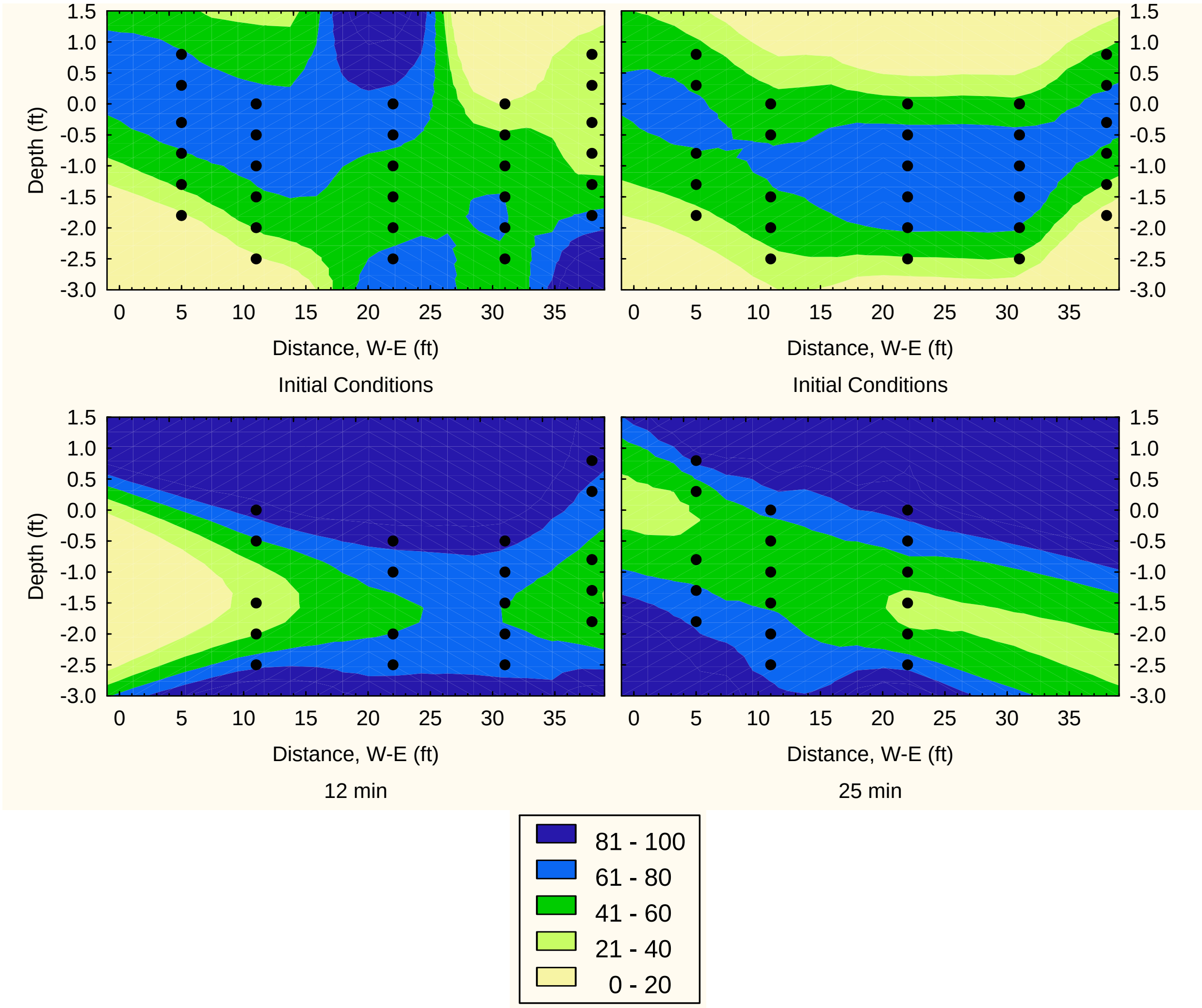

Figure A-42. West to east soil (north transect) moisture profile from March 19, 2008, DVD test at the Thompson Lake bioretention cell.

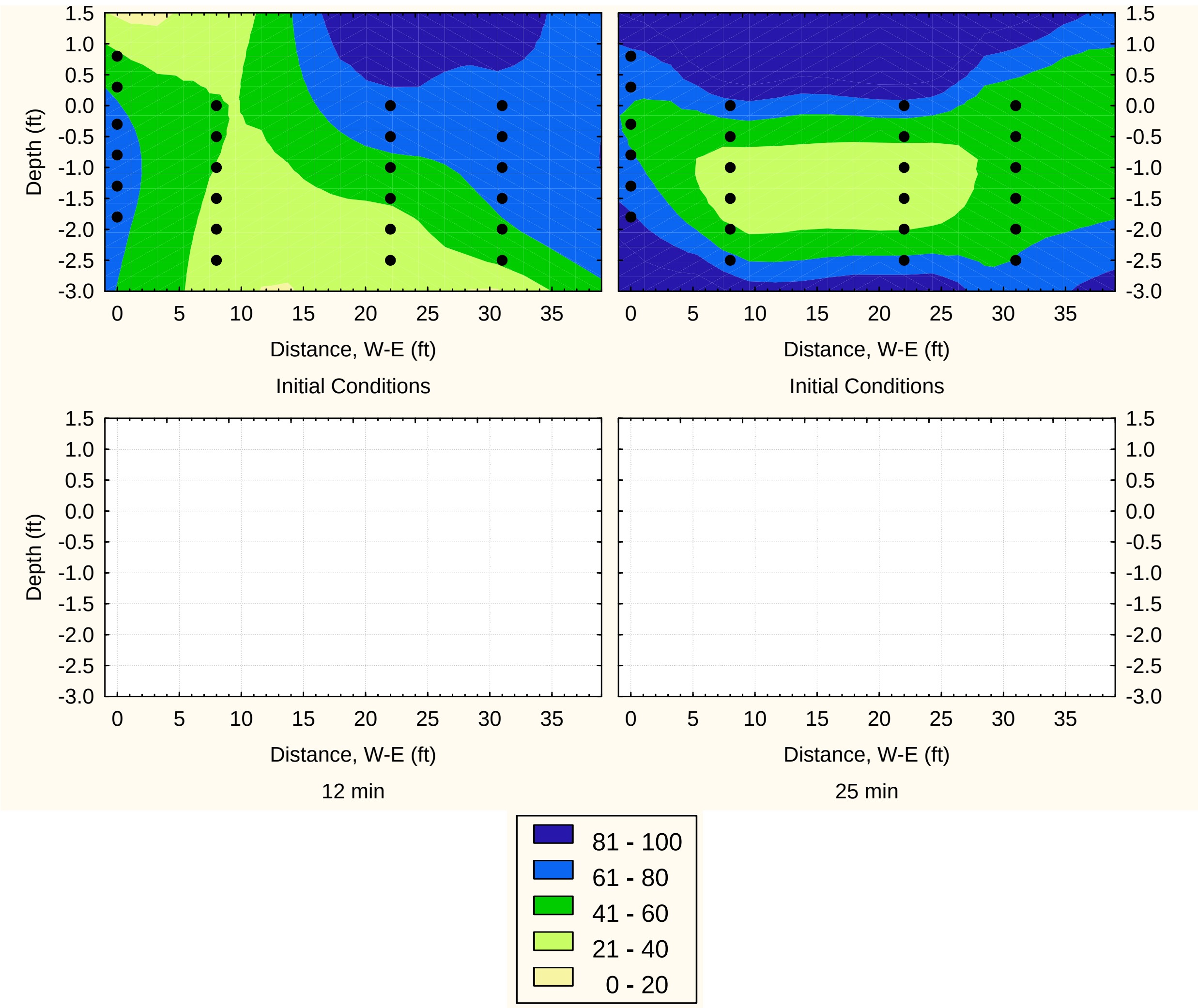

Figure A-43. West to east soil (middle transect) moisture profile from March 19, 2008, DVD test at the Thompson Lake bioretention cell.

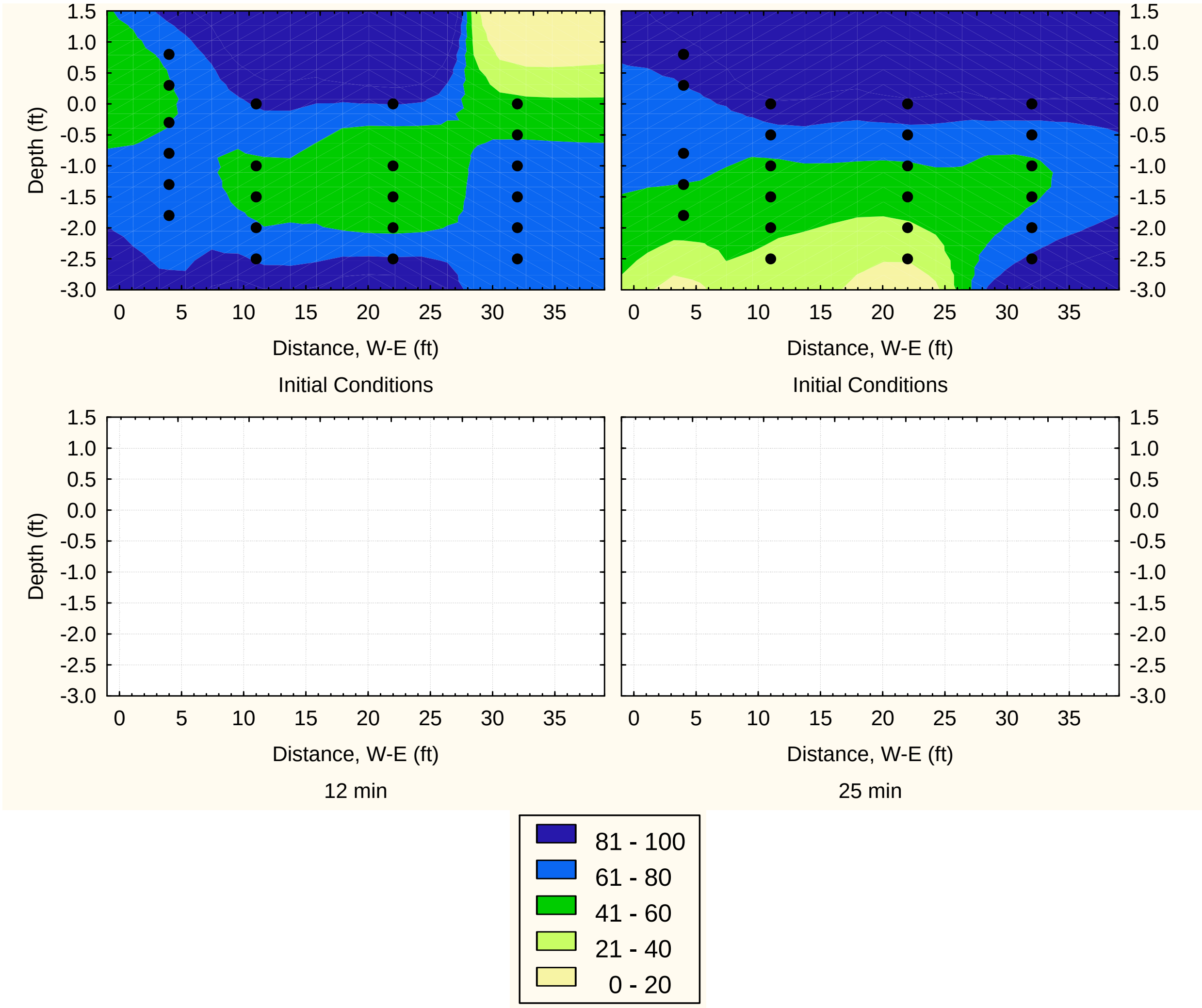

Figure A-44. West to east soil (south transect) moisture profile from March 19, 2008, DVD test at the Thompson Lake bioretention cell.

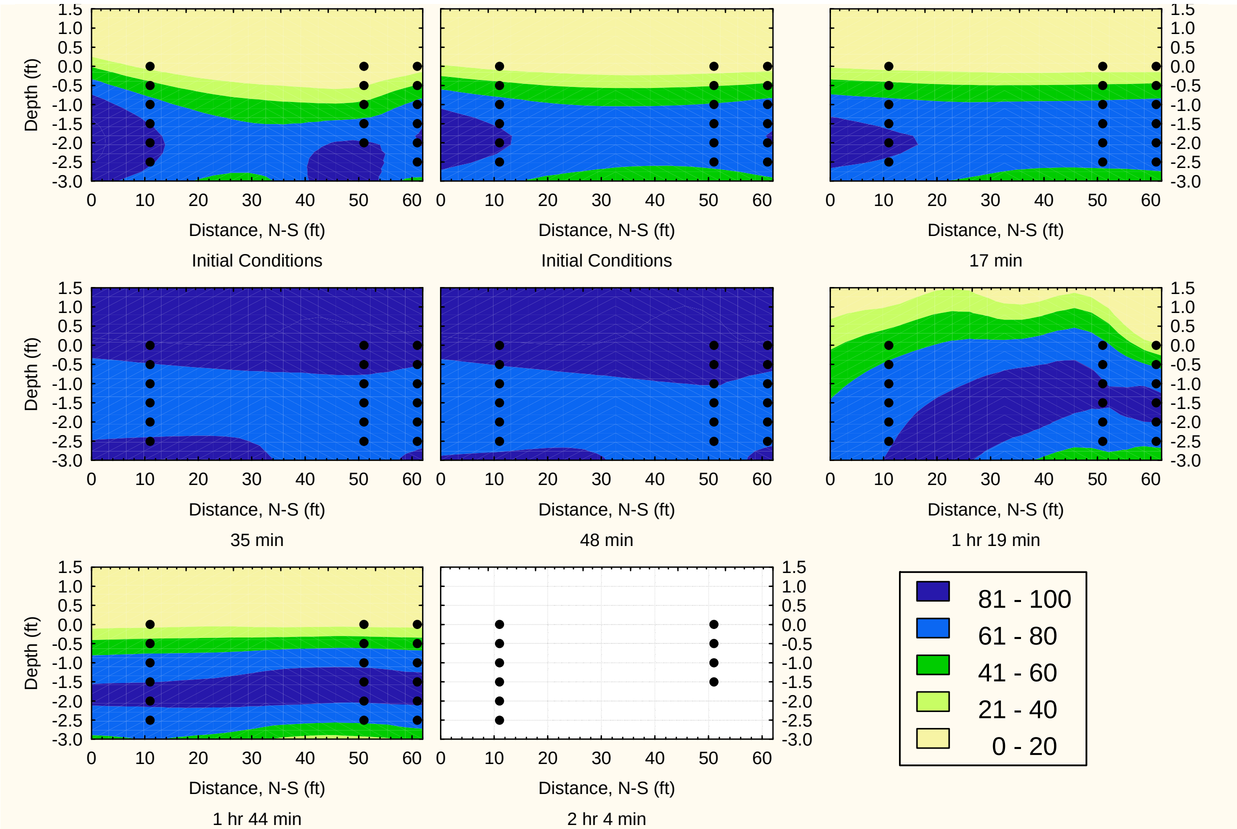

Figure A-45. North to south soil moisture profile from April 1, 2008, DVD test at the Thompson Lake bioretention cell.

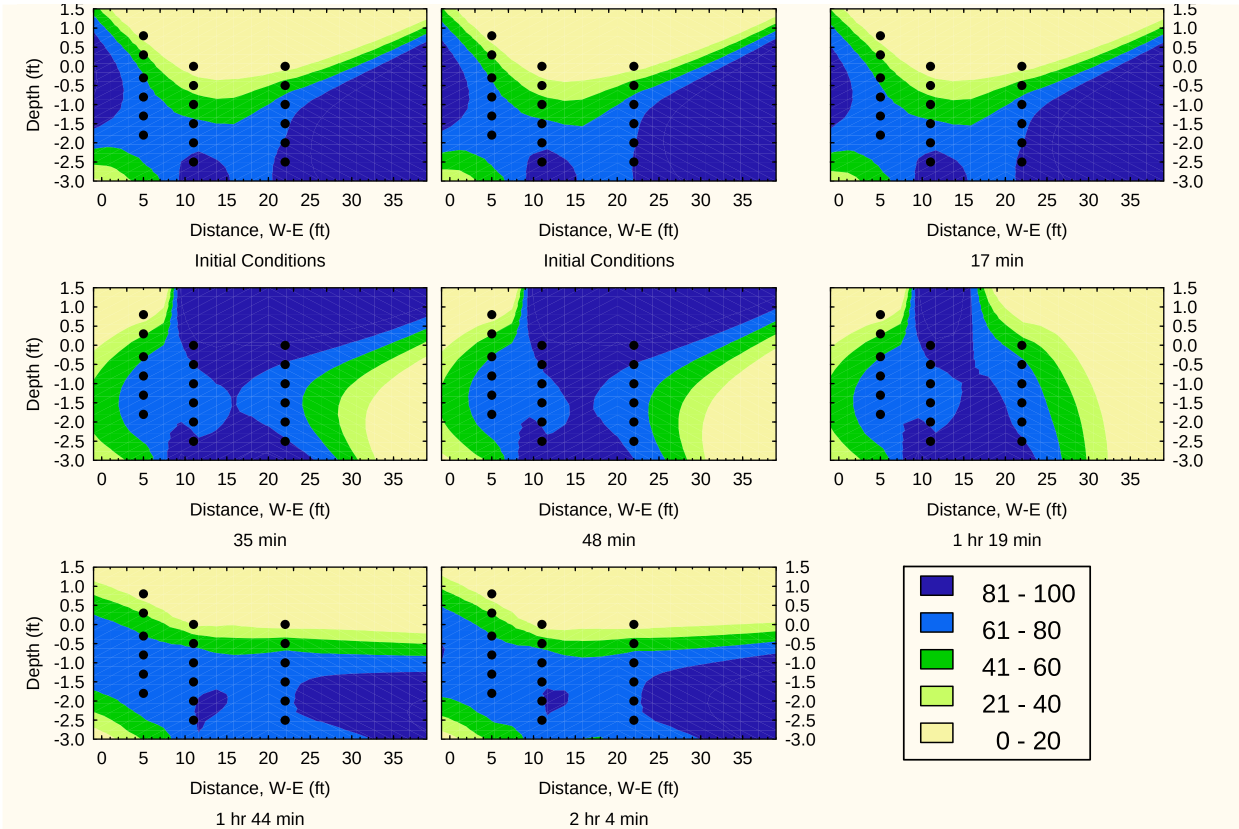

Figure A-46. West to east soil (north transect) moisture profile from April 1, 2008, DVD test at the Thompson Lake bioretention cell.

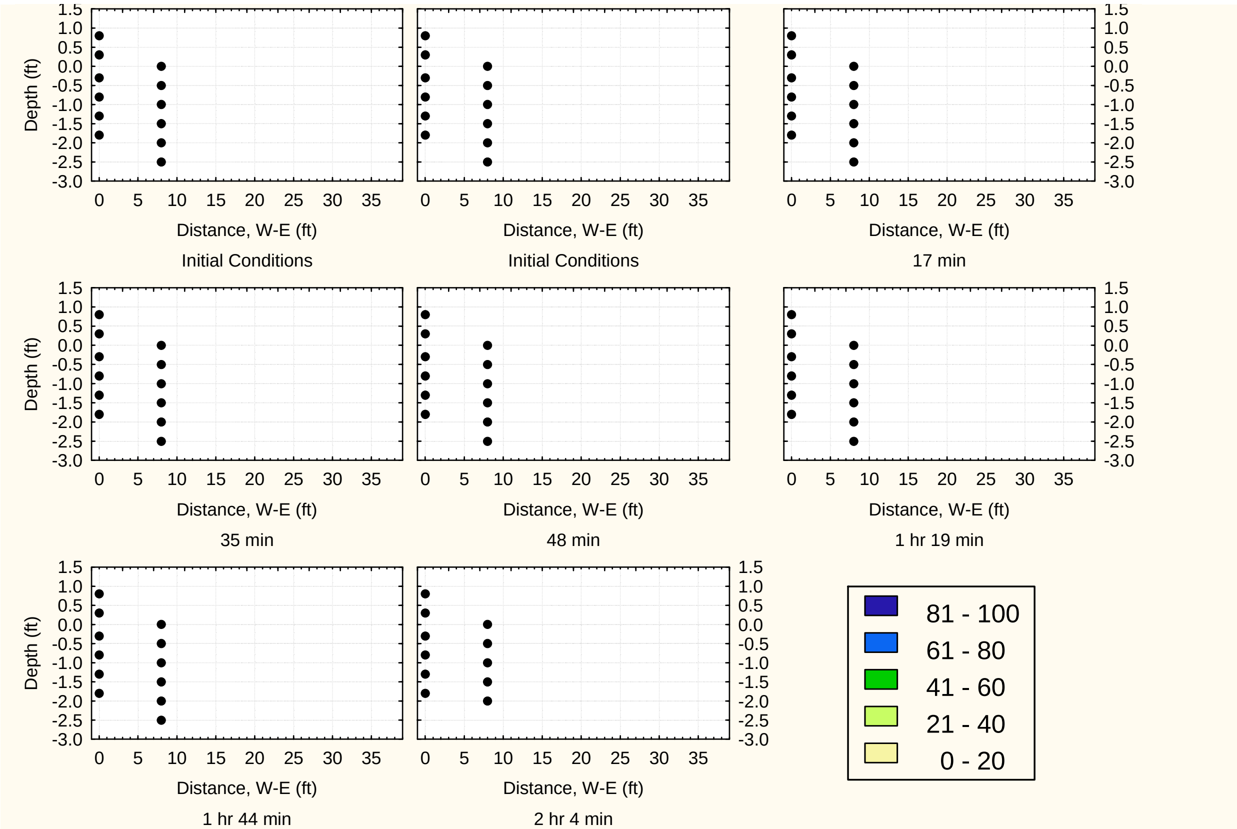

Figure A-47. West to east soil (middle transect) moisture profile from April 1, 2008, DVD test at the Thompson Lake bioretention cell.

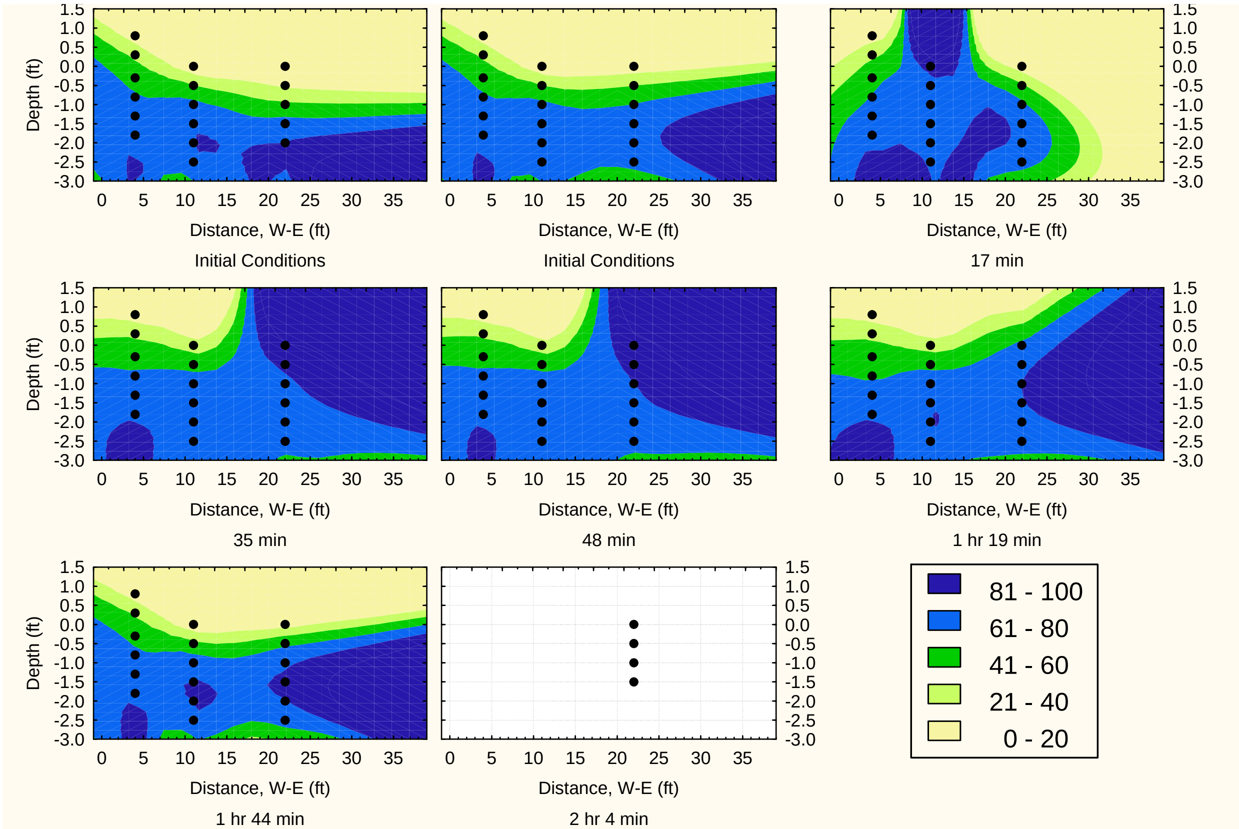

Figure A-48. West to east soil (south transect) moisture profile from April 1, 2008, DVD test at the Thompson Lake bioretention cell.

Table A-3. Site conditions and infiltration rates for DVD tests at the Cottage Grove bioretention cell.

DVD Test Date (season number)	Infiltration Rate from End of Test Water Appli-cation (in/hr)	Inflow Rate from Start of Test Water Application (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth^Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/22/2006* (1)	11.5	4.2•	31.2	32.1	32.7	6.8	10.7	0.5	37.5	N/A	10	0	200^	Heavy water content of snow; basin completely full of snow; may be frost to 1m but on borderline.
2/22/2007* (2)	1.2	N/A**	29.8	26.3	26.5	2.9	6.2	1.5	45.6	53.4	0	0	200	Some ice in basin from previous day; some water seeped through overflow structure cracks.
3/22/2007 (2)	9.0	6.2	33.8	32.5	32.5	5.7	12.4	0	47.0	32.0	0	0	200	Frost tubes frozen in ground.
12/20/2007 (3)	13.2	9.6	28.9	31.7	36.4	3.1	7.2	0.5	27.1	50.0	6.5	99	250	
1/8/2008 (3)	11.5	6.7	32.0	32.4	34.7	3.9	7.8	0.5	38.1	49.6	7	99	250	
2/22/2008 (3)	0.3	N/A**	23.1	24.6	28.4	3.4	6.4	1.5	12.1	50.9	4.5	110	225	Main cluster frost tube frozen in ground, layer of ice at bottom of basin.
3/19/2008 (3)	2.0	N/A**	32.0	30.8	30.7	8.0	32.2	1.5	37.6	N/A	0.25	124	200	Some water went through outlet structure cracks.

* No soil moisture data.
Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

^ Assumed value.

** Not able to be determined because of standing water at end of test period.

• Extrapolated since zero depth was nearly achieved by end of the test.

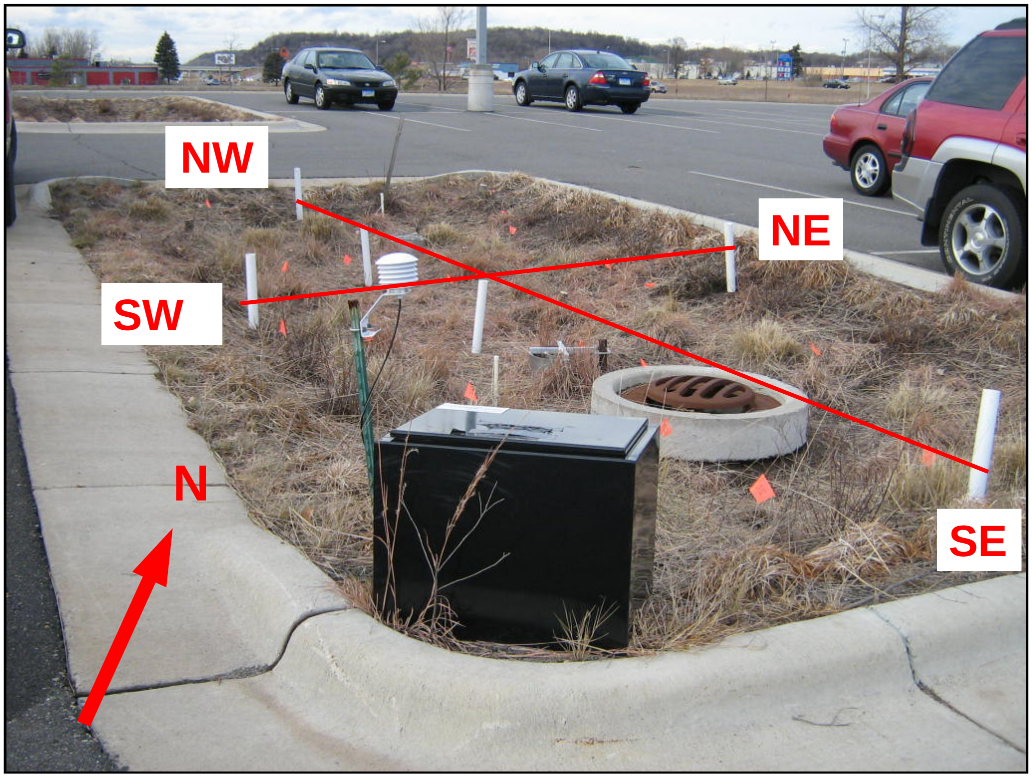

Figure A-48. Soil moisture probe transect locations for the Cottage Grove bioretention cell.

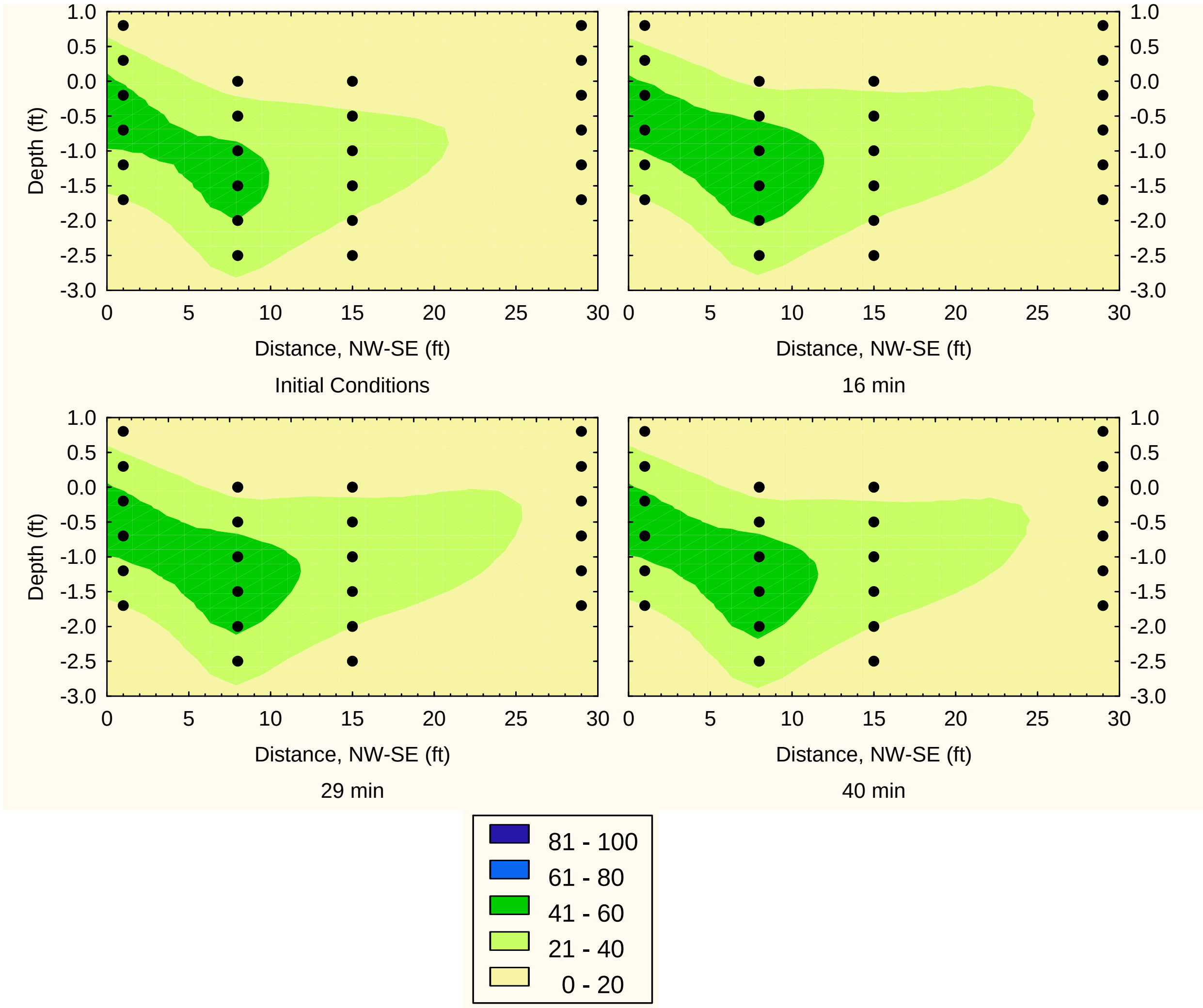

Figure A-49. Northwest to southeast soil moisture profile from March 22, 2007, DVD test at the Cottage Grove bioretention cell.

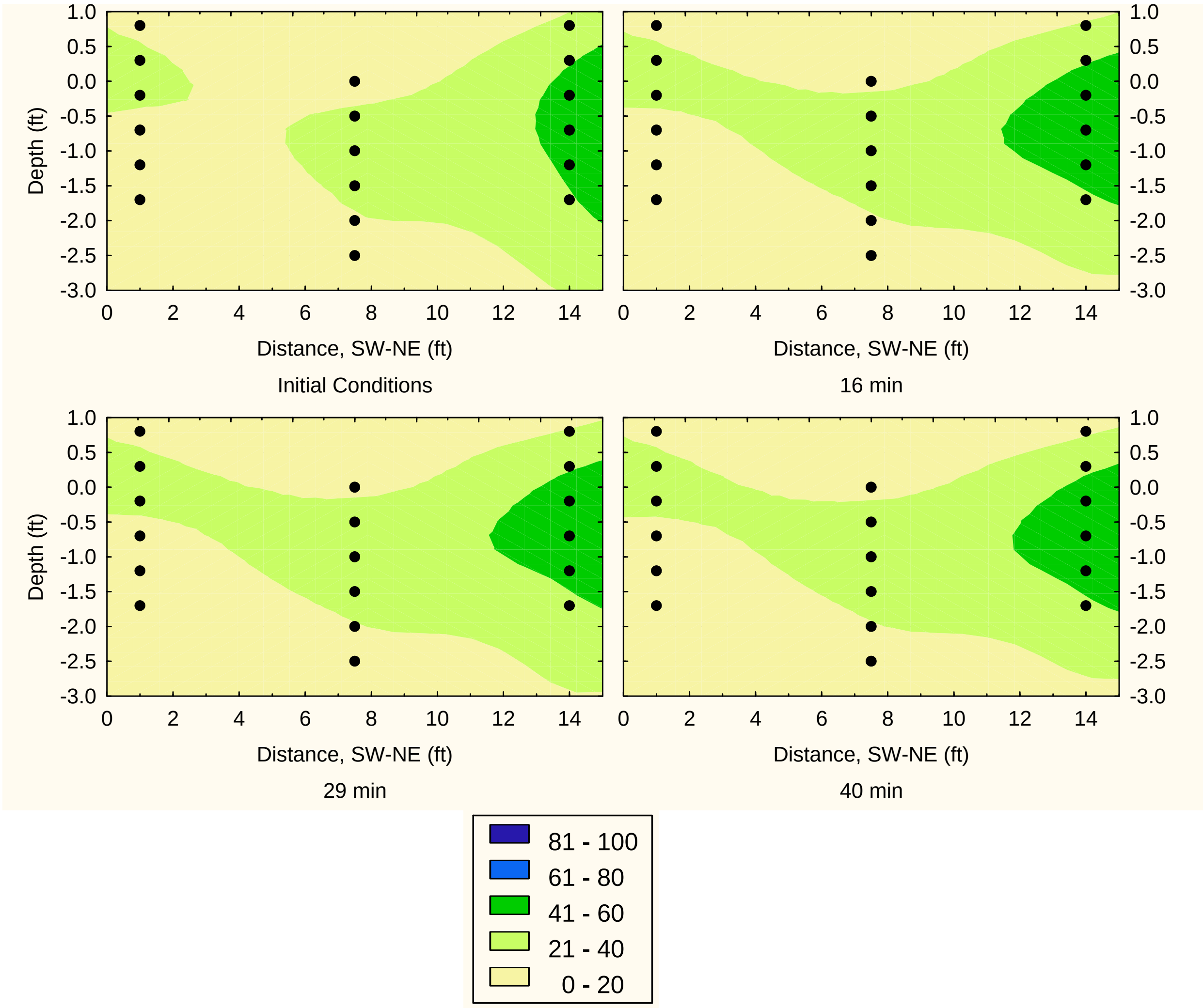

Figure A-50. Southwest to northeast soil moisture profile from March 22, 2007, DVD test at the Cottage Grove bioretention cell.

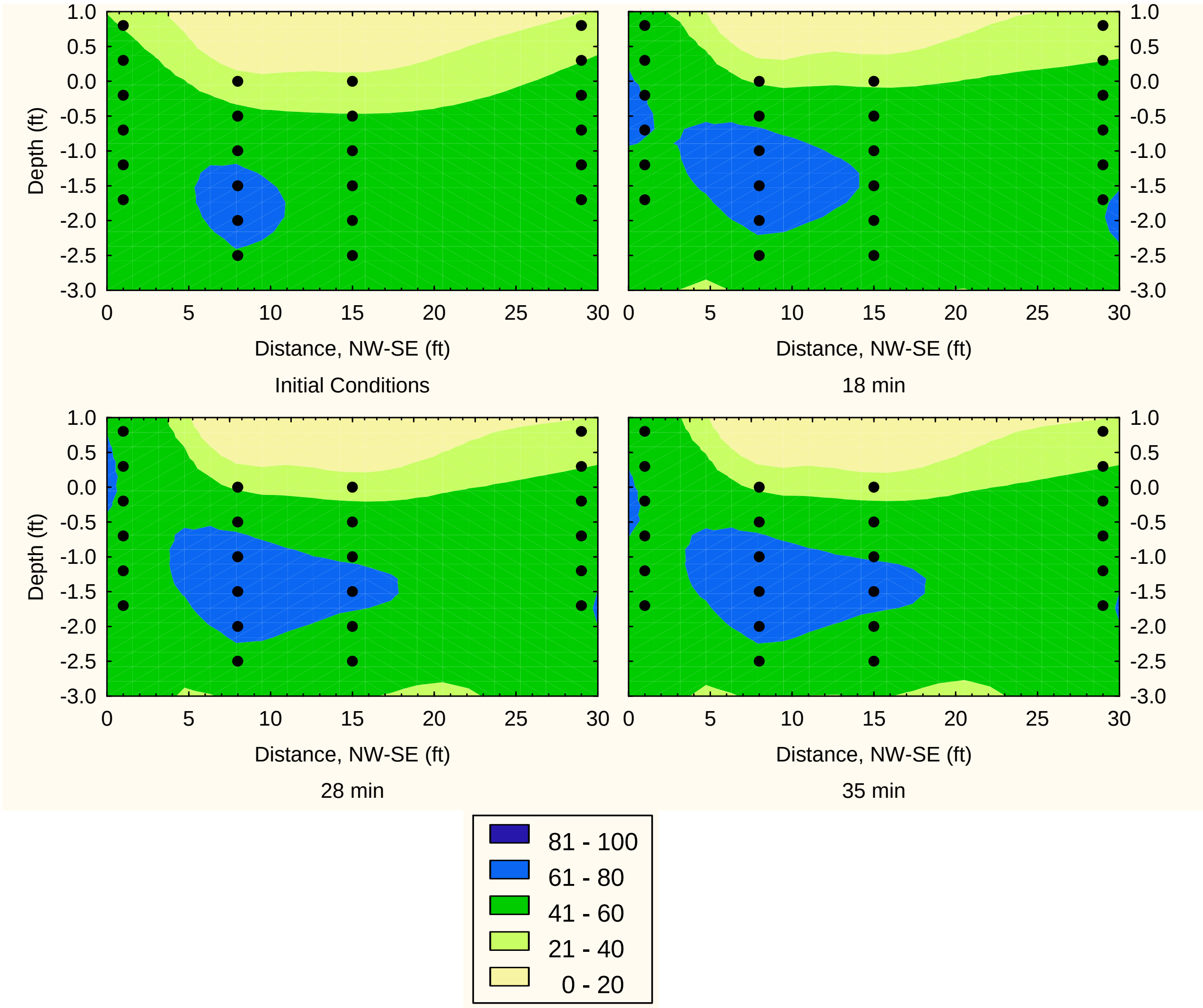

Figure A-51. Northwest to southeast soil moisture profile from December 20, 2007, DVD test at the Cottage Grove bioretention cell.

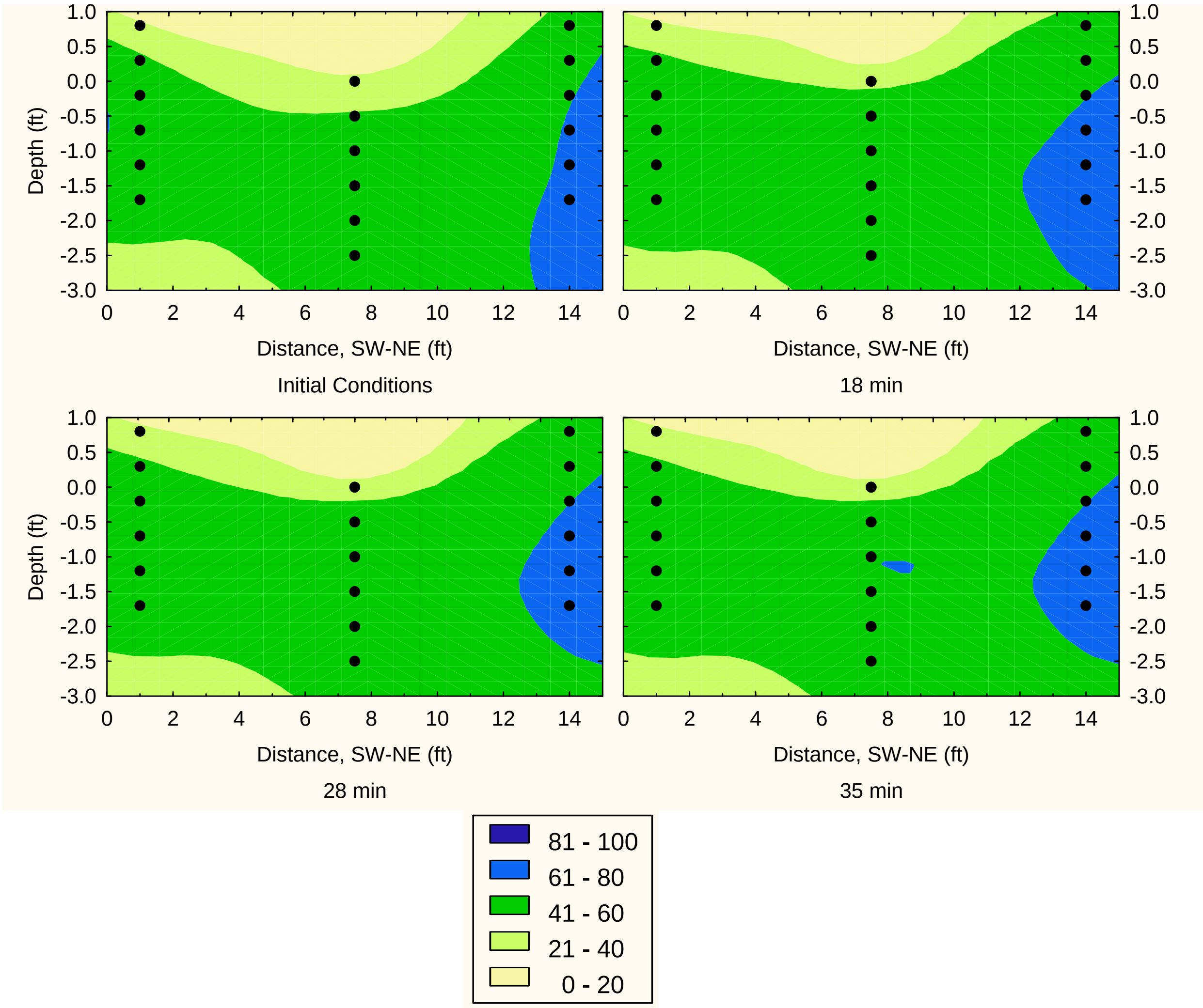

Figure A-52. Southwest to northeast soil moisture profile from December 20, 2007, DVD test at the Cottage Grove bioretention cell.

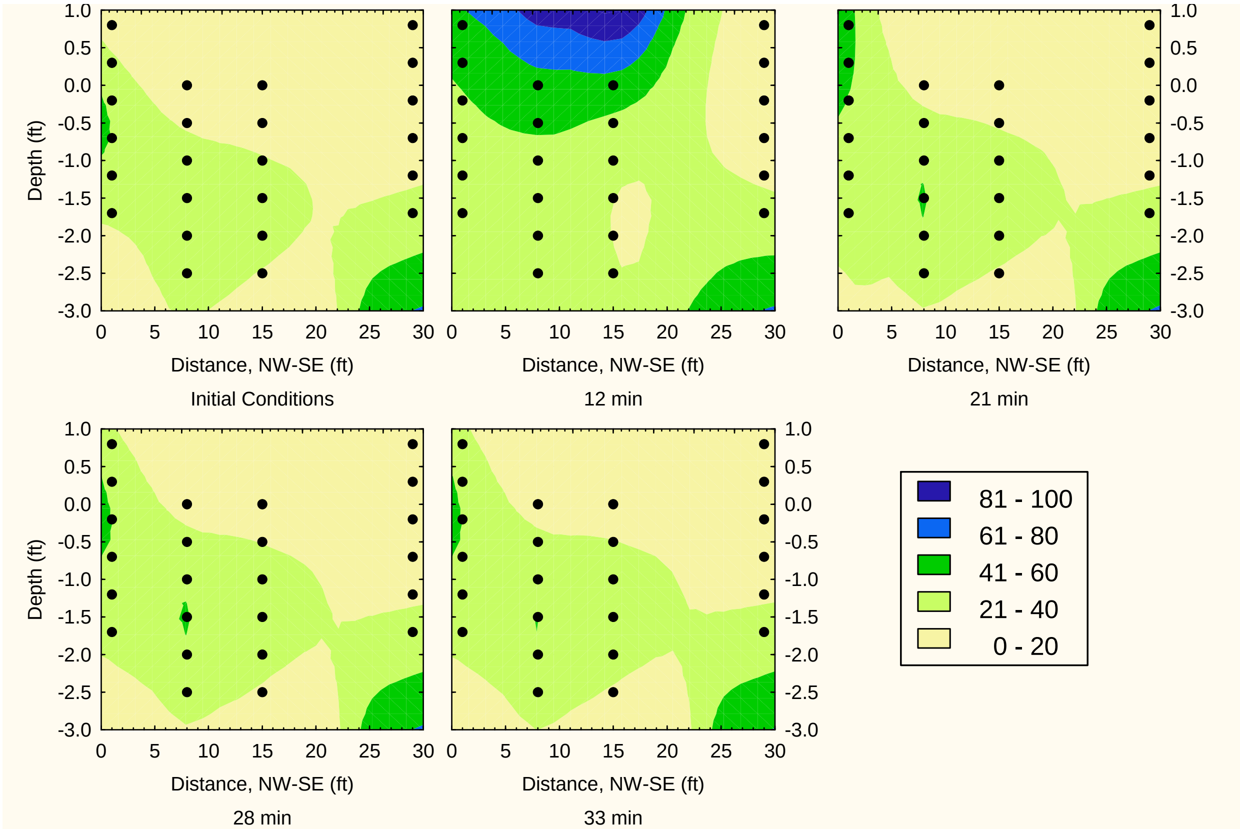

Figure A-53. Northwest to southeast soil moisture profile from January 8, 2008, DVD test at the Cottage Grove bioretention cell.

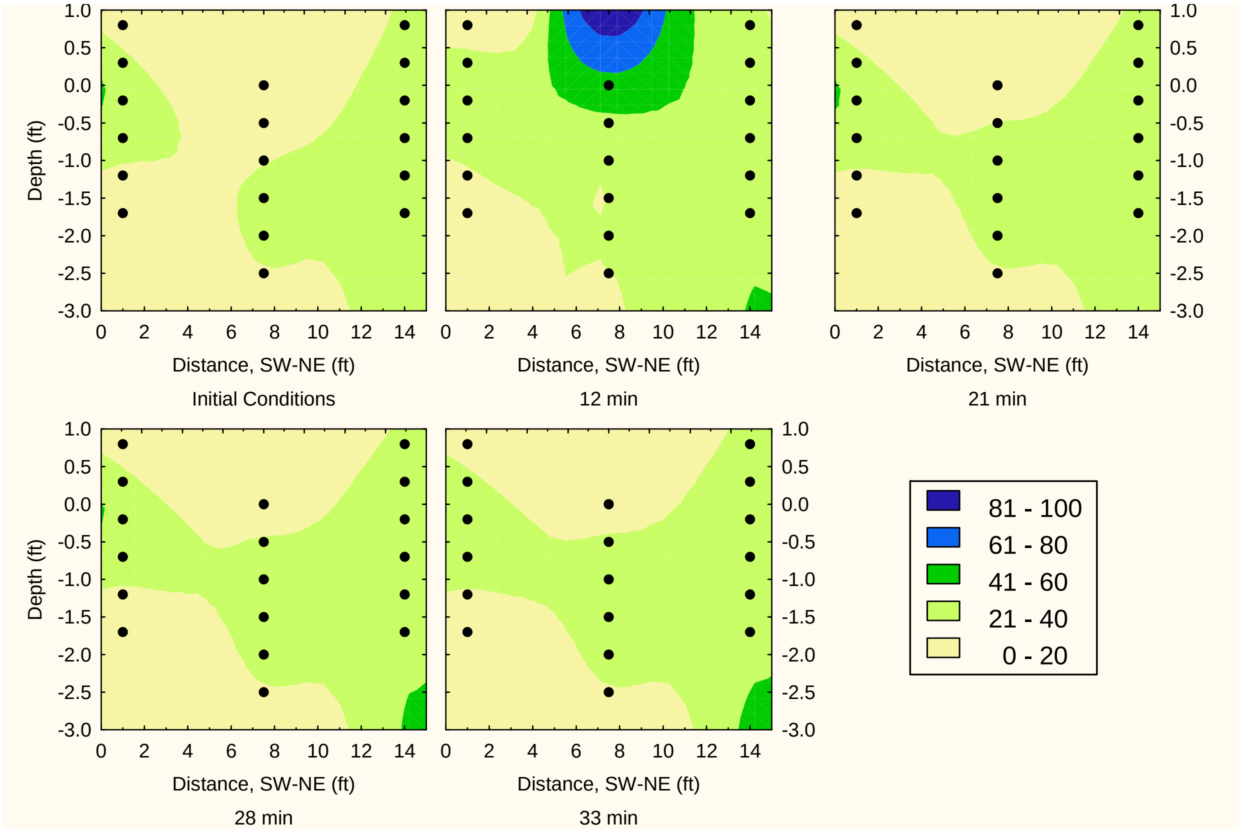

Figure A-54. Southwest to northeast soil moisture profile from January 8, 2008, DVD test at the Cottage Grove bioretention cell.

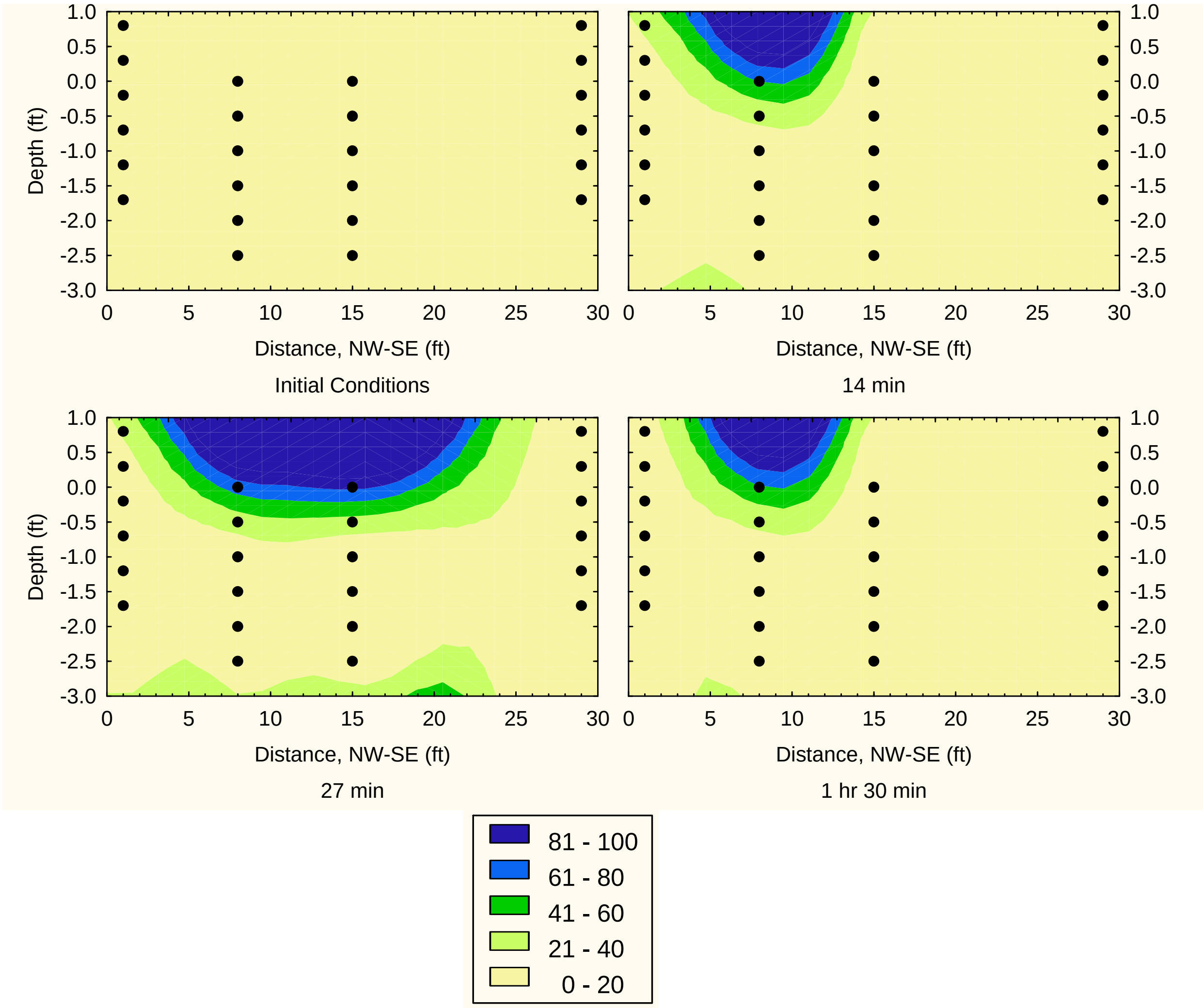

Figure A-55. Northwest to southeast soil moisture profile from February 22, 2008, DVD test at the Cottage Grove bioretention cell.

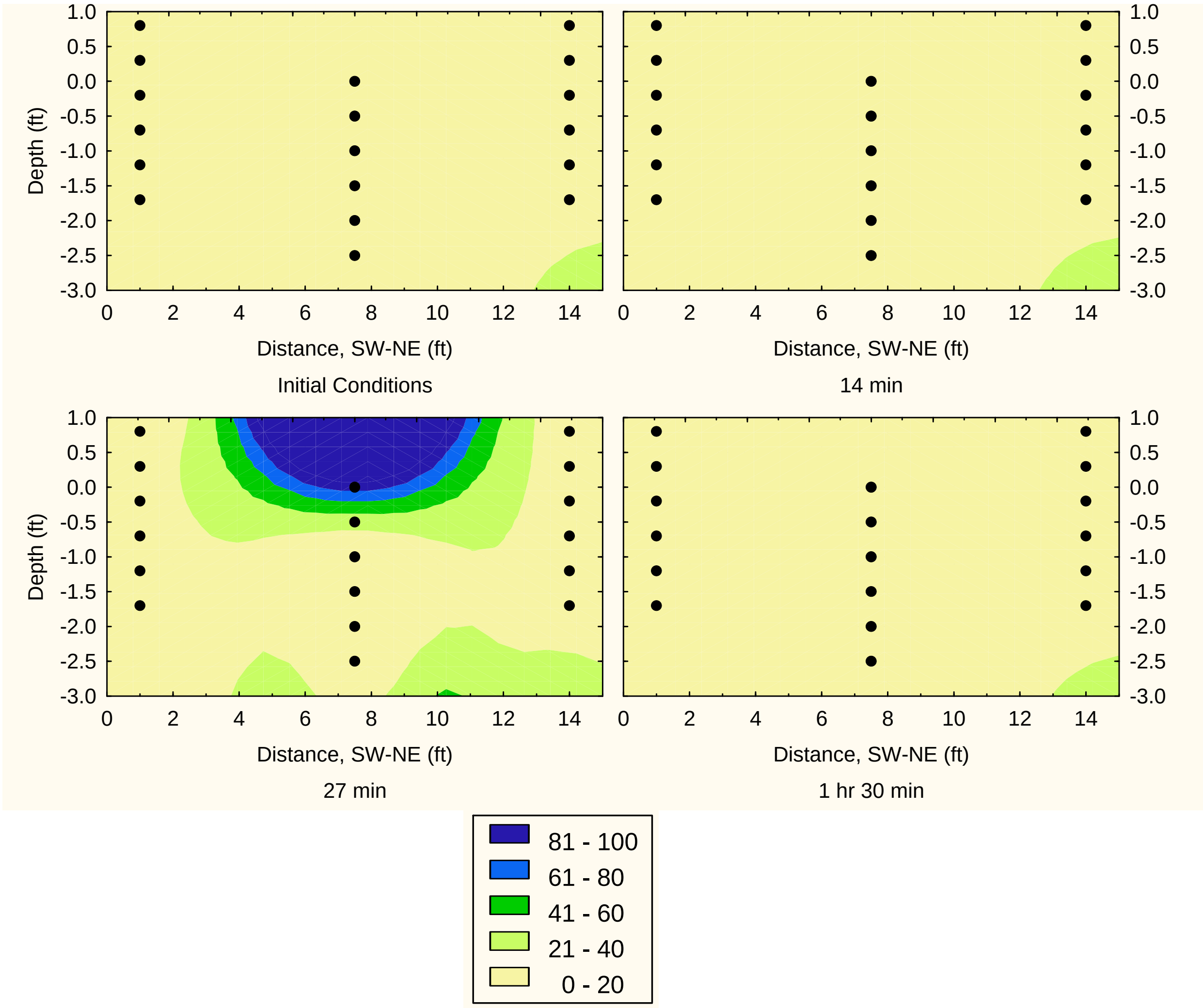

Figure A-56. Southwest to northeast soil moisture profile from February 22, 2008, DVD test at the Cottage Grove bioretention cell.

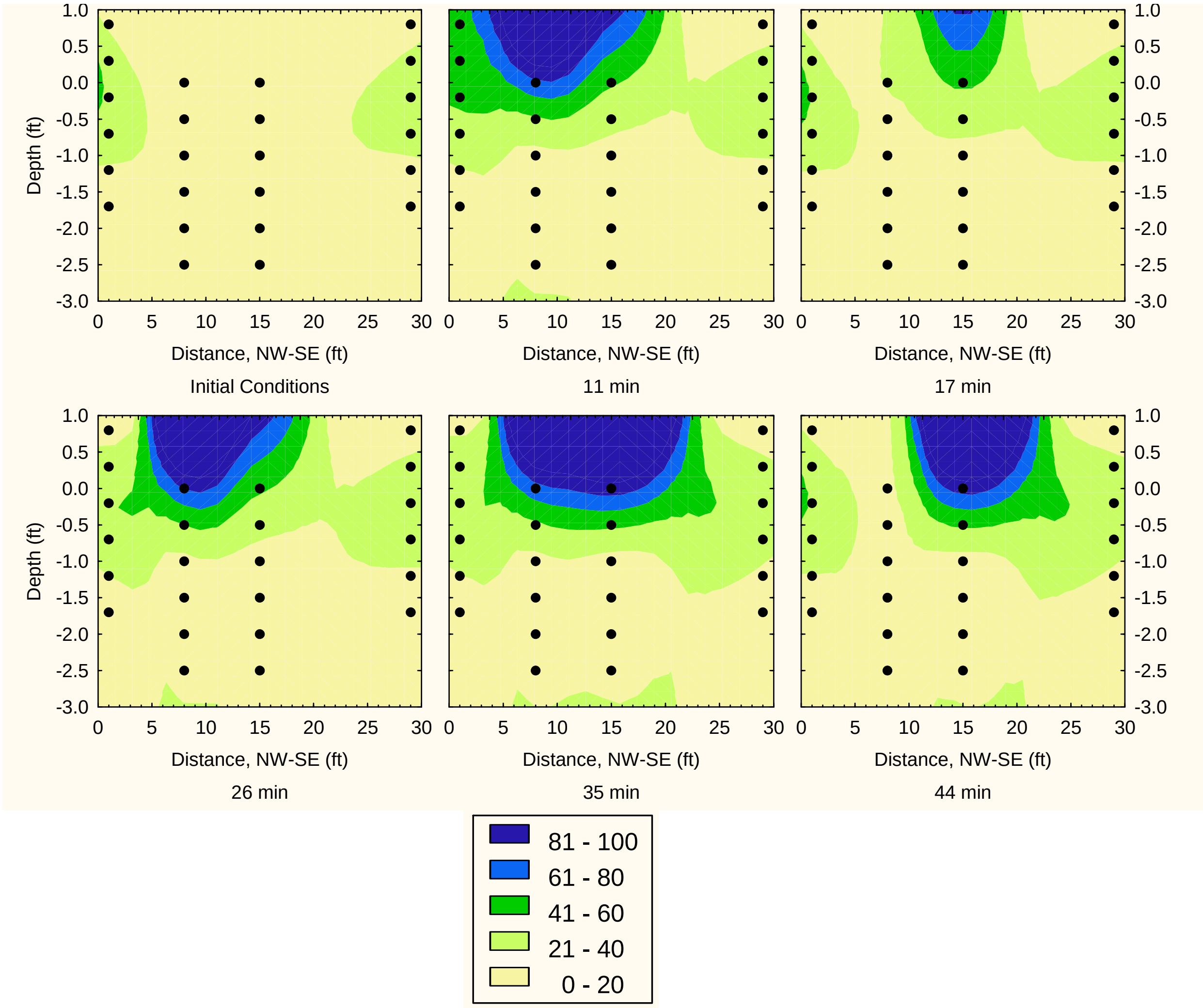

Figure A-57. Northwest to southeast soil moisture profile from March 19, 2008, DVD test at the Cottage Grove bioretention cell.

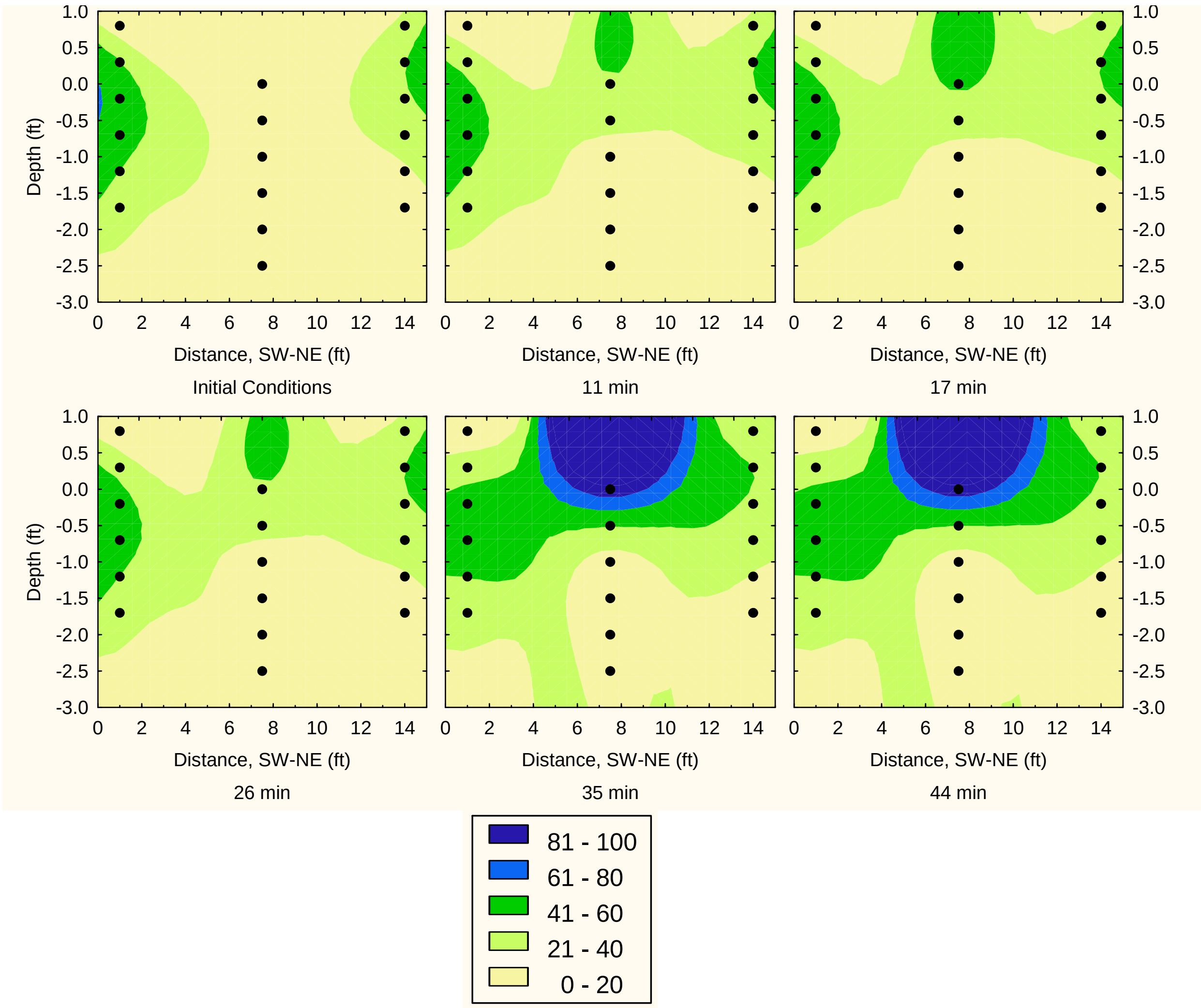

Figure A-58. Southwest to northeast soil moisture profile from March 19, 2008, DVD test at the Cottage Grove bioretention cell.

Table A-4. Site conditions and infiltration rates for DVD tests at the Stillwater bioretention cell.

DVD Test Date (season number)	Infiltration Rate from End of Test Water Appli-cation (in/hr)	Inflow Rate from Start of Test Water Appli-cation (gpm)	Surface Soil Temp, 3-day Avg Daily High (deg F)	0.5-m Soil Temp, 3-day Avg Daily High (deg F)	1-m Soil Temp, 3-day Avg Daily High (deg F)	6-in Water Content, 3-day Avg (%)	12-in Water Content, 3-day Avg (%)	Frost Depth ^Δ (m)	Air Temp, 3-day Avg Daily High (deg F)	Test Water Temp (deg F)	Snow Cover (in)	Cl Conc. in Test Water (mg/l; ppm)	DVD Vol-ume (gal)	Field Notes/Anecdotes
3/22/2006*° (1)	6.1	N/A**	32.7	32.7	35.2	30.9	17.3	0.5	38.4	48.2	5.25	0	N/A	Outlet pipe is taking most (or all) of the water out of the garden; pipe is 6-in diameter; spotty ice up to 17 inches deep.
2/21/2007* (2)	0.4	N/A**	29.4	28.5	32.9	10.0	5.9	1	35.6	43.9	0	0	250	Some meltwater in basin previous to DVD test; poured water on parking lot - had to clear curb cut for it to get to cell; snowmelt from the parking lot added to pool depth at last pool depth reading.
3/22/2007 (2)	0.7	N/A**	37.9	32.2	33.6	33.0	24.3	0	47.4	N/A	0	0	200	Possible 7-inch top thaw.
10/10/2007•	1.8	4.9	67.4	65.7	65.7	36.2	21.5	0	66.8	N/A	0	0	200	Ground may be saturated from 1.5 inches of rain on 10/5 - 10/8.
12/20/2007 (3)	N/A	N/A**	31.4	35.9	39.4	24.1	13.9	0.5	27.0	38.3	6	124	200	Soil moisture probe started to quit operating, no infiltration measurements.
1/8/2008 (3)	3.7	N/A**	31.8	34.9	37.7	33.2	24.2	0.5	37.6	38.7	4.5	99	250	2-inch frost in frost tube.
2/22/2008 (3)	0.2	N/A**	23.6	28.1	31.9	21.9	15.3	1.5	12.4	37.8	2.5	99	250	
3/19/2008 (3)	0.8	N/A**	31.7	30.4	32.4	74.0	57.3	1.5	37.2	N/A	0	124	200	Main frost tube frozen in ground.

* No soil moisture data.

^Δ Based on Campbell Scientific automated soil temperature data and cross-checked with field notes and excavation, where available; 1.5 m implies >1 but the distance >1 is unknown.

° Overflow through unplugged outlet (2-inches above bioretention cell bottom) during testing; plugged for all other tests. The 3/22/06 observed infiltration rate of 6.1 in/hr is artificially high.

• Not utilized for correlations because not within the 'winter' months.

** Not able to be determined because of standing water at end of test period.

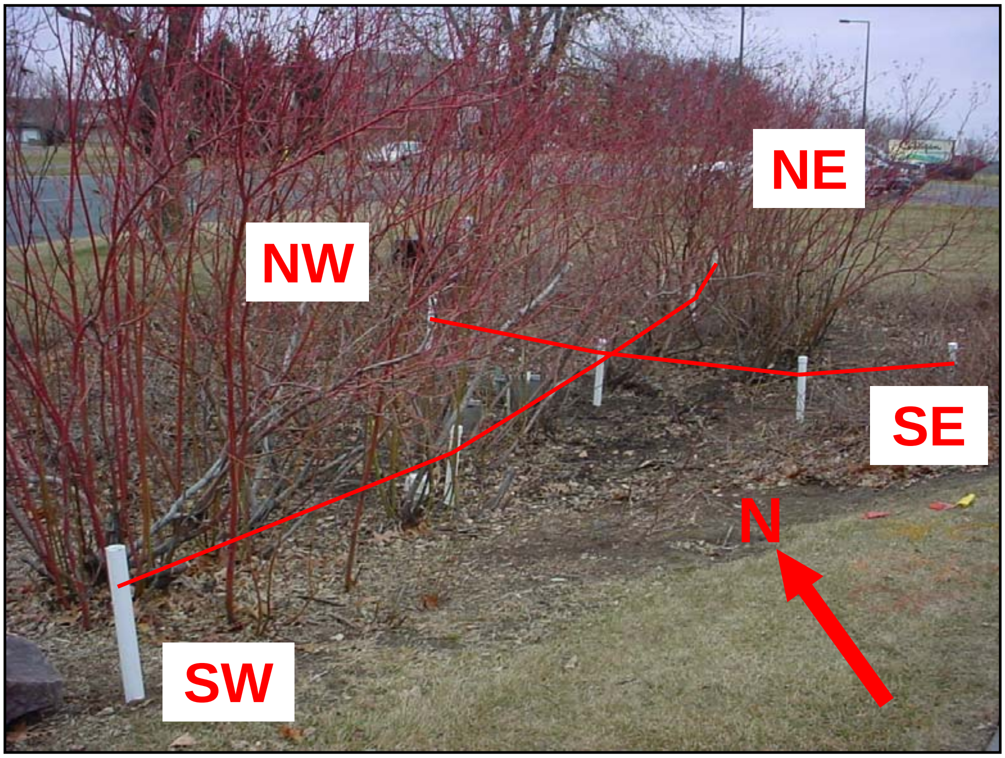

Figure A-59. Soil moisture probe transect locations for the Stillwater bioretention cell.

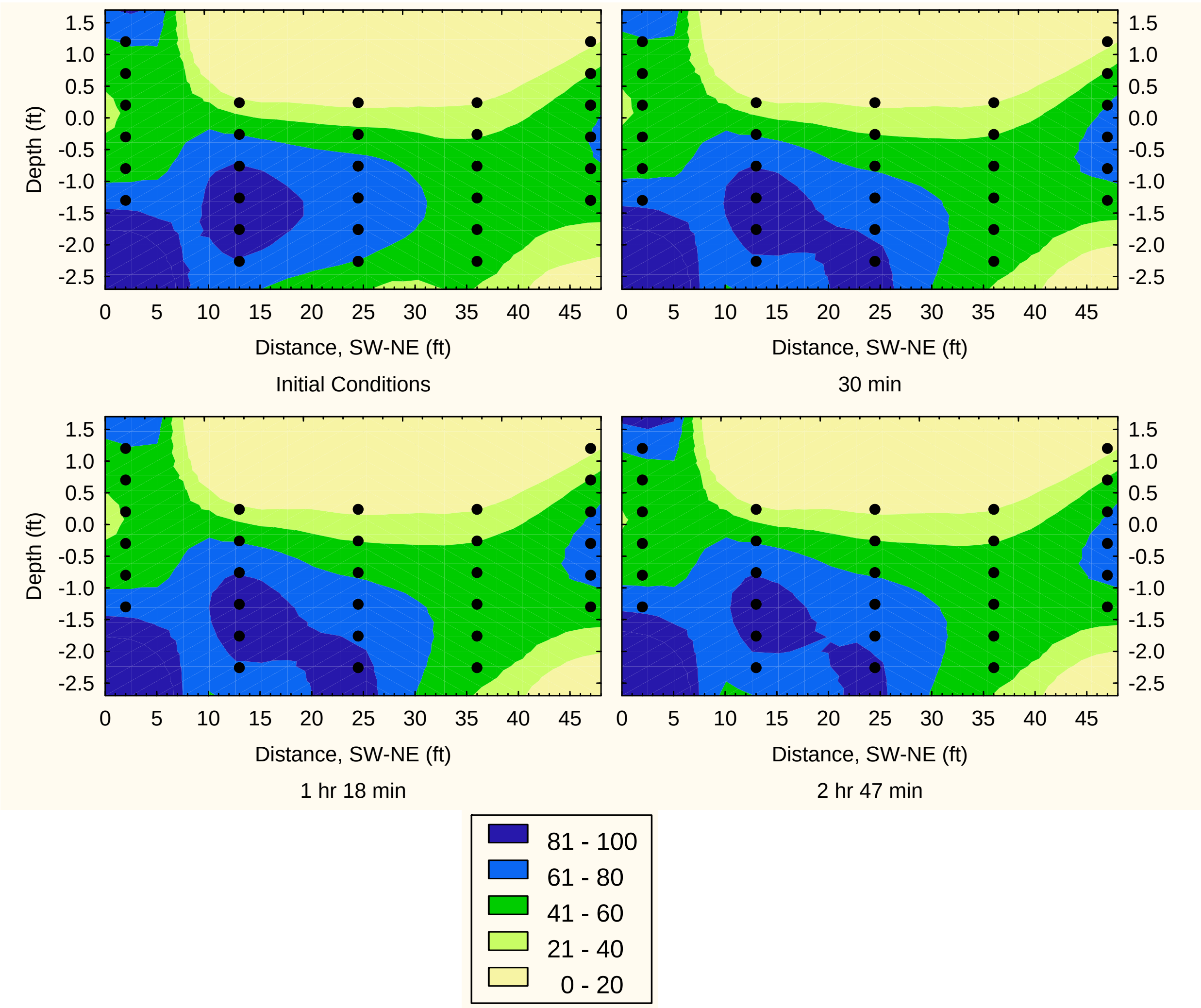

Figure A-60. Southwest to northeast soil moisture profile from March 22, 2007, DVD test at the Stillwater bioretention cell.

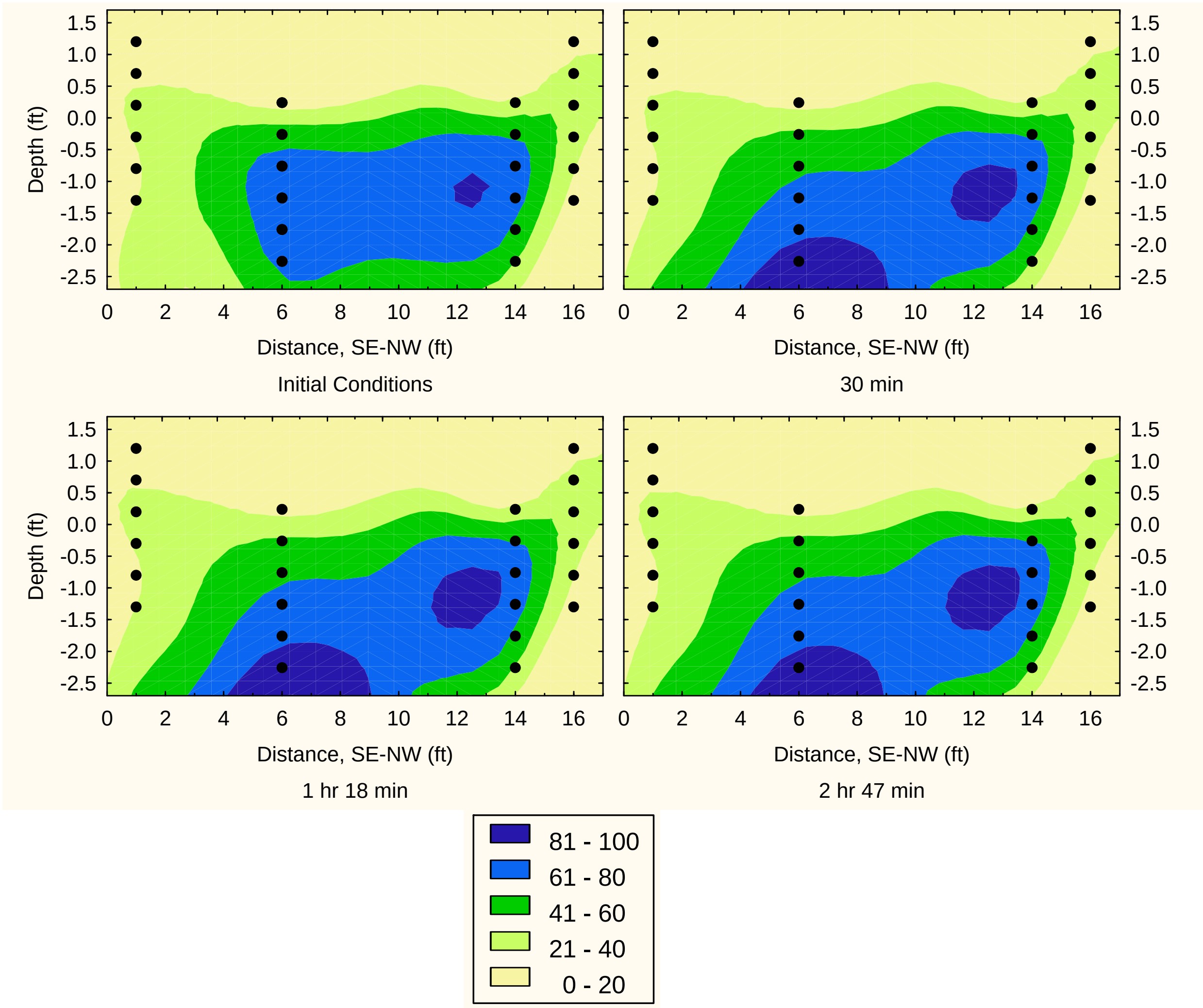

Figure A-61. Southeast to northwest soil moisture profile from March 22, 2007, DVD test at the Stillwater bioretention cell.

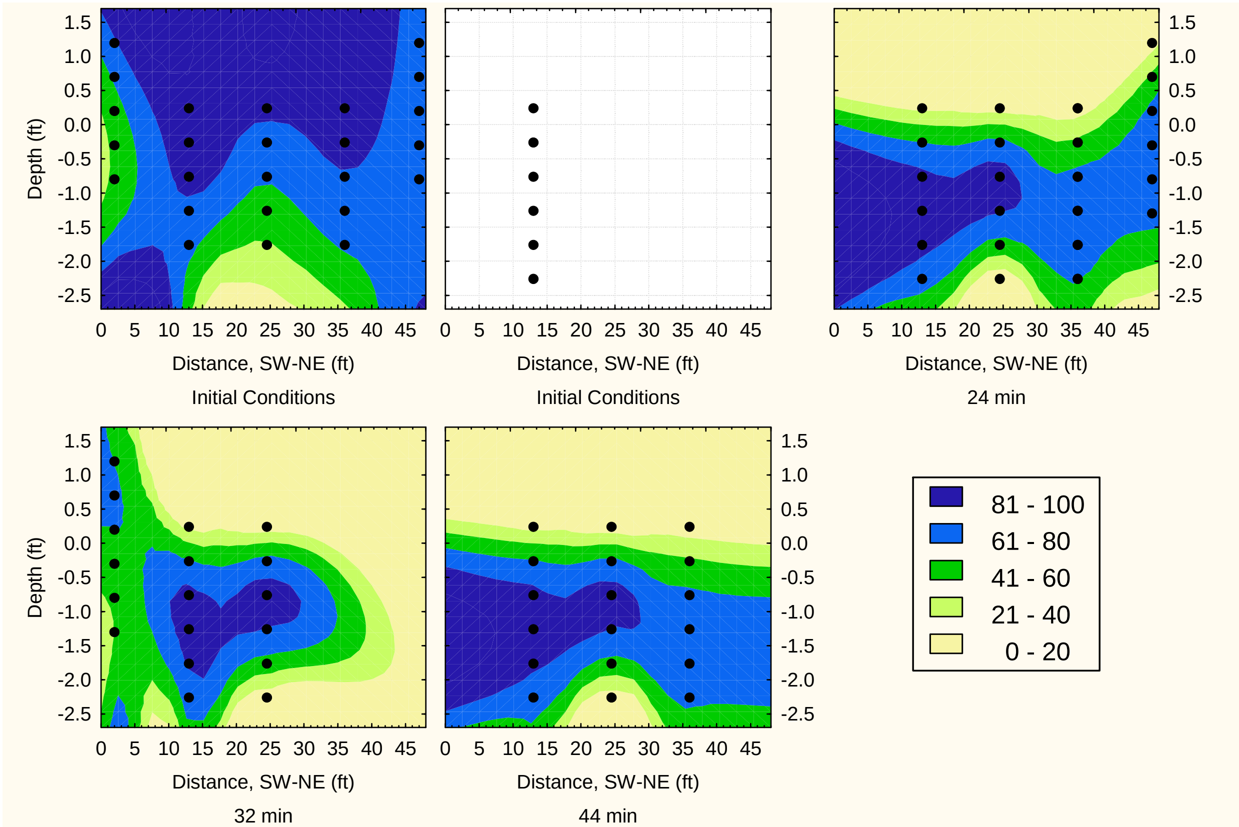

Figure A-62. Southwest to northeast soil moisture profile from October 10, 2007, DVD test at the Stillwater bioretention cell.

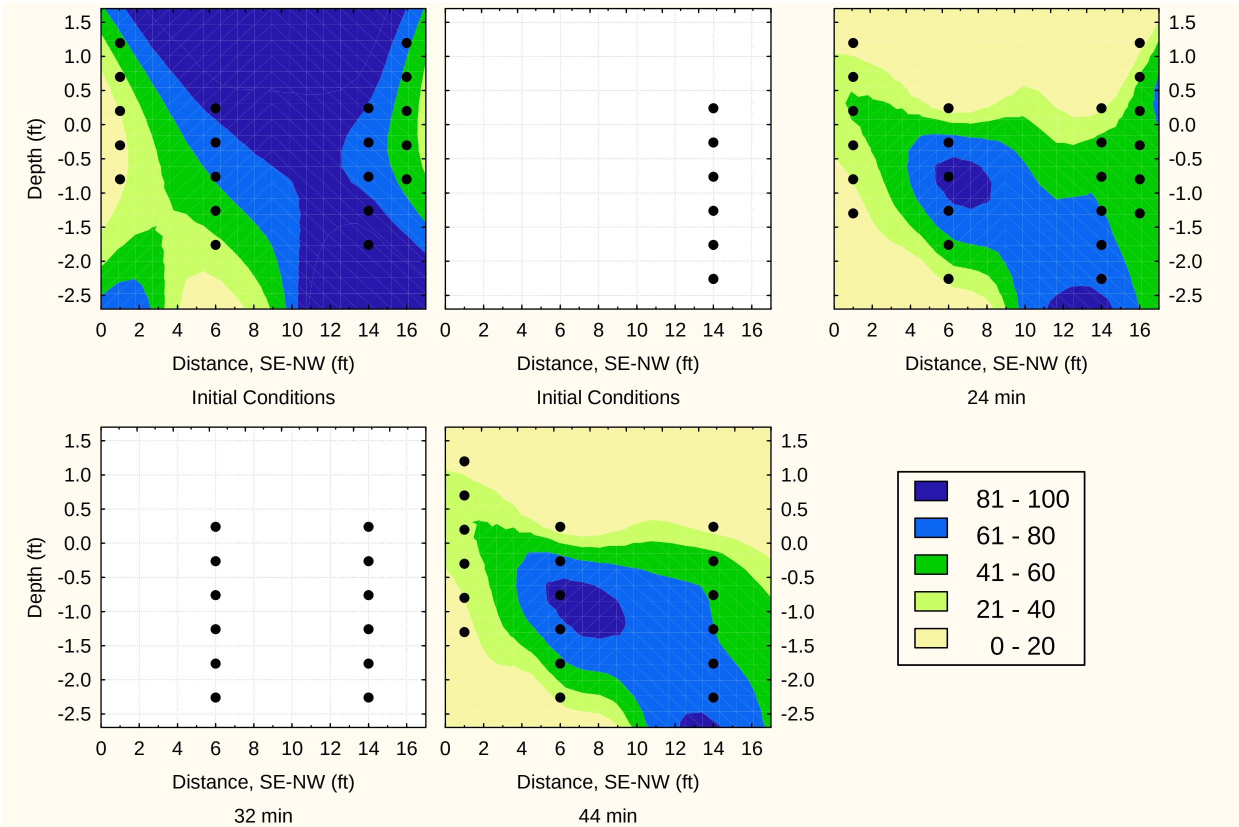

Figure A-63. Southeast to northwest soil moisture profile from October 10, 2007, DVD test at the Stillwater bioretention cell.

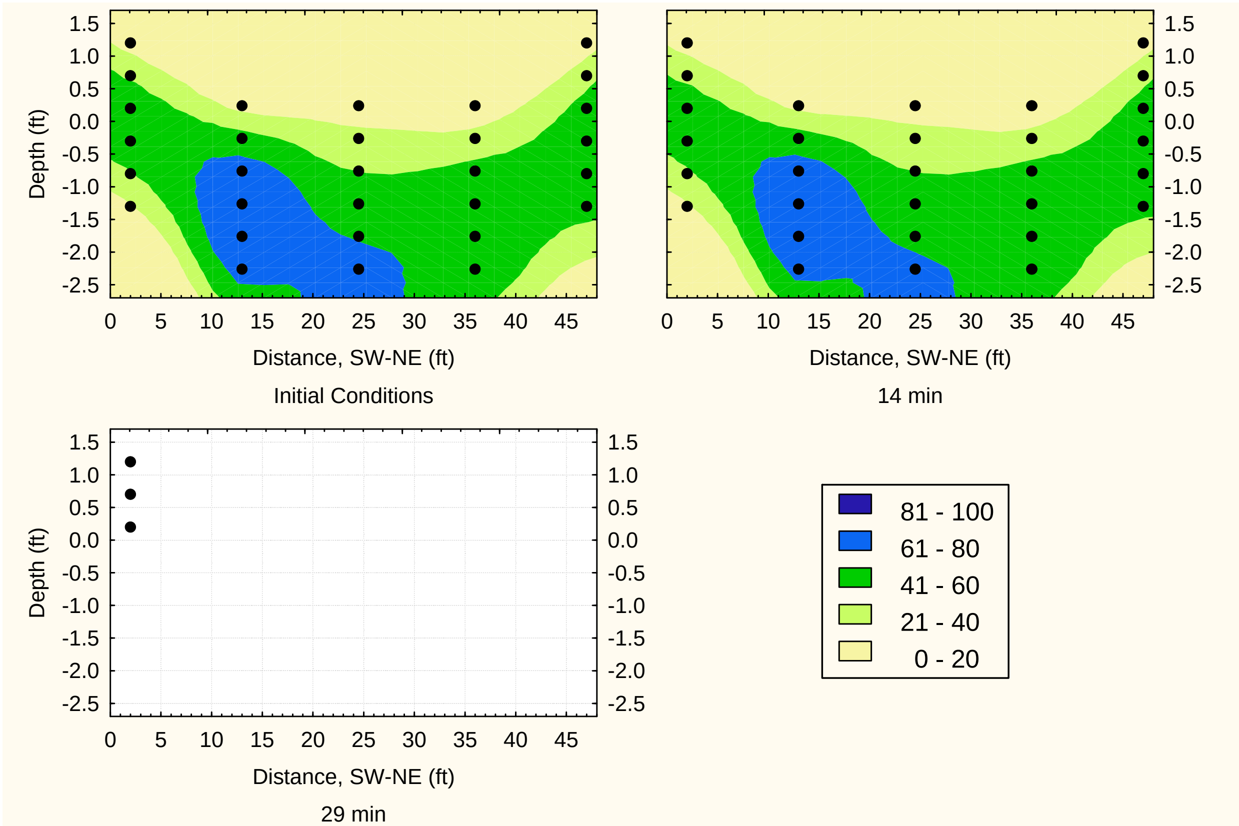

Figure A-64. Southwest to northeast soil moisture profile from December 20, 2007, DVD test at the Stillwater bioretention cell.

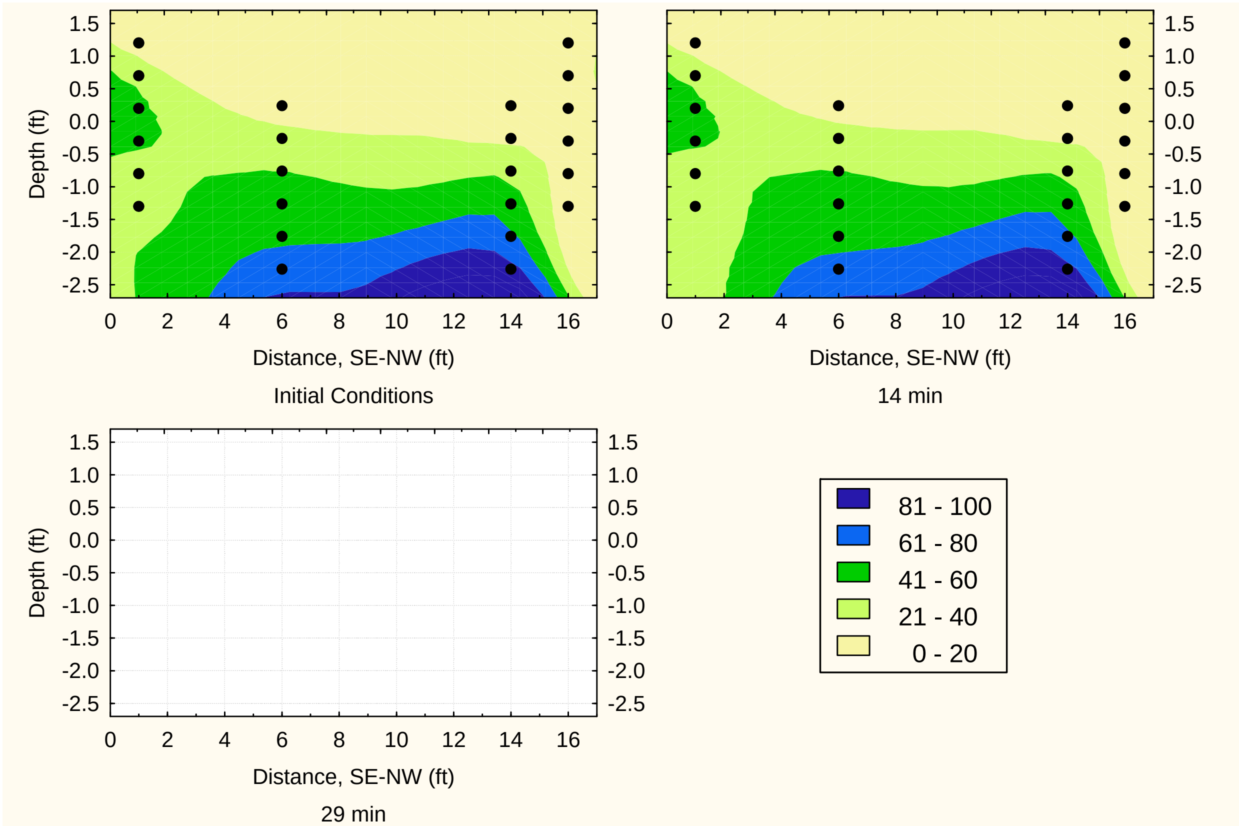

Figure A-65. Southeast to northwest soil moisture profile from December 20, 2007, DVD test at the Stillwater bioretention cell.

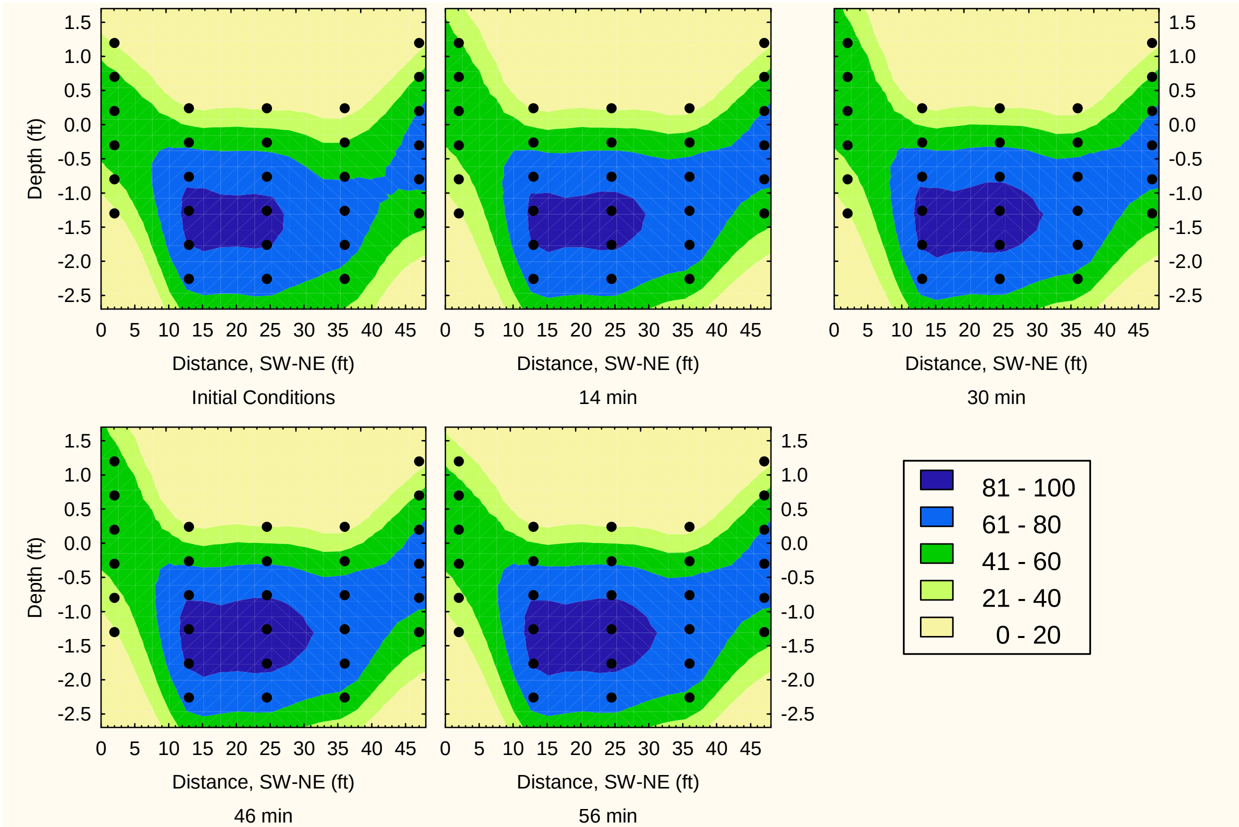

Figure A-66. Southwest to northeast soil moisture profile from January 8, 2008, DVD test at the Stillwater bioretention cell.

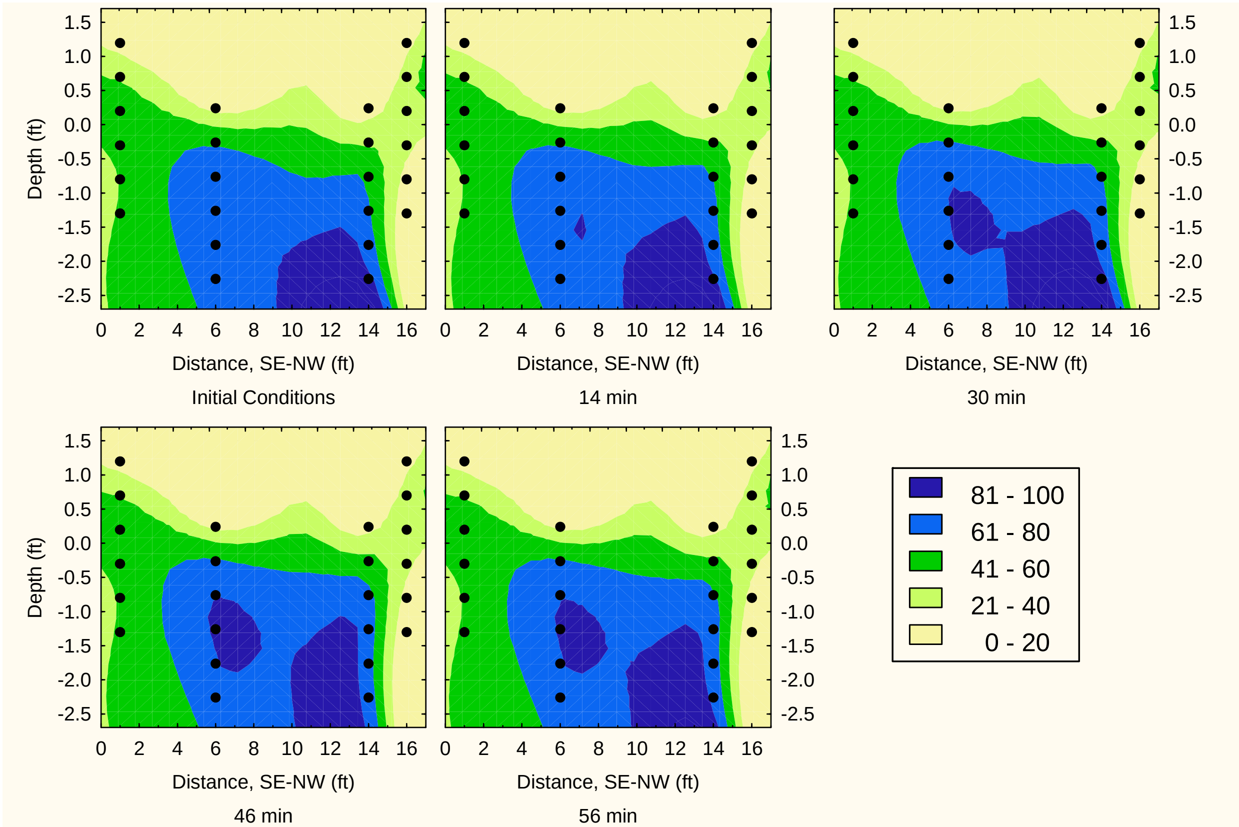

Figure A-67. Southeast to northwest soil moisture profile from January 8, 2008, DVD test at the Stillwater bioretention cell.

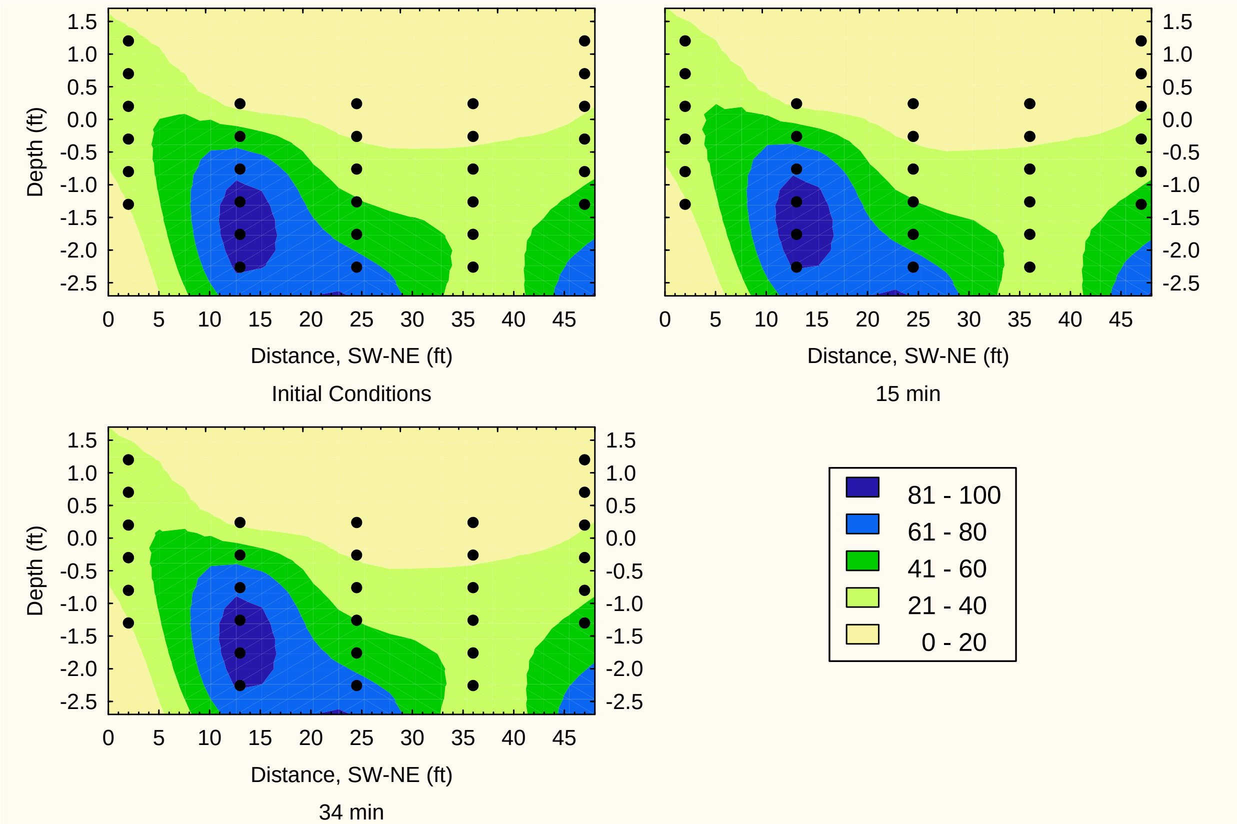

Figure A-68. Southwest to northeast soil moisture profile from February 22, 2008, DVD test at the Stillwater bioretention cell.

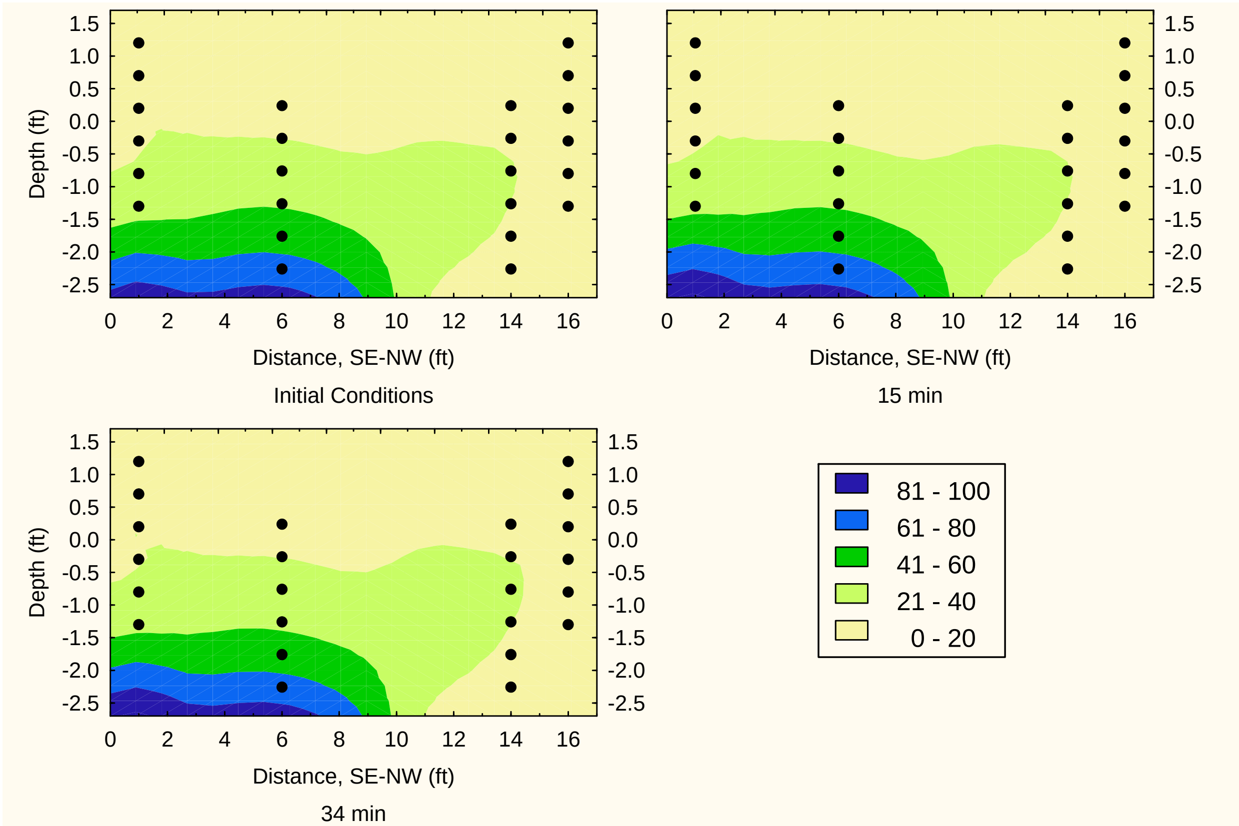

Figure A-69. Southeast to northwest soil moisture profile from February 22, 2008, DVD test at the Stillwater bioretention cell.

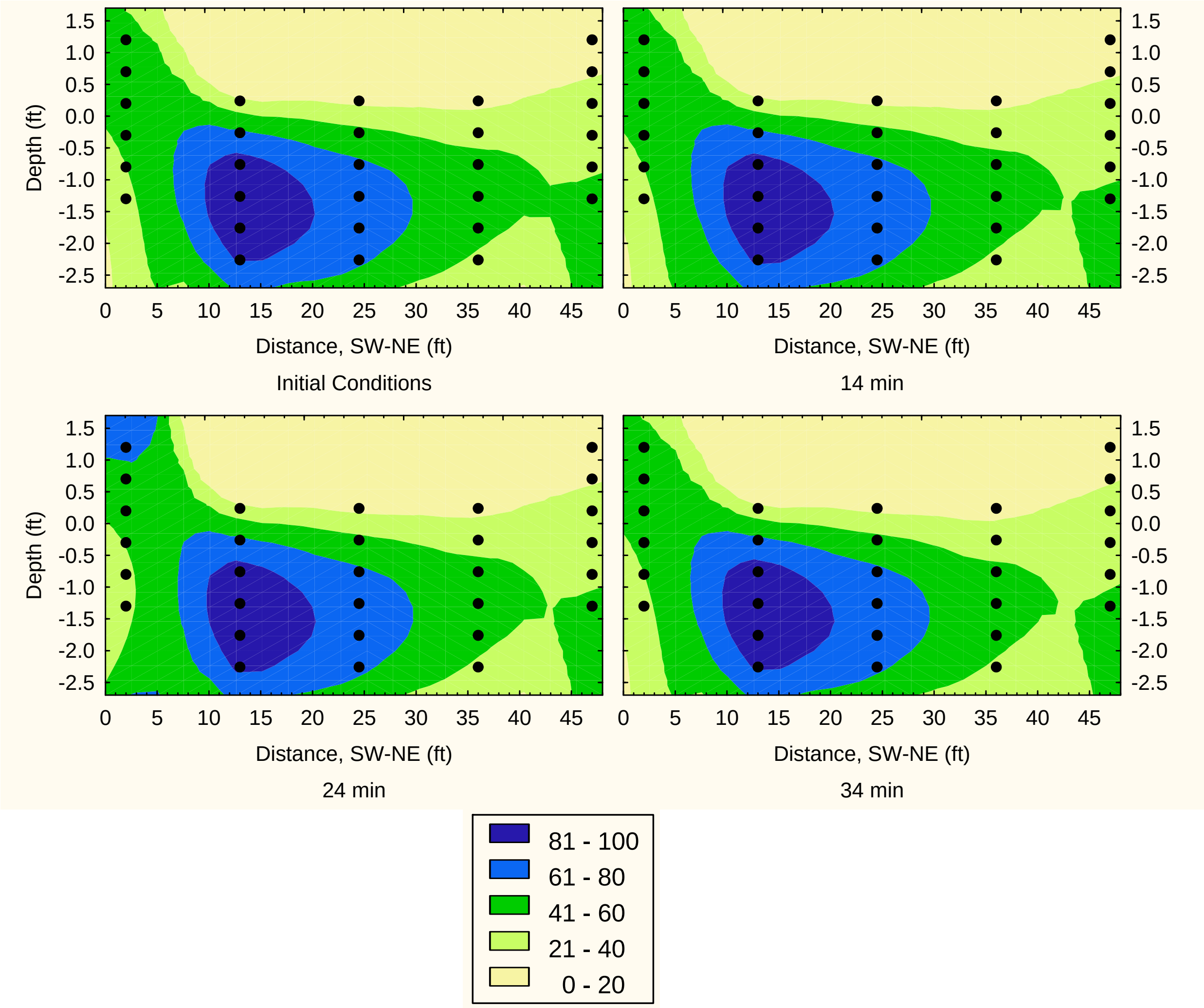

Figure A-70. Southwest to northeast soil moisture profile from March 19, 2008, DVD test at the Stillwater bioretention cell.

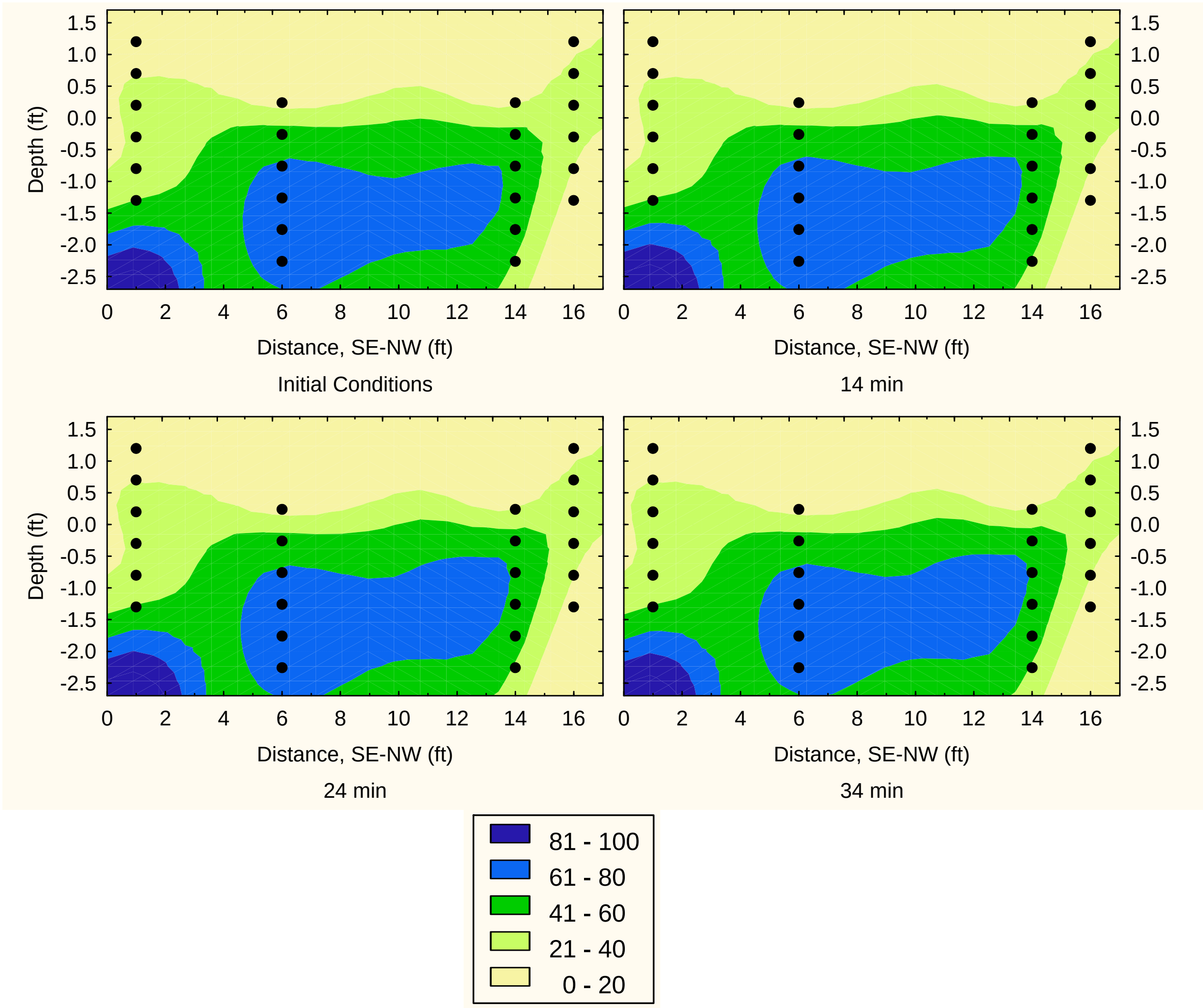

Figure A-71. Southeast to northwest soil moisture profile from March 19, 2008, DVD test at the Stillwater bioretention cell.

APPENDIX B

ANTECEDENT CONDITIONS

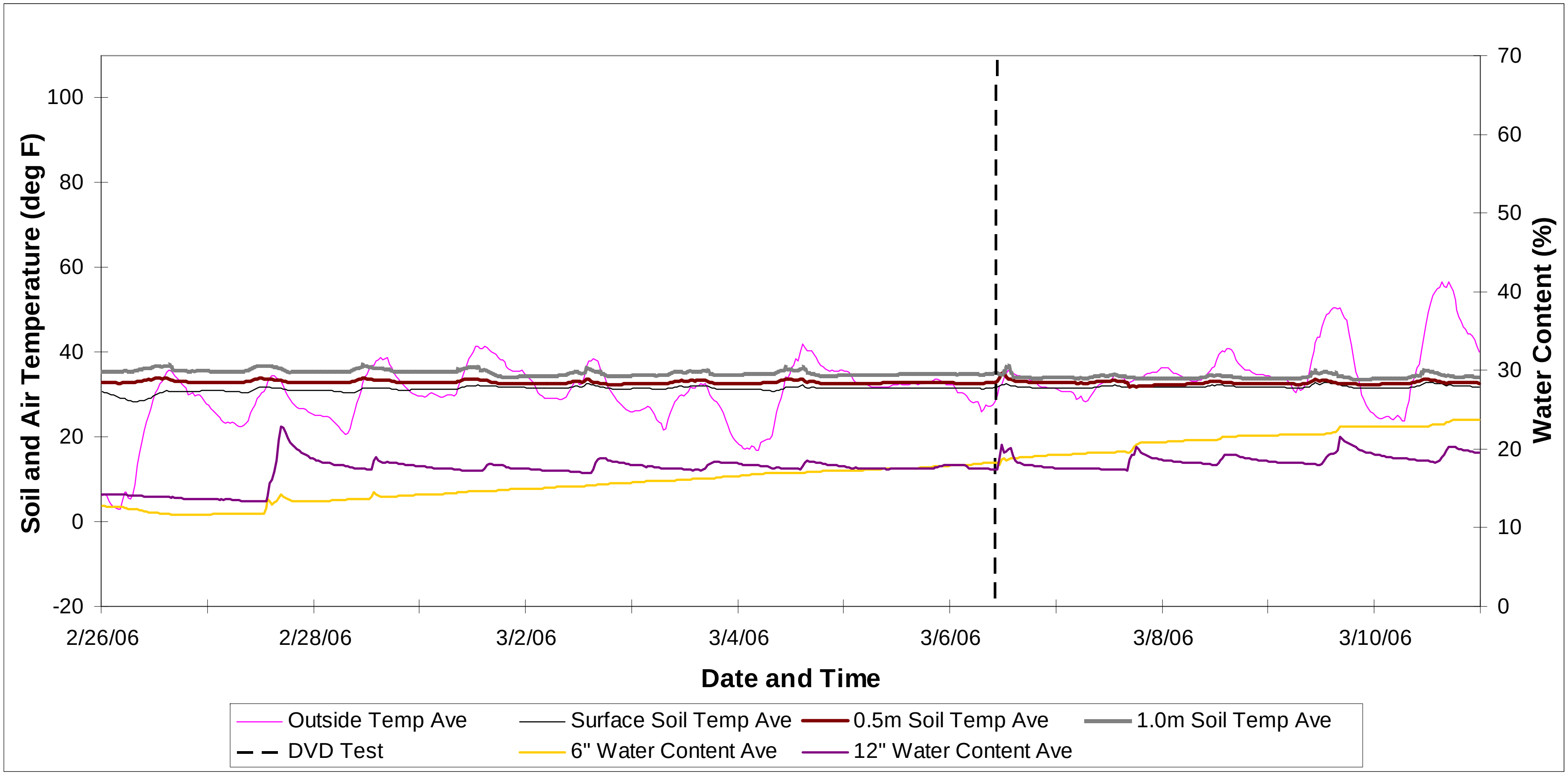

Figure B-1. Antecedent conditions Season 1 (Winter 2005-2006) at the Crystal Lake bioretention cell.

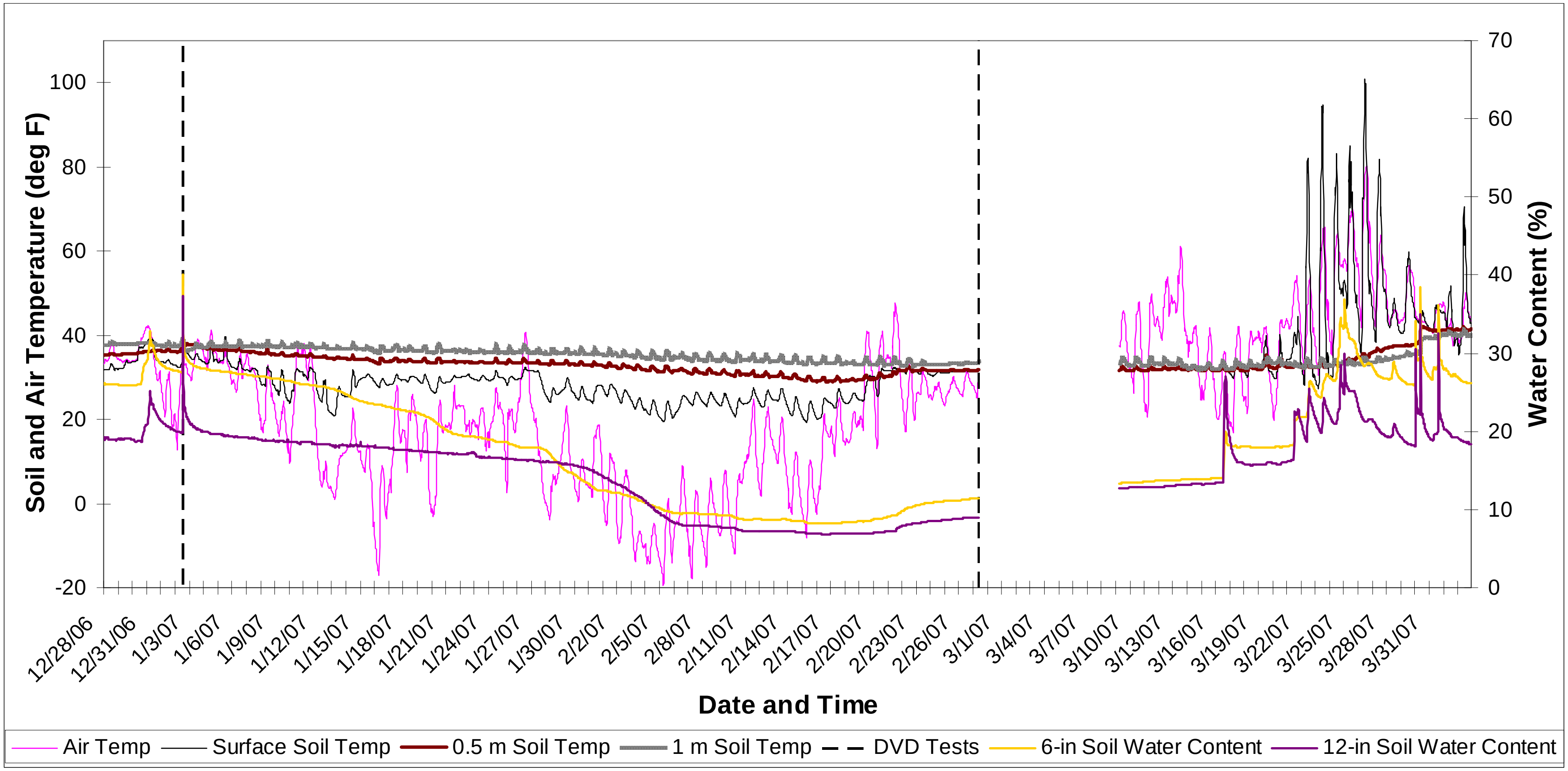

Figure B-2. Antecedent conditions during Season 2 (Winter 2006-2007) at the Crystal Lake bioretention cell.

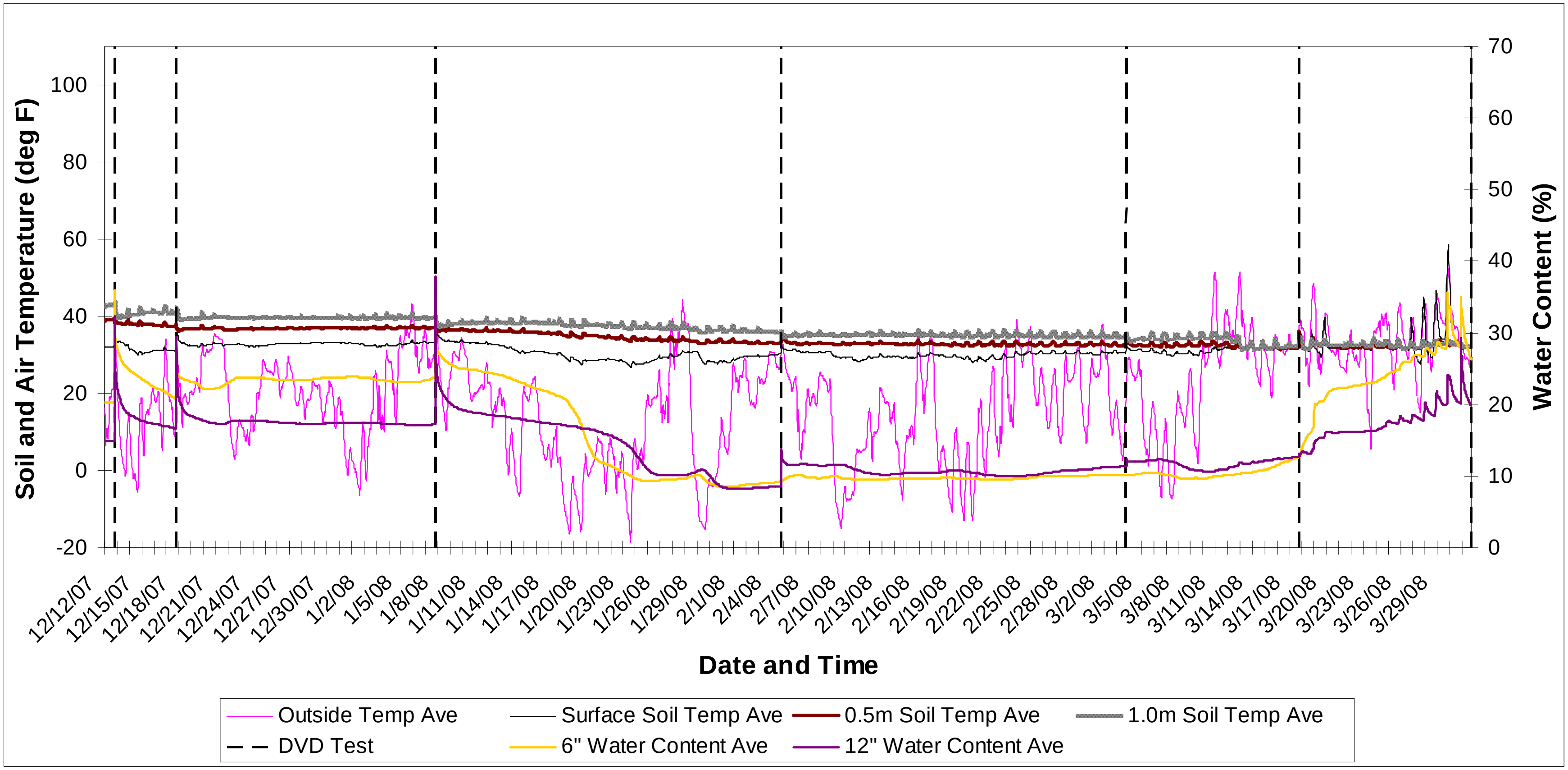

Figure B-3. Antecedent conditions during Season 3 (Winter 2007-2008) at the Crystal Lake bioretention cell.

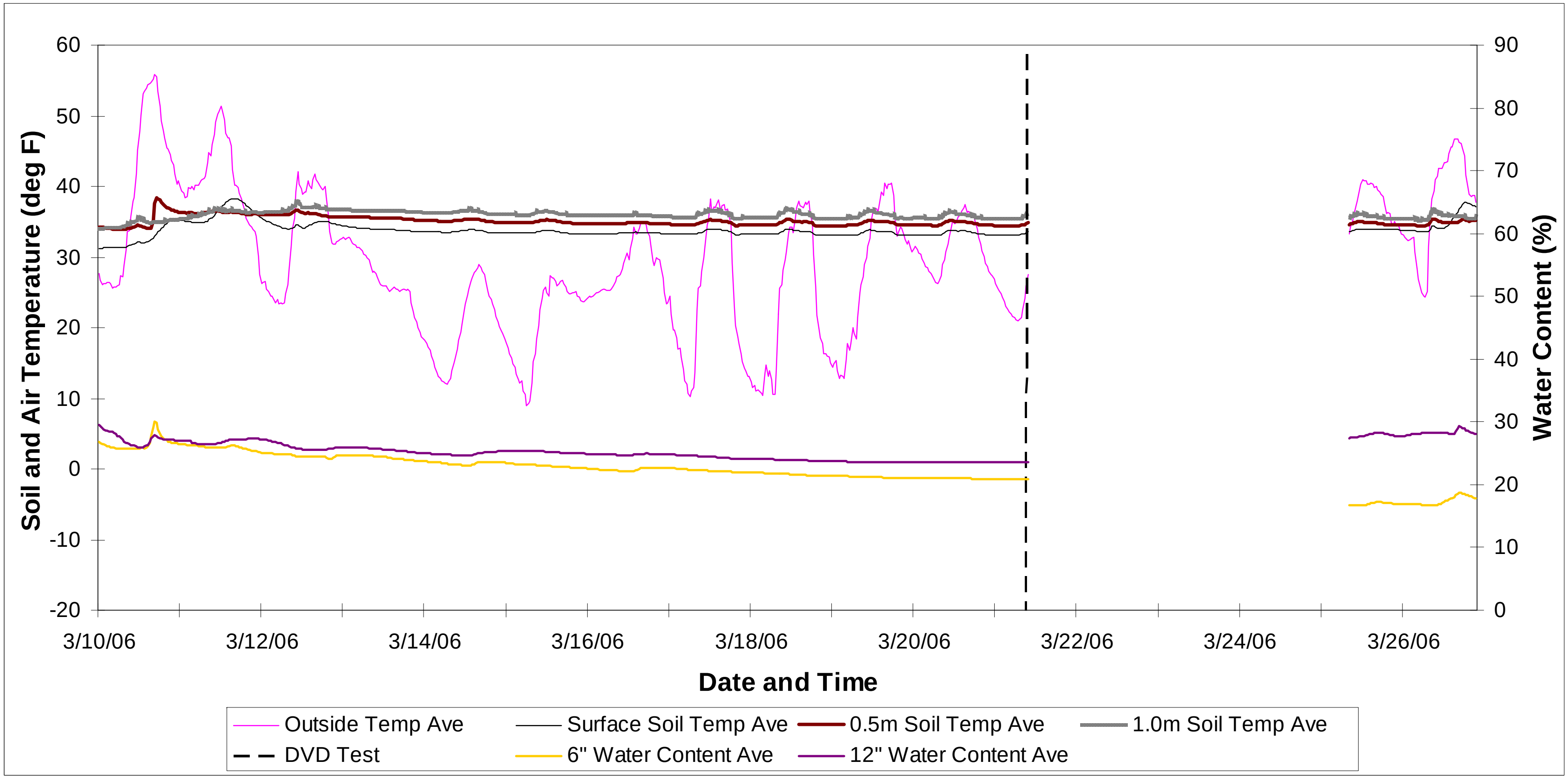

Figure B-4. Antecedent conditions Season 1 (Winter 2005-2006) at the Thompson Lake bioretention cell.

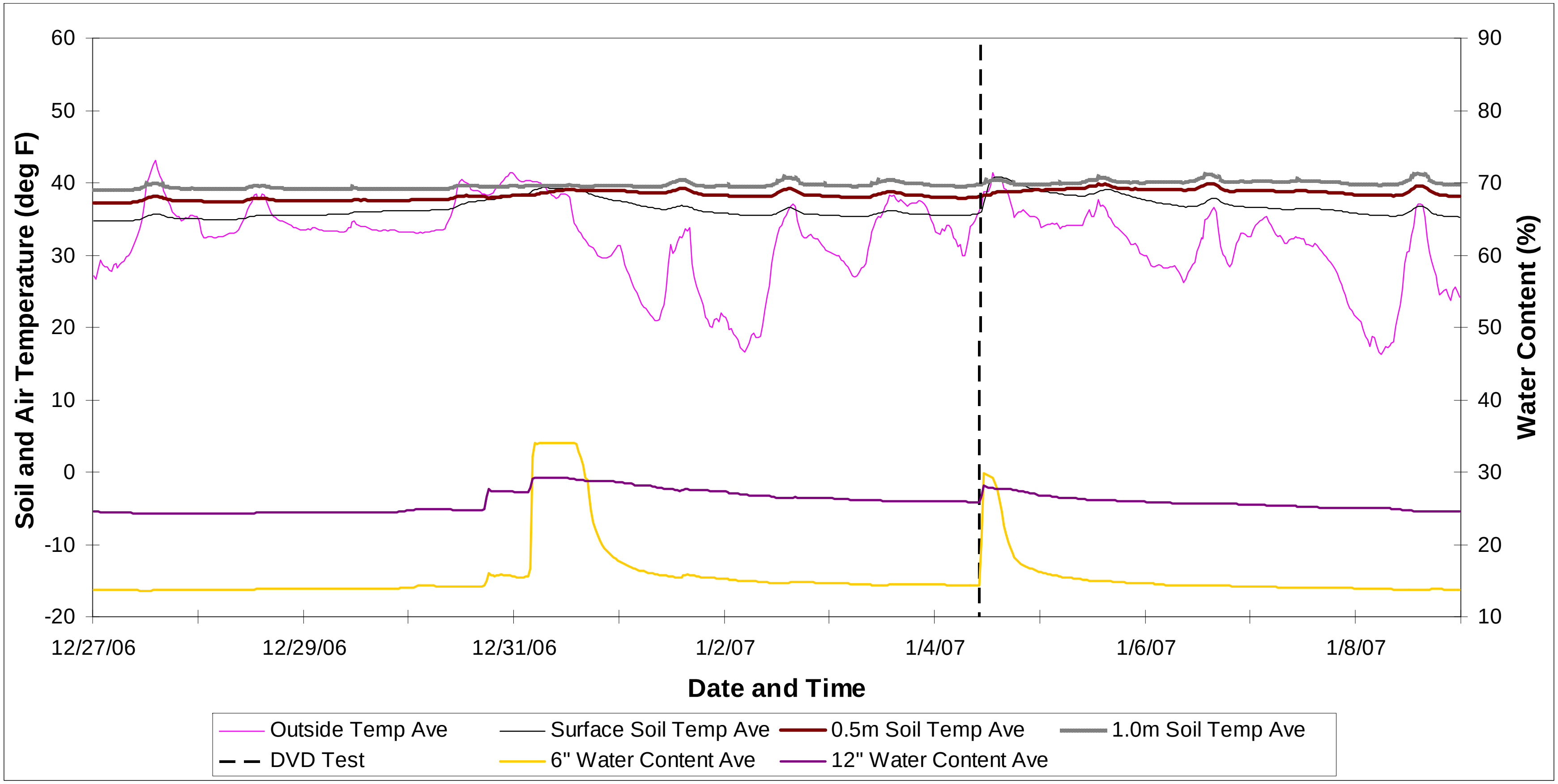

Figure B-5. Antecedent conditions Season 2 (Winter 2006-2007) at the Thompson Lake bioretention cell.

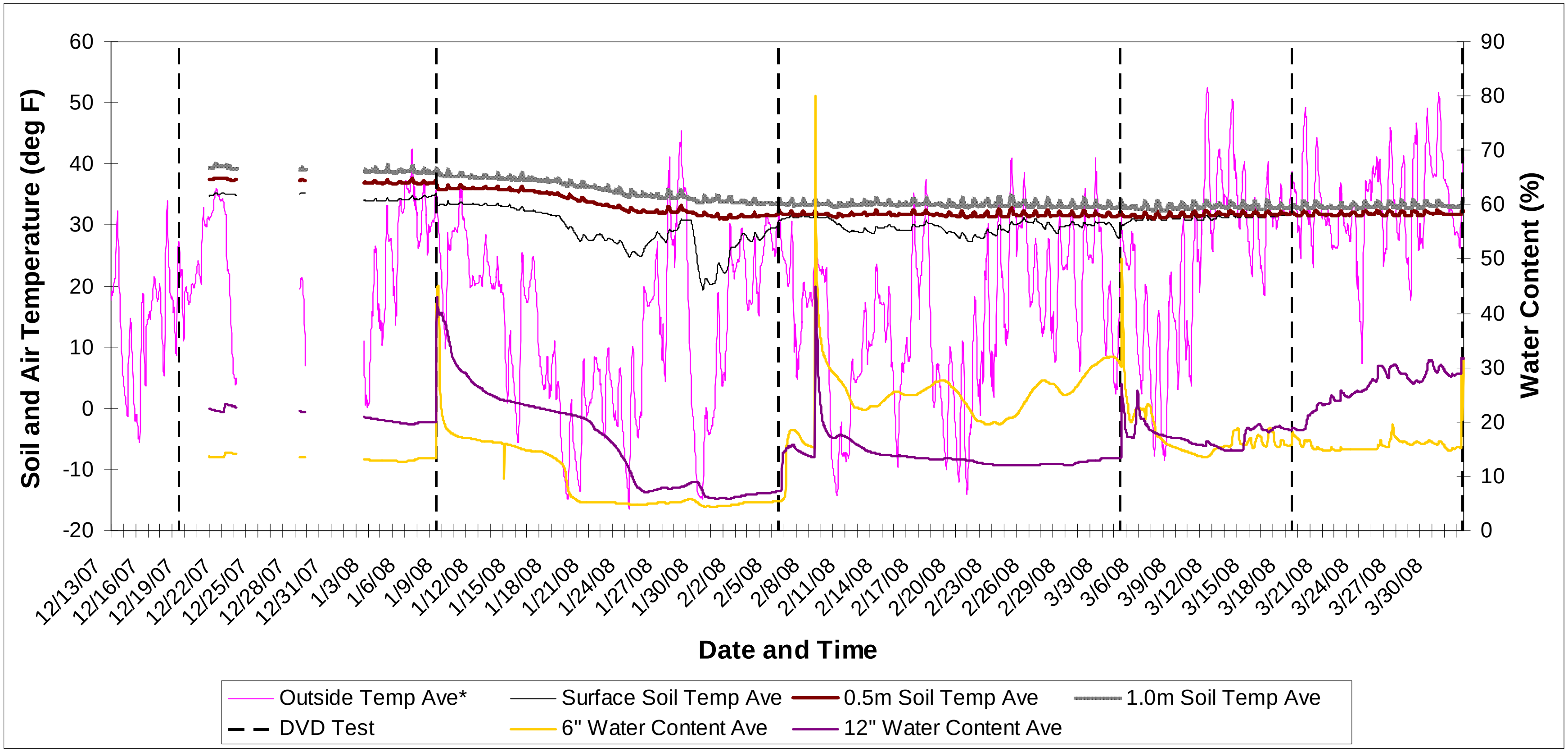

Figure B-6. Antecedent conditions Season 3 (Winter 2007-2008) at the Thompson Lake bioretention cell; pre-12/21/07 temperature data from Crystal Lake Rain Garden.

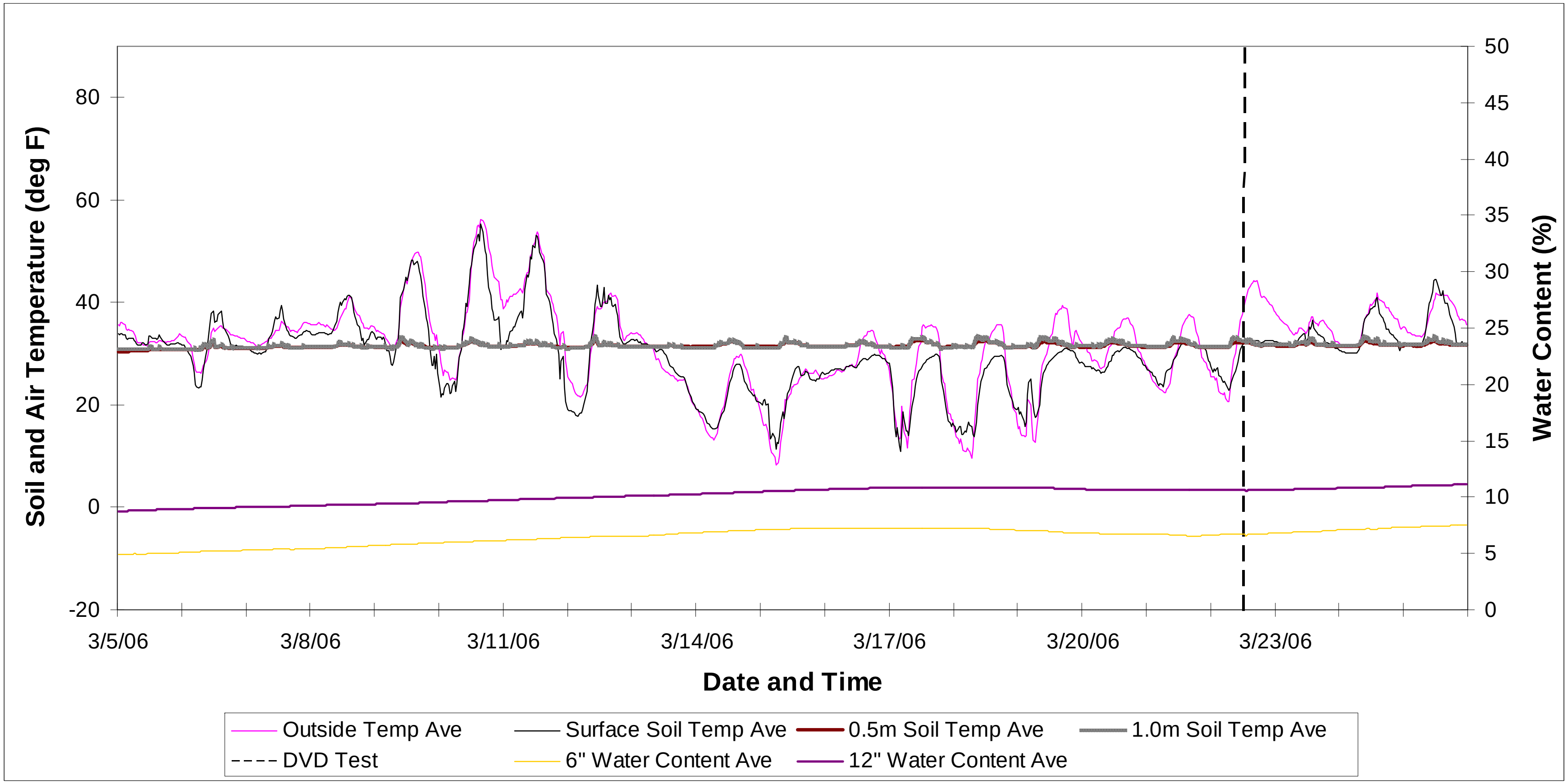

Figure B-7. Antecedent conditions Season 1 (Winter 2005-2006) at the Cottage Grove bioretention cell.

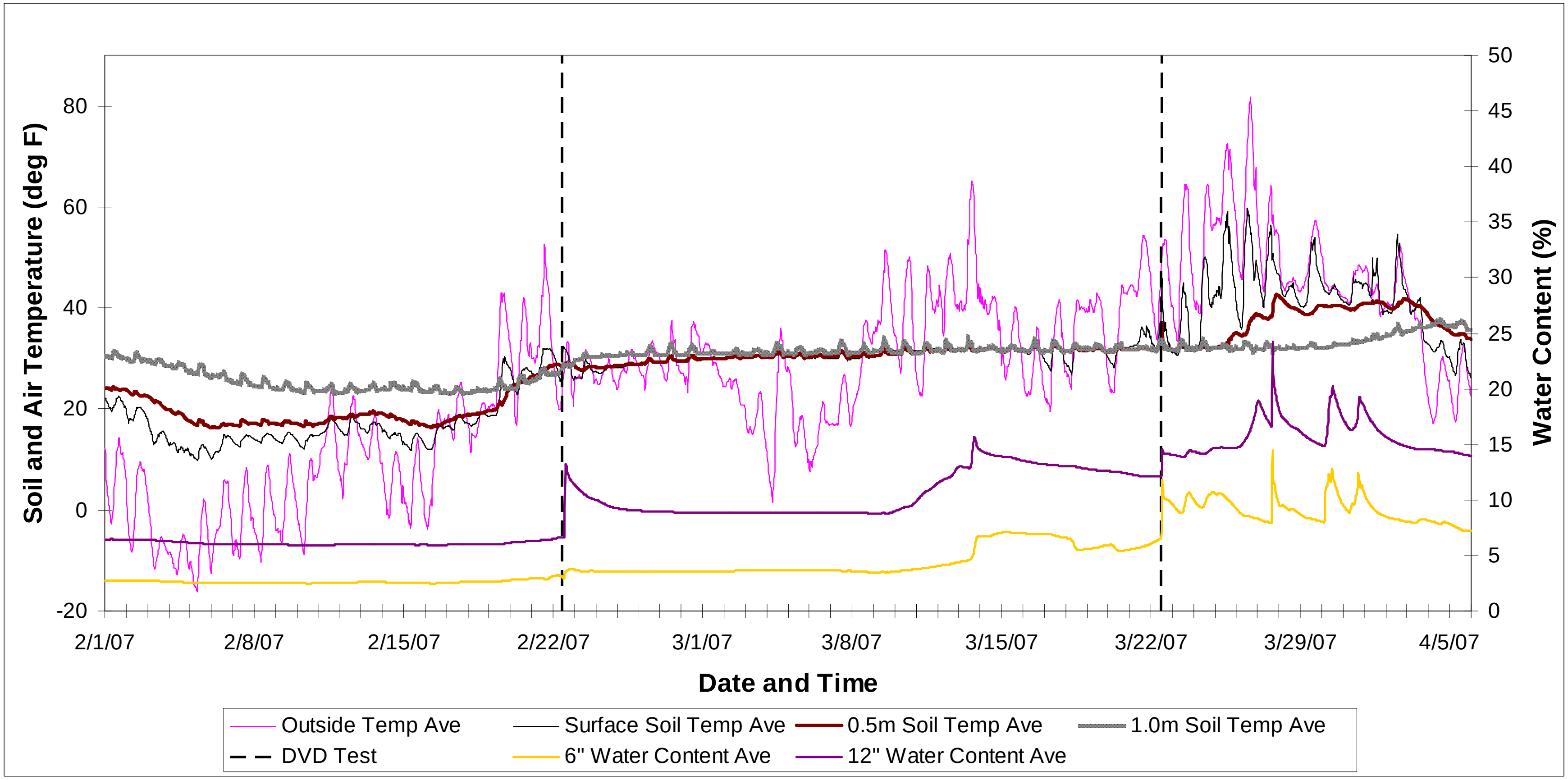

Figure B-8. Antecedent conditions Season 2 (Winter 2006-2007) at the Cottage Grove bioretention cell.

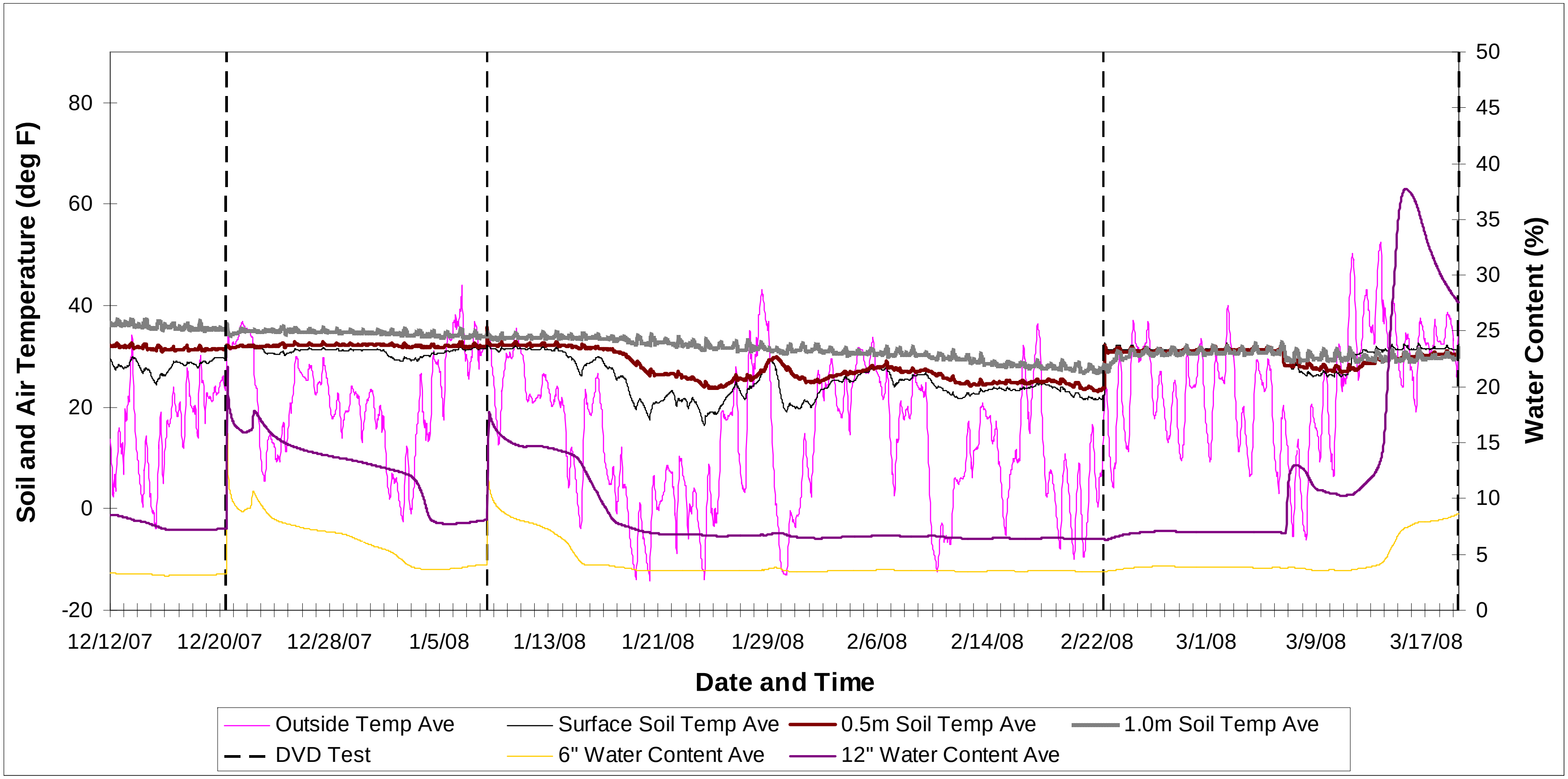

Figure B-9. Antecedent conditions Season 3 (Winter 2007-2008) at the Cottage Grove bioretention cell.

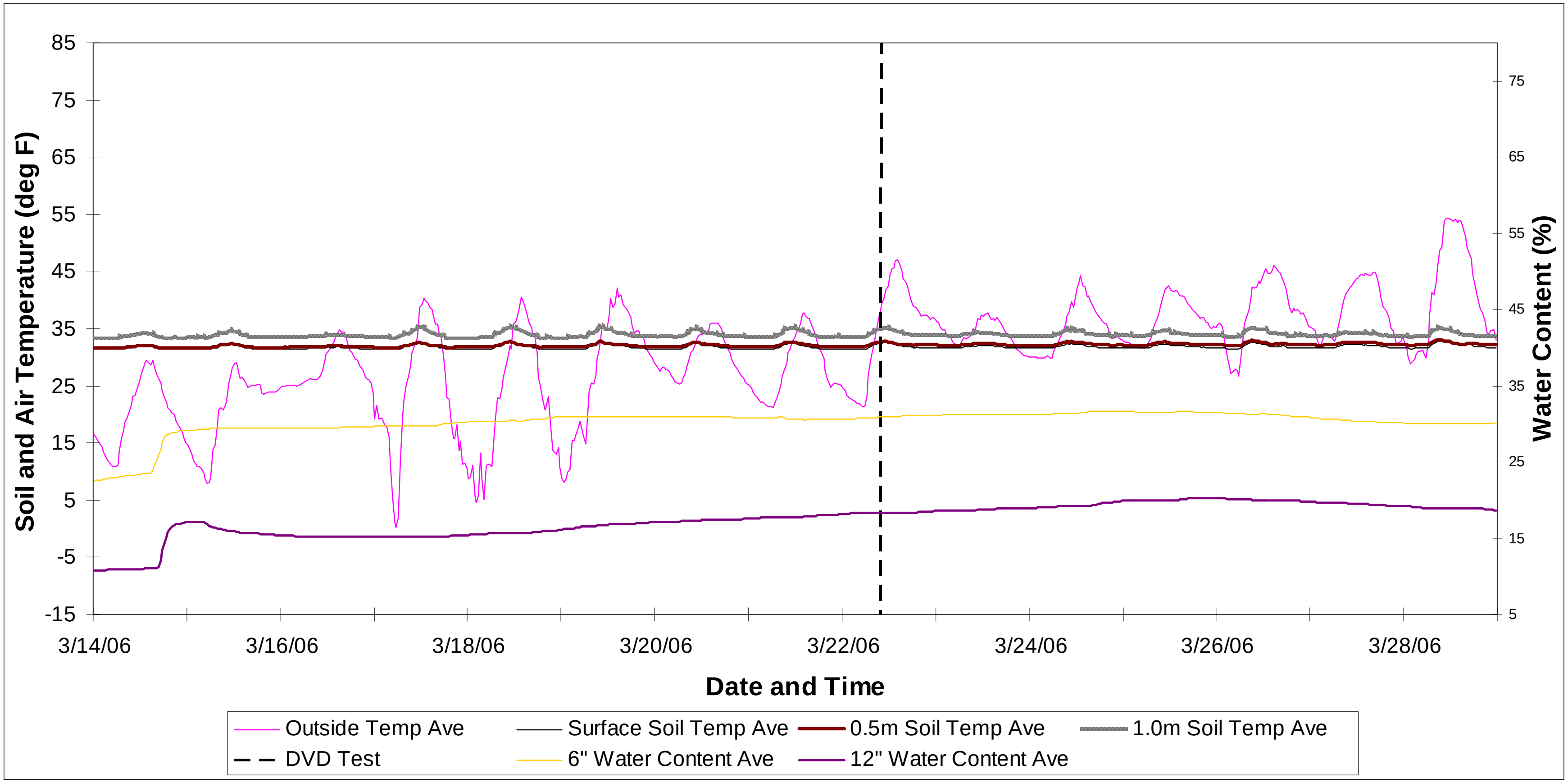

Figure B-10. Antecedent conditions Season 1 (Winter 2005-2006) at the Stillwater bioretention cell.

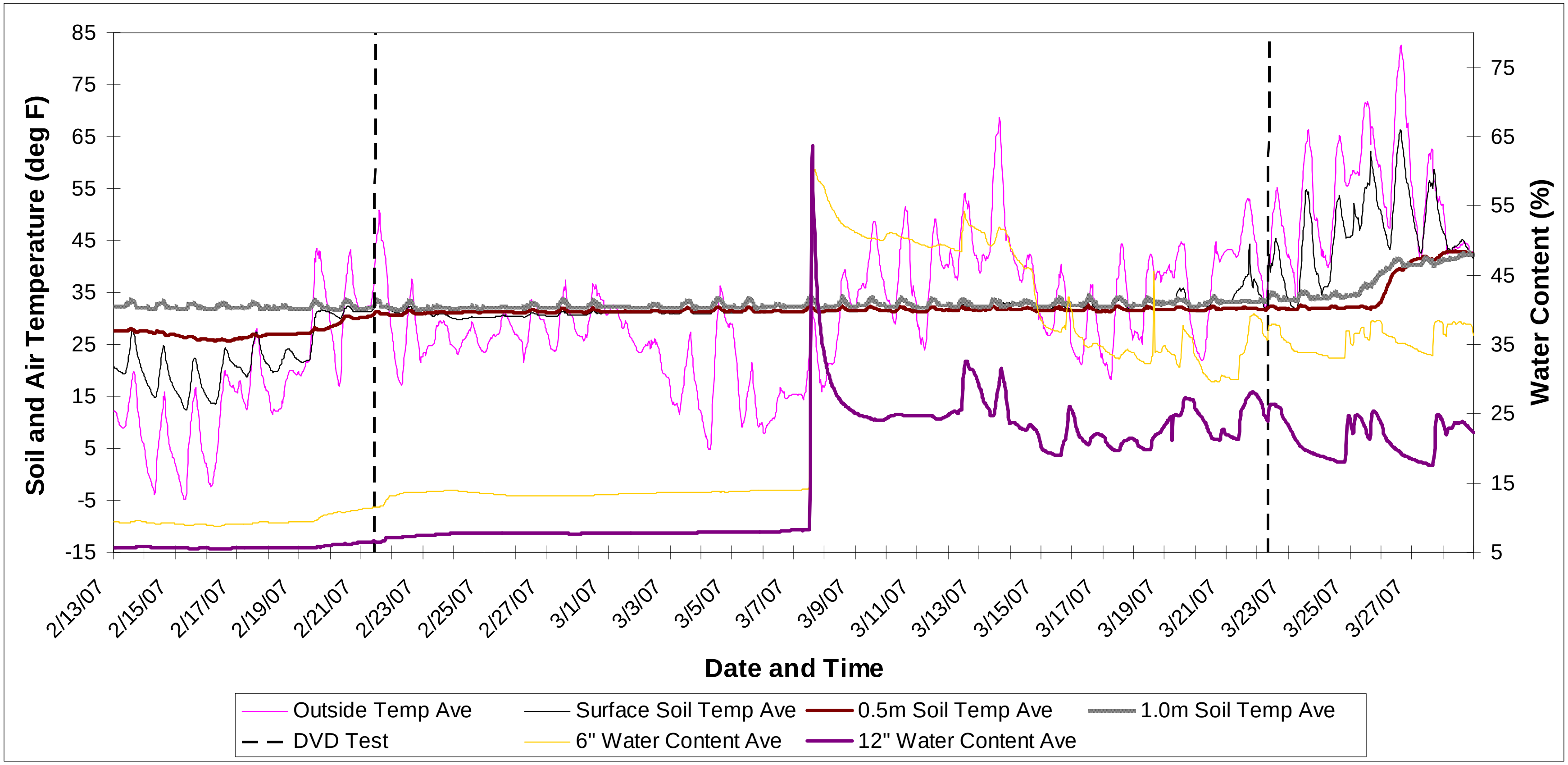

Figure B-11. Antecedent conditions Season 2 (Winter 2006-2007) at the Stillwater bioretention cell.

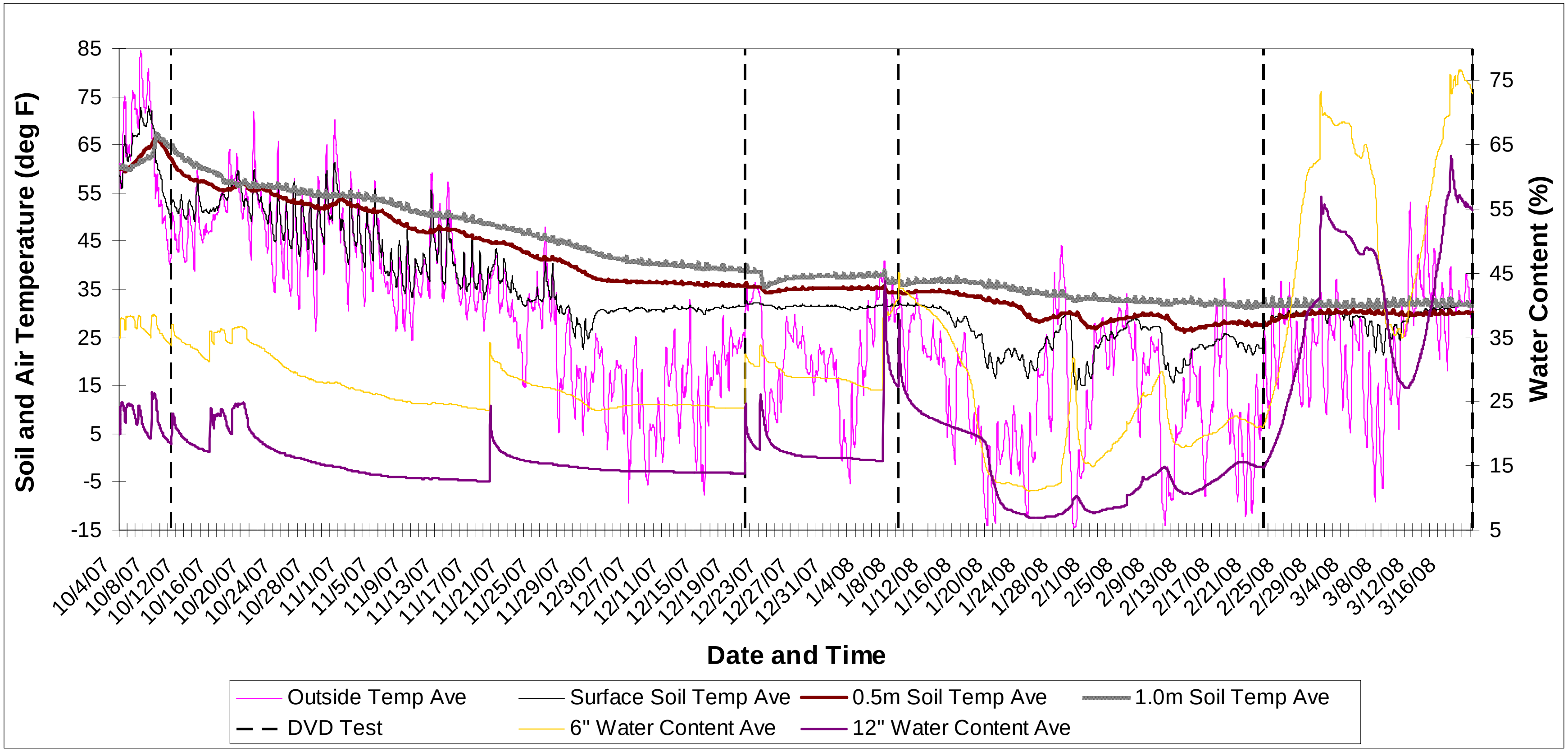

Figure B-12. Antecedent conditions Season 3 (Winter 2007-2008) at the Stillwater bioretention cell.

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APPENDIX C

DATA COLLECTION PROCEDURES

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Hydrologic Bioretention Performance and Design Criteria for Cold Climates

Water Environment Research Foundation (WERF) Project

WERF Project No. 04-DEC-13SG

October 15, 2008

Data Collection Procedures

Submitted by: James D. Davidson, CPESC, CPSWQ
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WERF Project: 04-DEC-13SG
Data Collection Procedures

Data must be collected from the monitoring equipment installed at the Thompson County Park, Burnsville Crystal Lake, Cottage Grove Park and Ride and Stillwater Dental Clinic sites once every 2-weeks. The equipment must be inspected to verify proper functioning.

Data Collected

Precipitation: Bi-weekly representative snow depth measurements shall be taken both inside and outside of the raingardens during winter testing season.

Soil Moisture: Year Around automatic sampling of daily soil moisture content at two depths (6" and 12") near the main infiltrometer location.

Frost Depth: Bi-weekly measurements taken at both the main and satellite infiltrometer locations during winter testing season.

Soil Temperature: Year around automatic sampling at 30 minute intervals for temperature at three depths – 0, .5 M, and 1.0 M

Air Temperature: Year around automatic sampling at 30 minute intervals for temperature.

Download Collected Data

1. Prepare a Field Data Sheet (or PDA form) and note any special or unusual conditions.
2. Check condition of equipment and download data from data logger using Campbell Scientific software.
3. Open downloaded data file in Excel to verify successful data transfer.
4. Test battery strength and secure equipment.

Measure Frost Depths

1. Pull inner frost tube and note where mixture has turned red. Gently bend the tube to locate the freeze limits.
2. Measure from the bottom of the cork to the bottom of the freeze limit and record on the Field Data Sheet.
3. If top thaw is observed- measure from the bottom of the cork to the top of thaw limits and record measurement.
4. Reinstall inner frost tube. Verify the tube is seated at the bottom.
   (Reminder at Thompson Lake sites to subtract offset measurement on outer frost tube)

Direct Volume Discharge

1. This test will occur at representative times during the season – early winter, mid-winter, early thaw, late thaw, and spring.
2. The test is to document infiltration rates under the conditions that exist at the time of the test for the wetted basin area. Infiltration rates will indicate acceptance during initial wetting stage. Longer duration tests to establish the hydraulic conductivity curve of the saturated soil are not needed. Note the site conditions and run the test under actual conditions without pre-wetting.
3. Use a known volume of at approximately 425 to 1,500-gallons or more of water between 32 to 50F. Note if chloride was added to test water. Chloride concentration to be representative of the sampling results obtained at each site. Record temperatures of test water and any standing water in raingarden.
4. Site conditions and representative snow depths should be recorded inside and outside of the raingarden before testing. Note if snow, surface ice or standing water coverers the bottom area prior to the test.
7. Rapidly fill the raingarden basin with the volume of test water and note the time when basin filling has been completed.
8. Immediately measure the distance from the top of the infiltrometer cross bar to the water surface. Periodically repeat the measurement and record the depth and time as the level of water drops within the basin.
9. Measure and record soil moistures at 6,12,18,24,30 and 36 inch depths at each tube location.
10. End test when the water has nearly infiltrated or at least one hour of testing.

Direct Volume Discharge Test Procedures

Each round of Direct Volume Discharge testing completed at the Crystal Lake and Thompson Lake sites required the coordinated efforts of three Implementation Team members. The equipment used and the process the team followed is described below.

- (2) Pickup trucks
- (1) Trailer with 425 gallon tank
- 3"- 8hp water pump & hoses, fuel
- Ice auger and ice saw
- Shovels
- (1) 60 & (4) 5 gallon containers
- Solar salt & measuring container
- AquaPro sensor & PDA
- Field data sheets
- Laptop computer
- Ruler & stop watch
- Thermometer
- Camera
- Calculators

Recording snow depth prior to DVD test.

8:00 am

The morning of a scheduled test day, a brief Implementation Team meeting is held at the office to confirm weather conditions are acceptable for testing. One team member is sent to load the water pump, fill a 425-gallon water tank mounted on a trailer and haul the test water to the Crystal Lake site.

The other two team members finish loading the remaining test equipment and leave the office to prepare the Crystal Lake site for testing. Site conditions are recorded and (2) rounds of AquaPro readings are completed to record soil moisture just prior to a DVD test.

Probing antecedent ice conditions.

Antecedent conditions prior to a DVD test.

DVD test water tank and pump.

Adding NaCl brine to DVD test water

<u>10:00 am</u>

The test water arrived onsite and a measured concentration of salt brine is mixed into the tank. The tank is emptied into the basin to begin the DVD test.

Recording pool temperature.

<u>10:30 am</u>

Timed measurements are taken to record the change in water levels while AquaPro reading record changes in soil moistures during the test. After about 1 hour, two team members leave to prepare the Thompson Lake site for testing. One member remains onsite to download the data logger and take final DVD measurements.

DVD test water pool.

Soil moisture probe and access tube.

<u>12:30 pm</u>

The site preparations needed for the Thompson DVD test include setting up and calibrating the pump, recording site conditions and (2) rounds of AquaPro readings to record soil moisture just prior to beginning the DVD test. The underlying sub-drain system is checked for any discharge flow prior to beginning the test.

DVD test pool at Thompson Cell

Calibrating pump discharge flow.

<u>1:30 pm</u>

When the three team member rejoin at the Thompson site, the test water is pumped from the lake into the basin while a measured concentration of salt brine dosed into the flow. The basin is filled with between 3,000 to 6,000 gallons of water to begin the DVD test. Timed measurements are taken to record the change in water levels while AquaPro reading record changes in soil moistures during the test. After about 2 hours, one team member leaves to return the tank, pump and trailer equipment while two members remain onsite to download the data logger and take final DVD measurements. The team members return at the office around 4:30 pm.

Downloading data logger.

Recording observed infiltration rates.

Recording soil moistures during DVD test.

DVD Test at Cottage Grove Park and Ride

DVD Test at Stillwater Dental Clinic Raingarden

DVD Test at Ramsey Washington Metro Watershed District Raingarden