Appendix I

Summary of Infiltration Issues Related to Cold and Arid Climates

Appendix I

Summary of Infiltration Issues Related to Cold and Arid Climates

1 Cold Climate Considerations

1.1 Overview of Cold Climate Factors

1.1.1 Overview

Cold climates and winter conditions present challenges to maintaining the operational efficiency of infiltration BMPs. Modifications may be needed during design and construction, and continue through operations and maintenance, to ensure efficiency is not reduced due to conditions affecting infiltration [1]. The following factors should be considered when evaluating the feasibility of installation in cold and sub-freezing climates to preserve the infiltration capacity and efficiency.

1.1.2 Temperature

The rate of infiltration into frozen soils is limited; therefore, BMPs that rely on infiltration are less effective when the soil is frozen. Sustained cold temperatures can result in the development of thick ice layers at the surface of some BMPs. Ice lenses can form below the surface, with layers of frozen material that cause the soil to rise or heave due to expansion of pore water as it freezes under the ground surface. Frost heave in infiltration BMPs can damage structural components (inlet/outlet pipes) [2]. Extreme cold may result in rapid freezing, which can cause pipes to burst or crack due to ice expansion. Installing structures below the frost line protects them from frost heave and prevents water from freezing in pipes or underground permanent pools.

Frozen ground in a normally pervious watershed can cause an increased volume of runoff to flow to the infiltration facility, a volume which may overwhelm the facility during rain-on-snow events or other melt events [3] [4]. Fourie et al. (2006) found that with repeated infiltration of water into partially frozen soils, the pore space will become saturated with ice, restricting any additional infiltration of water [5].

1.1.3 Length of Growing Season

Some regions that receive snowfall as precipitation (including arid regions) experience dramatic swings in temperature. As a result, frost may occur much of the year, despite high maximum daily temperatures. For some BMPs, such as bioretention facilities, swales, and grass filter strips, vegetation is central to the proper functioning of the BMP. When the growing season is shortened, establishing and maintaining this vegetation can be more difficult. Some plant species cannot succeed in shortened growing seasons; different plant species may be more appropriate under these conditions. In addition, the application of deicers to roadways can further limit the vegetative options, as chloride-tolerant vegetation species should be considered for those regions.

1.1.4 Snow Depth

The amount of snowfall a region receives dictates the amount of sand and deicing salt applied to the roadways; this affects the runoff flowing to the infiltration facility. Frequent snowfall results in increased applications of salt and sand. Those accumulate in snowmelt runoff, which can impact vegetation, decrease infiltration, or decrease the capacity of the BMP. Soils can become compacted and vegetation can be affected by being smothered under heavy snow accumulation.

A snow management plan can be developed for public works practices to approach the management of snow, snowmelt, and stormwater facilities. Such a plan should consider snow removal and disposal; sand/salt type, storage and application; winter construction control; pollution prevention efforts; and opportunities for BMP adaptation. Infiltration features should not be used as snow storage areas, as that use may result in debris build-up, plant damage, and reduced infiltration rates. UDFCD (2010) and Minnesota Stormwater Manual contain detailed snow and ice management guidance that can be included in such a management plan [6] [7].

1.1.5 Sand Loadings

In cold climates, the application of sand to the roadways for improved vehicle traction causes increased sediment load in the runoff, causing the surface of infiltration facilities to become clogged or plugged. Increased sediment load can also result from unmanaged upstream sediment sources or construction activity. Accumulated sediment will also build up in the infiltration feature and reduce its capacity.

1.1.6 Deicing Salt Loading

The application of sodium and/or chloride salts as roadway deicers can cause changes in the soil structure that result in clogged pores and decreased infiltration. Kakuturu and Clark (2015) found that the peak snowmelt can be potentially highly contaminated with sodium and chloride ions from road salt and lead to premature failure of infiltration devices [8], a breakdown of soil structure, and decreased infiltration rates [7]. Deicing salts can burn foliage, while salt buildup in soils can decrease the water available to plants and cause plant stress [9]. Morin et al. (2000) found excess soil salinity leads to a deterioration of soil structure due to soil crusting, and the clogging of soil pores by entrapment of dispersed soil clay and silt particles [10]. Soil crusting reduces shoot emergence and root penetration of both surface and subsurface seeds, thus reducing plant establishment. Clogging of soil pores reduces soil aeration, which in turn reduces the oxygen supply to plant roots and can affect root growth. Sumsion and Guthrie (2013) found that deicers can also affect articulated concrete blocks installed in BMPs by causing cracking and salt scaling or degradation of the block surface [11]. Deicing salts can affect the curing process of some types of permeable pavement.

1.2 Applicability of BMP Types in Cold Climates

Research results vary as to the effectiveness of infiltration in cold climates. In Minnesota, infiltration trenches are shown to operate effectively in cold climates if properly designed and maintained [7]. Zimmer et al. (2007) found that the sub-freezing conditions and snow cover during the winter months can reduce the capacity of infiltration BMPs [12]; Heasom et al. (2006) observed that the hydraulic conductivity of soil receiving infiltration during the winter at a site near Philadelphia, Pennsylvania, was about half the summer value [13]. However, research from Connecticut, Pennsylvania, and New Hampshire demonstrate that infiltration BMPs can function satisfactorily under winter conditions [14].

Overall, most infiltration BMPs are feasible and applicable for cold climates with certain design, operations, and maintenance modifications. Bioretention, infiltration, sand filtration, permeable pavement, and vegetated swales all can be modified to work in cold climates. In Fairbanks, Alaska, the most effective BMPs were found to be dry extended detention ponds; vegetation strips and swales, infiltration trenches, and basins [23]. Caraco and Claytor (1997) found that the stormwater managers surveyed recommended the following BMPs for use in cold climates: wetlands, wet ponds, (both of which are not infiltration BMPs) swales, and filter strips [2]. The reliance of certain BMPs on infiltration and vegetative growth in cold climates requires a focus on design and proper installation that incorporates considerations of the climate (length of successively freezing temperatures), frequency of sand/salt applications, snow plowing, available area for installation, and depth of piping or underdrain systems. In regions that experience permafrost, infiltration basins may not be feasible. There are challenges when the surface of the basin becomes frozen and therefore inoperable [2]. Infiltration basins, trenches, galleries, permeable pavement, and bioretention systems are not recommended where high sediment loads are expected in runoff from sanded roadways, unless pretreatment is provided [25].

Porous or permeable pavement has been shown to have variable success in cold climates. Those are most applicable for use in parking lots and road shoulders, especially where surfaces will not be sanded. In Fairbanks, Alaska, the concern regarding the use of porous pavements was the potential for freeze-thaw impacts and frost heave [23]. Kuosa et al. (2014) noted challenges that relate to extreme cold and frost penetration into the porous media [15]. Permeable pavements can also be susceptible to decay by the sand and salt that are applied to the roads, as well as the potential impact of studded tires and chains. However, freeze-thaw was not found to be an issue for permeable pavements or infiltration if a well-drained subbase remains open in the winter. In a review of numerous cold-climate case studies of pervious pavement applications, in multiple states and under different conditions of use (parking lots, roadways, intersections), Weiss et al. (2015) found that with proper mix design and construction practices, permeable pavements can provide a significant reduction of stormwater year-round [16].

1.3 Design Approaches to Mitigate the Challenges of a Cold Climate

If properly designed and maintained, infiltration can operate effectively in cold climates. Stormwater filtering systems need to be modified to protect the system from clogging, freezing, and frost heaving, while surfaces should be kept free of compacted snow and ice to maintain infiltration (8). The following general design practices to mitigate the challenges of a cold climate are applicable to all infiltrating BMPs.

1.3.1 Well-Draining Soils

Well-draining soils maintain infiltration capability. Design should include highly permeable, well-draining, coarse granular materials to decrease the duration of soil saturation, minimize freezing, and maintain infiltration [17]. If underlying soils are less permeable, this could be achieved by a well-drained sand layer at the surface such that the underlying soils are below the frost line.

Textured soils containing silt or clay particles should not be used as filter media; they infiltrate slowly, increasing susceptibility to freezing. Clay is also susceptible to impacts from deicing salts.

1.3.2 Proper Sizing of Facility/Storage Volume

Designers may wish to increase the volume of BMPs to account for the unique conditions in cold climates, particularly when the spring snowmelt, rain on snow, or rain on frozen ground may warrant higher treatment volumes. As a rule, additional storage (25%) and treatment capacity should be included in standard designs [2]. Hydrographs from melt events typically show a period of little to no runoff, despite a high melt rate, followed by accelerating flow as the saturated ground no longer infiltrates the melting snowpack. Recognizing this behavior while designing infiltration BMPs is important. If one of the purposes of the BMP is flood control, the critical event may be this type of large snowmelt event, rather than the storm events typically used for sizing BMPs [2]. Extensive guidance on the sizing and design of infiltration facilities in cold climates can be found in Caraco and Claytor (1997) [2]. The Minnesota Stormwater Manual provides a detailed review of the hydrology of the melt sequence [7].

1.3.3 Location of Pipes and Features Below the Frost Line

To maintain infiltration under freezing conditions, it is recommended to extend the filter bed and underdrain pipe below the frost line, oversize the underdrain, or both. This applies to bioretention and media filter drain BMPs. Increasing the diameter of the underdrain makes freezing less likely and provides a greater capacity to drain standing water from the filter [1]. This increased drainage capacity prevents the filtering medium from becoming saturated, thus decreasing the impact of freezing on the permeability of the filter. To prevent pipes from freezing, an underdrain diameter of at least 8 inches is recommended, in a 1-foot gravel bed. The porous gravel bed prevents standing water by promoting drainage, and gravel is less susceptible to frost heaving than finer grained materials [18].

1.3.4 Type of Vegetation

Using plant species that are tolerant to cold and salt is encouraged. Healthy vegetation supports plant root growth, which promotes infiltration [3]. Suggested plant species for various regions that are tolerant to salt and cold temperatures are found at https://stormwater.pca.state.mn.us/index.php?title=Cold_climate_plant_materials_of_the_upper_midwest_with_known_salt_tolerance,_listed_from_wet_to_ery_soil_moisture.

1.3.5 Pretreatment

Pretreatment is essential to prevent an excess sediment load from entering an infiltration feature. Coarse sediments should be trapped before they enter the feature, thus reducing the maintenance burden and ensuring the longevity of the primary treatment [18]. Inlets of facilities should include appropriate pretreatment to remove particulate materials that could clog the pore spaces and result in a system failure, which is common adjacent to roadways that use sand for improved vehicle traction [1]. A weir can be placed between the pretreatment chamber and the filter bed as a more effective substitute for a traditional standpipe orifice; the weir will be less susceptible to ice formation. Additional treatment volume can be provided with the use of a forebay [20]. Under conditions of high sediment load from adjacent roadways, the higher potential for clogging warrants attention to pretreatment.

1.3.6 Seasonal Operations of Facilities

A seasonally operated infiltration facility can improve the performance of infiltration BMPs in cold climates. Such design can include flow diversions or multi-level outflow control valves, accompanied by extra storage capacity in the basin [20]. The underdrain system and level control valves can be incorporated in the design, where the valves are opened at the beginning of the winter season and the soil is allowed to drain. As the snow begins to melt in the spring, the valves are closed, and the snowmelt is infiltrated until the capacity of the soil is reached. This requires attention to operations to ensure the valves are operated. Massachusetts DEP provides useful figures on this concept and practice [20].

If the infiltration BMP is complemented with other treatment approaches (e.g., swales, filter strips), a seasonal bypass could be considered, such that runoff with elevated salt content receives treatment, but does not infiltrate.

Bioretention devices can also be designed to operate in a two-stage seasonal mode that draws water levels down before winter; this strategy will provide extra capacity in the spring to capture snowmelt. Davidson et al (2008) details an off-line system designed to bypass high flows, where the same entrance and exit flow path are used when pooling capacity is reached [21]. Cells should be off-line designs that only allow low flow to enter the cell during interim snowmelt events, to create a shallow working pool depth that effectively infiltrates into the soils before freezing. Cells should be designed to fill to overflow capacity during the large spring melt event and allow the high flows to bypass the cell. Bioretention devices can be fitted with an underdrain with an accessible cap or valve at its outlet to allow it to be operated like that of an infiltration system [17]. Detailed guidance for designing seasonal facilities can be found in [2, 3, 7, 18, 21, 26].

In addition to the general conditions outlined above, some BMP-specific design factors are presented below.

1.3.7 Bioretention Design

Novotny et al. (2008) evaluated bioretention cells in cold climate conditions, finding the influencing factors of soil temperature, soil texture, and soil moisture combined to affect the observed infiltration rate dramatically [21]. LeFevre et al. (2009) found that a well-draining soil type is the single most important design characteristic [17]. The inlets of bioretention facilities should include appropriate pretreatment to remove particulate-materials that could clog the pore spaces and result in a system failure [18]. Also, the filter bed and underdrain pipe should be extended below the frost line, or the underdrain should be oversized to prevent freezing [2].

While pollutant removal effectiveness may decrease during the winter, standing vegetation in bioretention areas still provides a measure of filtration [2]. When bioretention areas are located along roads, care must be taken during plowing operations to prevent snow from being plowed into the bioretention areas. Marti et al. (2009) suggest that to prevent soil compaction, bioretention areas should not be used as dedicated snow disposal areas [25].

1.3.8 Infiltration Design

Challenges will be presented when the surface of the basin becomes frozen, or if the volume of snowmelt runoff is greater than the capacity of the basin. If the infiltration device treats roadside runoff, a flow diversion may be used in the winter to prevent sand and chlorides from impacting the infiltration facility and groundwater resources, and to prevent clogging. Runoff that contains high concentrations of chloride can be routed away from an infiltration system that might operate during three seasons, but not in the winter [7].

Inlet pipes should have a minimum slope of 1% or 2% to prevent standing water that could freeze [18]. The device outlets should also be extended below the frost line.

1.3.9 Vegetated Swale Design

In cold or snowy climates, swales may serve a dual purpose by acting as both a snow storage/treatment area and a stormwater management practice. This dual purpose is particularly relevant when swales are used to treat road runoff; in that case, they should incorporate salt-tolerant vegetation. In climates where significant snowfall is expected, the setbacks of linear features such as vegetated swales should be designed to account for snow storage. Consider using sod-forming grasses and vegetation that tolerates cold climates adjacent to roadway shoulders and within vegetated swales.

1.4 How the Construction and Establishment of Infiltration BMPs Differs for Cold Climates

The construction of infiltration BMPs should be completed before the winter months begin. Since cold climates have shorter growing seasons, the vegetation types and their germination periods should be part of the early planning process for infiltration BMPs. The time of construction and planting should be tightly specified in construction documents.

Hydroseeding stabilizers are ineffective when it is cold, and limited seed germination can be expected during winter months. For some BMPs, such as bioretention facilities, vegetated swales, and grass filter strips, where vegetation is central to the proper functioning of the BMP, establishing and maintaining this vegetation becomes more difficult, and it is important to adjust the planting window to ensure establishment of vegetation [20].

In some situations, it is necessary to replace poorly draining soils amended soils. Over-excavating and backfilling with gravel or sand protects against frost heaving [2].

1.5 Operation and Maintenance in Cold Climates

The operation and maintenance of infiltration BMPs can be challenging in cold climates due to the impacts of freezing soils/media, snow and ice cover, sediment buildup, and clogging.

The application of sand for improved vehicle traction on roads and parking lots can lead to the accumulation of sediment in infiltration systems. While BMP selection and design should incorporate adequate storage volume to trap sediment left behind by melting snow, more frequent maintenance should be planned to remove the accumulated sediment to ensure capacity is maximized, infiltration is not impeded, and the surface is not clogged. Frequent inspection of these facilities is essential, particularly in the early spring, when larger amounts of sand are washed from paved surfaces into runoff conveyance and treatment systems.

To maintain infiltration rates during cold weather, it is essential to have the infiltration practice free of standing water or ice. If drawdown times are slow, it is important to monitor them leading up to frost and correcting the practice to improve the drawdown time. This can be done by various methods including limiting inflow, underdrainage, and surface disking.

The effects of sand and salt applied to the roadways also require inspection and maintenance to ensure the health of the vegetation in BMPs. While the design should incorporate the appropriate type of vegetation (grass, wetland, shrub, or tree species to maintain vegetative cover) that is able to withstand cold temperatures and salt inputs, inspections must be conducted to ensure the vegetation is successful. The thickness of vegetation cover and any wilting or discoloration should be noted.

Frequency of maintenance depends on the basin’s vegetation, capacity, sediment load, and other factors. Infiltration and biofiltration BMPs should inspected for sand build-up in the filter chamber following the spring melt event.

As with any climate (but more so when road sand is used), sediment pretreatment is critical. Preventive maintenance to decrease the amount of sediment that enters the infiltration feature includes catch basin cleaning and street sweeping, tilling, erosion control, and debris and litter removal [23]. Use of pretreatment BMPs will significantly minimize the maintenance requirements of the structure itself. Removing accumulated sediment from a sump pit or a vegetated swale is considerably less difficult and less costly than a complete rehabilitation of the primary facility.

The local agency may develop a Snow Management Plan that dictates snow storage operations. Typically, snow is moved to the side of the road. Snow deposits should not be placed directly over a designed infiltration facility, since the debris in the snow could potentially clog the facility. A confounding problem faced in cold climates is that the largest volume of snowmelt water can occur at the end of the winter, when frozen ground under infiltration basins or frozen permanent pools and clogged outlets for pond systems may be at their worst, as maintenance usually occurs at the beginning of spring (after the runoff). Thus, the effectiveness of BMPs can be compromised during critical peak flow runoff events, such as rain on snow or high-volume snowmelt itself. Given this, it is critical to have secondary overflow pathways such that the roadway can drain even if the infiltration BMPs is not fully functional.

Snow removal with conventional plowing equipment has been deemed suitable for all kinds of pervious pavements. Some studies recommend that the plow should be plastic or rubber; metal plows should be avoided, or the plow kept slightly above the surface [16].

1.6 Annotated Bibliography for Cold Climate Considerations

1. Novotny, V., Smith, D.W., Kuemmel, D.A., Mastriano, J. and Bartošová, A. 1999. *Water Environment Research Foundation's Urban and Highway Snowmelt: Minimizing the Impact on Receiving Water.* WERF Project 94-IRM-2**.**

This WERF publication is a collection and synopsis of many pieces of cold climate research and data, primarily from the US and Canada. The focus is on highways, but the report is very informative on all aspects of urban cold climate runoff behavior.

2. Caraco and Claytor. 1997. *Center for Watershed Protection's Stormwater BMP Design Supplement for Cold Climates and revision session in Maine* (2003).

Based on surveys of stormwater management experts in cold climates prepared for US EPA by a leading organization in the watershed management and stormwater management field. Defines what is meant by cold climate and why this presents challenges for BMP design. Includes recommended modifications for infiltration and other stormwater BMPs in cold climates. The document is available from CWP at http://owl.cwp.org/mdocs-posts/caracod-_sw_bmp_design_cold_climates/

3. *Additional Design Considerations.* 2006. Northwest Area (NWA) Inver Grove Heights Stormwater Manual. Chapter 6. Inver Grove Heights, Minnesota.

This volume contains 30 pages (pages 167-197) on the purposes, applicability, site suitability, design, and maintenance of infiltration BMPs relative to cold climates. There is extensive detail on the nature of the problems that infiltration BMPs face in cold climates, key challenges in engineering and design, and design adaptations for cold climates. Also included are extensive quantity and quality considerations of snowmelt runoff. This document is very similar to the Minnesota Stormwater Manual. Retrieved from http://www.ci.inver-grove-heights.mn.us/DocumentCenter/Home/View/276

4. Nie, L., Lindholm, O.G., Astebol, S.O., Saegrov, S., and Thorolfsson, S. 2011. *Integrated Urban Stormwater Management in Norway – Best Management Practices (BMPs) in cold climate*.

Presented at 12th International Conference on Urban Drainage, Porto Alegre/Brazil. This brief article presents data collection for design of BMPs in cold climates, with a particular focus on data collection. Full article Retrieved from https://web.sbe.hw.ac.uk/staffprofiles/bdgsa/temp/12th%20ICUD/PDF/PAP005328.pdf

5. Fourie, W.J., Barnes, D.L., and Shur, Y. 2007. *The formation of ice from the infiltration of water into a frozen coarse-grained soil.* Cold Regions Science and Technology, Vol. 48, pp. 118-128.

Results from this study using a conceptual model indicate that the presence of fine particles in a coarse-grained soil greatly impact the depth at which the pore space initially becomes saturated with ice. A thorough discussion of infiltration, melt water, and soils. Full article can be purchased online at http://www.sciencedirect.com/science/article/pii/S0165232X06001315

6. *Urban Storm Drainage Criteria Manual Volume 3.* 2010. Urban Drainage and Flood Control District, Denver, Colorado.

Volume 3, Stormwater Quality, of this three-volume manual includes a Structural Control BMP Fact Sheet (S-10) for Snow and Ice Management. It provides guidance on snow removal and management practices, as they can adversely impact vegetation, soils, water quality, and air quality. Snow removal contractors and operators should be knowledgeable of these potential impacts and choose management measures with the fewest adverse impacts. Retrieved from https://udfcd.org/wp-content/uploads/2014/07/S-10-Snow-and-Ice-Management.pdf

7. Minnesota Stormwater Manual. 2005. Chapter 9: *Cold Climate Impact on Runoff Management. Volume 2, Technical and Engineering Guidance*. Minnesota Pollution Control Agency, St. Paul, Minnesota.

This volume contains 30 pages (pages 167-197) on the purposes, applicability, site suitability, design, and maintenance of infiltration BMPs relative to cold climates. There is extensive detail on the nature of the problems that infiltration BMPs face in cold climates, key challenges in engineering and design, and design adaptations for cold climates. Also included are extensive quantity and quality considerations of snowmelt runoff. The entire volume can be downloaded from http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

8. Kakuturu, Sai P., and Shirley E. Clark. 2015. *Clogging Mechanism of Stormwater Filter Media by NaCl as a Deicing Salt*, Environmental Engineering Science 32, No. 2: 141-152.

This article looked at permeability reduction of stormwater filtration media due to blocking of pore throats by dispersed particles and biofilms. Permeability reduction of the media with compost was larger, because compost-salt interactions were comparatively greater than the soil-salt interactions. Results of this study suggest that salt-laden snow should not be piled up near the bioretention facilities built with compost-included media. This article can be downloaded from http://online.liebertpub.com/doi/abs/10.1089/ees.2014.0337

9. Bauder, J.W. and T.A. Brock. 1992. *Crops species, amendment, and water quality effects on selected soil physical properties*. Soil Science Society of America Journal. 56: 1292-1298.

Looked at saline and sodic soils in irrigated areas of Montana, assessing cropping systems that promote maximum efficacy of surface-applied amendments for reclamation. In particular, the effects of crop species, amendment, and water quality on alteration of selected physical properties soils.

10. Morin, J., Y. Benyamini, and A. Michaeli. 1981. *The dynamics of soil crusting by rainfall impact and the water movement in the soil profile*. Journal of Hydrology. 52: 321-335.

Discussion of effects of soil crusting on permeability, Retrieved from http://www.sciencedirect.com/science/article/pii/0022169481901785

11. Sumsion, Eric S., Guthrie, W. Spencer. 2013. *Physical and Chemical Effects of Deicers on Concrete Pavement: Literature Review*. Final Report, prepared for Utah Department of Transportation Research Division.

The purpose of this research was to conduct a review of the literature and summarize the effects of several commonly used deicers on concrete pavement. Sodium chloride, calcium chloride, magnesium chloride, and calcium magnesium acetate (CMA) and the effects of their respective ions are specifically discussed, and 10 different studies published between 1995 and 2012 are summarized. Deicers can affect concrete both physically and chemically. Physical effects are typically manifested as cracking and salt scaling, while chemical effects can result from reactions involving cement hydration products, and aggregates. Retrieved from https://www.udot.utah.gov/main/uconowner.gf?n=8081525197623431

12. Zimmer, C. A., Heathcote, I.W., Whiteley, H.R. and Schroeter, H. 2007. *Low Impact Development Practices for Stormwater: Implications for Urban Hydrology*, *Canadian Water Resources Journal/Revue canadienne des ressources hydriques* 32, no. 3: 193-212.

This article presented a study that used watershed modeling to evaluate the capability of LID techniques to mitigate the impact of urbanization on hydrology on a site in Canada. In particular, this article discusses sensitivity of LID BMPs to infiltration rates. This article can be downloaded from http://www.tandfonline.com/doi/abs/10.4296/cwrj3203193.

13. Heasom, W, Traver, R.G., and Welker, A. 2006. *Hydrologic modeling of a bioinfiltration best management practice*. Journal of the American Water Resources Association 42(5), 1329-1347.

Provides an in-depth understanding of the influence of hydrologic and hydraulic factors on treatment performance to provide important guidance for effective bioretention basin design.

14. Roseen, R.M., Ballestero, T.P., Houle, J.J., Avellaneda, P., Briggs, J., Fowler, G., and R. Wildey. 2009. *Seasonal Performance Variations for Storm-Water Management Systems in Cold Climate Conditions*. Journal of Environmental Engineering, Vol. 135, No. 3.

Examines six LID sites, discuss cold climate conditions including frost related impacts, chloride toxicity, pipe freezing. While frost penetration was observed for all the filtration systems, it did not affect overall hydraulic performance. Retrieved from: https://www.unh.edu/unhsc/sites/unh.edu.unhsc/files/pubs_specs_info/jee_3_09_unhsc_cold_climate.pdf

15. Kuosa, H., Niemelainen, E., Kivikoski, H., and J. Tornqvist. 2014. *Pervious pavement winter performance—State-of-the-art and recommendations for Finnish winter conditions*. VTT Technical Research Centre of Finland.

This report evaluates winter performance of pervious pavement on frost heave, water infiltration and maintenance. Recommendations on frost heave protection and maintenance are included. Discusses sizing of underlayers to ensure performance. Retrieved from http://www.vtt.fi/files/sites/class/D2_4_CLASS_WP2_Winter_Performance.pdf

16. Weiss, P.T., Kayhanian, M., and Khazanovich, L. 2015. *Permeable Pavements in Cold Climates: State of the Art and Cold Climate Case Studies*. Final Report. Minnesota Department of Transportation, St. Paul, Minnesota.

This report included discussion of winter hydraulic performance of permeable pavements in different test cells and reported their structural and physical performance, as well as maintenance performance.

Different locations were studied (parking lots versus roads), as well as the impacts of sanding and sweeping. https://www.lrrb.org/pdf/201530.pdf

17. LeFevre, N. J., Davidson, J. D., and Oberts, G. L. 2009. *Bioretention of simulated snowmelt: Cold climate performance and design criteria. Cold Regions Engineering 2009: Cold Regions Impacts on Research, Design, and Construction.* 145-154.

This study reviewed design, installation and operation of four bioretention cells in the Minnesota region. It discusses frost impacts on infiltration rates, soils, and hydrologic performance testing. Retrieved from: https://trid.trb.org/view/904555

18. New York State Stormwater Management Design Manual. 2015. *Chapter 6: Performance Criteria. Center for Watershed Protection*, Ellicott City, Maryland.

This chapter contains 66 pages on the performance criteria for five groups of structural stormwater management practices (SMPs) to meet water quality treatment goals, including feasibility and cold climate design guidance. There are highly detailed plan and profile figures for all types of BMPs under varying conditions, as well as a cold climate sizing example in Appendix I. The entire document can be downloaded from http://www.dec.ny.gov/docs/water_pdf/swdm2015entire.pdf

19. BMP 6.4.8: Vegetated Swale. 2006. Pennsylvania Stormwater Best Management Practices Manual, Structural BMPs, *Chapter 6. DEPARTMENT OF ENVIRONMENTAL PROTECTION Bureau of Watershed Management*. Stormwater PA, Philadelphia, Pennsylvania.

This BMP Fact Sheet presents vegetation appropriate for swales, including those that are cold and salt tolerant. Table 6.8.1 presents the information extracted from the New Jersey BMP Manual (2004). Retrieved from http://www.elibrary.dep.state.pa.us/dsweb/Get/Version-48477/07_Chapter_6.pdf

20. *Choosing the Right Stormwater Treatment Practice in Cold Climates*. Massachusetts Statewide Stormwater Seminar Series.

This training presentation contains typical BMPs and adaptations of modifications to work in cold climate. Profile view figures are presented (from Oberts, 1990) that depict different BMPs under different cold climate scenarios. This is a very basics-oriented seminar on seasonal operations and cold climate modifications. Retrieved from http://projects.vhb.com/stormwaterseminars/presentations.asp

21. Davidson, J.D., Isensee, M., Coudron, C. and T. Bistodeau. 2008. *Water Environment Research Foundation's Hydrologic Bioretention Performance and Design Criteria for Cold Climates*. WERF Project 04-DEC-13SG.

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. Retrieved from http://www.ndwrcdp.org/documents/04-DEC-13SG/04DEC13SG%20FACTSHEET.pdf

22. Oberts, G. 2003. *Cold Climate BMPs: Solving the Management Puzzle.* Water Sci. Technol., 489 (9), 21-32.

Frozen conduits, thick ice layers, low biological activity, altered chemistry, and saturated or frozen ground conditions all work against effective treatment of melt runoff. Understanding the source, evolution and transition that occurs within a melt event, and defining the management objectives for specific receiving waters will help focus the search for effective management techniques. Not available online.

23. *BMP Effectiveness Report.* 2006. Alaska Department of Environmental Conservation, Water Quality Program. Fairbanks, Alaska.

This report discussed BMPs suitable for the climate of Fairbanks, Alaska. It presents a preliminary list of BMPs, as well as those that may be suitable with modifications, as well as BMPs not suitable. Also discussed is how porous pavement is not likely suitable for the conditions, using references of EPA guidance, but no actual investigations. Not available online.

24. Metropolitan Council of the Twin Cities Area. Barr Engineering Company & Minneapolis (Minn.). 2001. *Minnesota urban small sites BMP manual: Stormwater best management practices for cold climates*. St. Paul, MN: Metropolitan Council.

Details infiltration systems, with focus on site sensitivity and cold weather considerations. Not available online.

25. Marti, M., Giese, J. and Goddard, L. 2009. *Stormwater Maintenance BMP Resource Guide*. Prepared for Minnesota Department of Transportation.

This is a reference guide that focuses on BMPs used in cold climates, especially benefits or limitations. Includes detailed inspection and maintenance guidelines for BMPs. Retrieved from https://www.lrrb.org/pdf/2009RIC12.pdf.

26. *IDEQ Storm Water Best Management Practices Catalog*.

Provides technical guidance for construction site design and the selection of stormwater BMPs. The Fact Sheet for Sand Filter (BMP 4) provides guidance for pretreatment, off-line systems, proper maintenance to maximize infiltration to prolong the feature’s design life. Retrieved from http://www.deq.idaho.gov/media/618033-4.pdf

2 Arid Climate Considerations

2.1 Overview of Arid Climate Factors

Characteristics of arid regions present challenges for the efficient operation of stormwater BMPs. These watersheds' low annual rainfall, high-intensity storms, extensive droughts, and sparse vegetation must be considered in evaluating the feasibility of BMPs. Because of low annual rainfall levels, bioretention BMPs in arid areas may have difficulty sustaining vegetation. Plants must be able to withstand prolonged periods of no water and be drought and sometimes salt tolerant. Some arid regions receive snow as their primary form of precipitation, and the resulting presence of salt and sand in the runoff to the BMP must be addressed (See Cold Climate Considerations, above). Low annual rainfall contributes to sparse vegetation cover and, therefore, less stable soil, which means greater amount of sediment may be delivered to BMP from pervious areas during high-intensity storms.

BMP selection and design for arid climates should address factors such as potential clogging due to the higher sediment loading, the selection of appropriate vegetation, and the need for a higher level of pretreatment.

2.2 Applicability of Infiltration BMP Types in Arid Climates

Many infiltration BMPs require design, operation, and maintenance modifications (e.g., additional pretreatment) for arid climates when compared to more humid climates. However, infiltration BMPs are still applicable and can be effective in arid regions. Caraco (2000) found the preferred BMPs for arid watersheds are dry ponds and sand filters, while bioretention and infiltration are acceptable with design modifications [1]. Permeable pavement shoulders are also effective as long as binders are adequately designed for higher temperatures. Swales and filter strips either are not recommended or have limited use in arid watersheds. Pretreatment is a prerequisite for BMPs, while vegetation selection and water availability will dictate the selection of bioretention or other vegetative practices.

2.3 Design Approaches to Mitigate the Challenges of an Arid Climate

Rainfall patterns, soil characteristics, patterns of urbanization, and general climate contribute to differences in the stormwater generation process, and thus to the differences in the design and performance of stormwater BMPs (Gautam et al., 2010, [2]). Several basic design principles can improve the performance and longevity of stormwater infiltration BMPs in arid climates. Strategies should focus on careful selection and adaptation for an arid watershed, minimizing irrigation needs, protecting groundwater, and limiting sediment generation from the upstream watershed. Upstream erosion and a lack of sediment control during construction cause clogging in many infiltration practices. As a result, infiltrating BMPs, sand filters, and bioretention practices should be located so that they can only accept runoff from impervious areas [1]. Urbonas (2000) suggests an increase in bed filter size, and upstream detention to provide greater sediment pretreatment [3]. All stormwater practices in arid regions require greater pretreatment than in humid environments; pretreatment and oversizing can prevent the loss of storage or clogging associated with sediment deposition [1]. Native, drought-tolerant and even salt-tolerant plants should be considered. A detailed list of plant species appropriate for use in arid climates can be found in Appendix A of the Southern California LID Manual [4]. Without rainfall, vegetation that lacks a supply of water cannot be not sustained. Minimizing irrigation practices is an important aspect of stormwater practices in arid climates.

2.3.1 Infiltration Design

Sediment transport, loading, and clogging are the primary design challenges for infiltration BMPs in arid climates, identified by 75% of stormwater managers as the cause of major design and maintenance problems [1]. The soil, vegetation, and topography typical of arid regions are conducive to soil erosion and increased sediment transport during storm events in the watershed [2]. Although these regions have a lower total precipitation than other regions, the intensity of individual storms can be similar or higher than other regions. Sparse vegetation cover in the watershed can lead to sediment washed off from the land surface during high-intensity rainfall events, which contributes to sediment loading of BMPs.

Isolation of sediment producing areas is strongly recommended. Infiltration practices used in locations where they will only receive runoff from impervious areas, or frequent maintenance will be required. Pretreatment and oversizing can also help reduce clogging associated with sediment deposition. The Clogging Risk Assessment Tool in Appendix F can be used to help evaluate these factors.

2.3.2 Bioretention Design

Bioretention can be an effective practice in arid climates, with certain design modifications. Modifications for successful adaptation include xeriscape plantings, use of gravel instead of mulch as ground cover, and better pretreatment. In general, any vegetation used in a bioretention device should be native to the climatic region, drought resistant, tolerant of pollutants, and tolerant of brief rainfall inundations, and should require minimal fertilization and limited maintenance. Sprinkler irrigation of bioretention areas should be avoided [1]. Lizarraga et al. (2017) recommended self-sustained vegetation in favor of artificially irrigated features; wild grass, shrubs, and trees are favored, as they are more tolerant to changing hydrologic conditions [5]. The ability of grasses and succulent plants to store water and to withstand periods of drought makes them ideal for low-precipitation and high-evaporation conditions. Combining deep-rooted shrubs, which have taproots to access deep soil water, with grasses that produce extensive networks of shallow roots is recommended for optimal drought tolerance (EPA 2016) [6].

Irrigation during the establishment period may be needed even if plants are selected to not require long term irrigation. The City of Portland irrigates bioretention for approximately 2 years during the establishment period.

When bioretention devices are constructed in arid climates, a deeper layer of drainage rock is required to ensure that native vegetation can tolerate the deep watering and inundation from seasonal rainfall. A washed-gravel drainage layer should also be placed below the soil medium to increase the infiltration capacity of the bioretention system and provide temporary water storage for plants. Research recommends a gravel depth of 18 to 24 inches to provide water storage for deep-rooted desert plants. Medium-sized gravel serves as an effective mulch, retaining moisture and protecting against erosion. While the 18-inch minimum depth of engineered soil media can be used in some cases, 24 inches are recommended, and 36 inches are preferred to provide an adequate root zone for the chosen plant palate. Such a design also provides improved effectiveness in the removal of nutrients (Riverside County LID BMP Design Handbook, [7]).

2.3.3 Vegetated Swale Designs

There are few applications of grass swales for stormwater treatment in arid watersheds, as the dense turf typical of grass swales can only be maintained in arid conditions by using irrigation systems (Barrett et al., 1998) [8]. While irrigation is commonly used to establish and maintain stormwater practices in arid and semi-arid regions, the scarcity of water and the location of the practice in relation to a water supply limit their use in many roadside regions. Xeriscape or rock swales can be used instead of vegetation.

2.3.4 Permeable Pavement

When specifying permeable asphalt in hot climates, binders should be selected to be suitable for the temperature. A stiffer binder is typically needed for permeable asphalt than traditional asphalt in hot climates.

2.4 How Construction and Establishment of Infiltration BMPs Differs for Arid Climates

As with any infiltrating BMP, measures must be taken to remove upstream sources of sediment generated by the watershed, and to minimize the effect of construction on erosion and soil compaction. This may require an extended period of time in arid climates. If pervious area must be drained to the BMP, then an extended establishment period may be needed before the BMP is brought online. If the system must be brought online before stabilization of the watershed, O&M plans may need to call for rehabilitation of the system after the first one to two years of operation.

Vegetation establishment in BMPs is difficult in arid regions due to the minimal use of irrigation water. Irrigation is often required to establish a dense and vigorous cover, which may not be sensible or economical given scarce water resources [1]. While irrigation has been recommended for the first 1 to 2 years of establishment, to help root systems develop, it should not be required after this period (EPA 2016) [6].

2.5 Operation and Maintenance in Arid Climates

The operation and maintenance of infiltration BMPs is challenging in arid climates because of sediment buildup and clogging issues related to erodible desert soils and heavy seasonal rainfall. As a result, more frequent maintenance may be required to remove sediment from infiltration BMPs. Urbonas (2003) recommends a frequent sediment cleanout regime to account for the greater sediment buildup in arid watersheds, with removal after major storms and at least once per year [3]. The Clogging Risk Assessment Tool described in Appendix F of the Guidance Manual can be used to evaluate design approaches to reduce clogging risk.

Vegetation health should also be assessed, especially during establishment, to ensure proper function of the treatment. Healthy and dense vegetation will provide better filtering and protect soils from erosion. It likely that maintenance needs will change considerably as vegetation becomes more established. An adaptive approach for O&M is recommended.

2.6 Annotated Bibliography for Arid Climate Considerations

1. Caraco, D. 2000. *Stormwater Strategies for Arid and Semi-Arid Watersheds: The Practice of Watershed Protection*. Center for Watershed Protection, Ellicott City, MD. Pages 382-391.

Good discussion of key considerations in arid and semi-arid watersheds, including low rainfall depths, evapotranspiration, and sparse vegetative cover in the watershed. Table 4 includes design modifications for various stormwater practices and their use or inapplicability, with modifications, in arid and semi-arid watersheds. Available online at http://owl.cwp.org/mdocs-posts/elc_pwp66/

2. Gautam, M.R., Acharya, K. and M. Stone. 2010. *Best Management Practices for Stormwater Management in the Desert Southwest*. Universities Council on Water Resources, Journal of Contemporary Water Research and Education. Issue 146, pages 39-49.

This paper discusses BMP design in arid and semi-arid climates, focusing on the impacts of evapotranspiration, vegetative cover, watershed-produced erosion and propensity of infiltration BMPs to clogging. https://onlinelibrary.wiley.com/doi/full/10.1111/j.1936-704X.2010.00390.x

3. Urbonas, B.R. 2003. *Effectiveness of Urban Stormwater BMPs in Semi-Arid Climates.* Presented at regional conference on Experience with Best Management Practices in Colorado.

Discusses effects of urbanization on BMPs, effectiveness of BMPs, and suggestions for design and maintenance. http://www.uwtrshd.com/assets/effectiveness-of-bmps-in-semi-arid-climates.pdf

4. Low Impact Development Manual in Southern California. 2010. *Technical Guidance and Site Planning Strategies*.

Prepared for the Southern California Stormwater Monitoring Coalition, in cooperation with the State Water Resources Control Board, by the Low Impact Development Center, Inc. Available online at https://www.casqa.org/sites/default/files/downloads/socallid-manual-final-040910.pdf

5. Lizárraga-Mendiola, L.; Vázquez-Rodríguez, G.A.; Lucho-Constantino, C.A.; Bigurra-Alzati, C.A.; Beltrán-Hernández, R.I.; Ortiz-Hernández, J.E.; López-León, L.D. 2017. *Hydrological Design of Two Low-Impact Development Techniques in a Semi-Arid Climate Zone of Central Mexico*. Water, *9*, 561.

6. U.S. Environmental Protection Agency. 2016. *Arid Green Infrastructure for Water Control and Conservation: State of the Science and Research Needs for Arid/Semi-Arid Regions*. EPA/600/R-16/146.

Contains thorough compilation of green infrastructure, current research with significant literature review, and additional research that needs to be conducted. Retrieved from www.epa.gov/research .

7. Bioretention Facility, Fact Sheet 3.5. 2012. *Riverside County Low Impact Development BMP Design Handbook*. Prepared for Riverside County Flood Control and Water Conservation District, Riverside, California.

Includes significant detail on the design and sizing of bioretention facilities. Retrieved from http://rcflood.org/downloads/NPDES/Documents/LIDManual/3.5_Bioretention.pdf

8. Barrett, M., M. Keblin, P. Walsh, J. Malina and R. Charbeneau. 1998. *Evaluation of the Performance of Permanent Runoff Controls: Summary and Conclusions*. Center for Transportation Research. Texas Department of Transportation, University of Texas. Austin, Texas. 37 pp.

   The study investigated the capability of vegetative controls (grassed swales and vegetated buffer strips) and sedimentation/filtration systems for treating stormwater runoff. Includes specific recommendations for vegetative controls and sedimentation systems along highways. Retrieved from https://repositories.lib.utexas.edu/bitstream/handle/2152/6751/crwr_onlinereport97-3.pdf?sequence=2&isAllowed=y

9. Tenney, S., M. Barret, J. Malina, R. Charbeneau and G. Ward. 1995. *An Evaluation of Highway Runoff Filtration Systems*. Technical Report No. 265. Center for Research in Water Resources. University of Texas at Austin. 134 pp. Retrieved from https://repositories.lib.utexas.edu/bitstream/handle/2152/6740/crwr_onlinereport95-8.pdf;sequence=2

10. Claytor, R.A., and T.R. Schueler. 1996. *Design of Stormwater Filtering Systems*. The Center for Watershed Protection, Silver Spring, MD.

    The manual presents detailed engineering guidance on ten different filtering systems, including a diverse spectrum of stormwater treatment methods which utilize an artificial media to filter out pollutants entrained in urban stormwater. These filters are typically designed solely for pollutant removal and serve small development sites. The three broad groups include: sand filters (surface, underground, perimeter, organic, and pocket designs), bioretention and vegetated channels (grass channels, dry swales wet swales, and filter strips). The underlying concept of the manual is that a common and unified approach was needed to design each type of stormwater filter, so that this useful technology can gain wider engineering acceptance at the local level. The manual presents a single volumetric sizing requirement for each filter which is to capture and treat 90% of the runoff producing events that occur each year. Retrieved from http://owl.cwp.org/?mdocs-file=4553&mdocs-url=false

11. Sand Filter, BMP 4. Idaho Department of Environmental Quality. 2005.

    Extensive guidance on design, installation, filter type; explanatory figures. Retrieved from http://www.deq.idaho.gov/media/618033-4.pdf

12. Campbell, C. J. and Dick-Peddie, W. A. 1964. *Comparison of Phreatophyte Communities on the Rio Grande in New Mexico*. Ecology, 45: 492–502. doi:10.2307/1936102.

    Discusses type and extent of vegetative cover in an arid climate (New Mexico), especially phreatophytes. Retrieved from http://onlinelibrary.wiley.com/doi/10.2307/1936102/full