SUGGESTIONS FOR DESIGNING AND CONSTRUCTING BIORETENTION CELLS FOR A NORDIC CLIMATE

Forslag til dimensjonering og utforming av regnbed for nordiske forhold

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Abstract

Bioretention cells (also referred to as raingardens or biofilters) are constructed as shallow vegetated depressions and are generally considered a flexible practice for local stormwater management. Runoff is retained at the cell surface before it percolates to the ground or is conveyed to the stormwater system. Flood risk is reduced via retention and volume reduction of the surface runoff. Additionally, pollutants are removed from the stormwater via physical, chemical, and biological processes in the bioretention system. This paper suggests design principles for bioretention cells based on international literature and Norwegian experiences. The following topics are discussed: facility location, sizing, criteria for local soils and engineered bioretention media compositions, vegetation strategies, and maintenance. Bioretention cells have become popular in many parts of the world but are so far not implemented as a common practice in the Nordic countries. In order to make bioretention a more appealing practice in Nordic cities and communities this paper seeks to give guidance on how to design and build bioretention cells.

Key words – Bioretention, Biofilter, Raingarden, Stormwater, Cold Climate, Design, Infiltration, Saturated Hydraulic Conductivity, Low Impact Development, Sustainable Urban Drainage Systems

Sammendrag

Regnbed er et fleksibelt tiltak for lokal disponering av overvann. Anlegget fremstår som en beplantet forsenking i terrenget der vann lagres på overflaten og infiltrerer til grunnen eller videreføres til overvannsnettet. Gjennom fordrøyning og reduksjon av avrenningen hindres skadelig oversvømmelse. I tillegg vil fysiske, kjemiske og biologiske prosesser i regnbedet bidra til å tilbakeholde forurensninger fra overvannet. Denne artikkelen gjennomgår grunnprinsippene for utforming av regnbed basert på internasjonal litteratur og norske erfaringer: plassering av anlegg, beregning av størrelse, krav til stedegen jord eller innsetting av nytt filtermedium, prinsipper for valg av vegetasjon og vedlikehold. Regnbed er et meget populært tiltak i andre land, men er foreløpig lite benyttet i Norden. Denne artikkelen gir råd for utforming slik at regnbed-teknologien kan bli et attraktivt alternativ ved disponering av overvann i nordiske byer og tettsteder.

1 Introduction

A bioretention cell is a stormwater management practice where the surface runoff is managed locally. The main purpose of the bioretention cell is to retain surface runoff and to treat contaminated stormwater. A bioretention cell is designed as a terrestrial depression vegetated with a variety of species. The depression allows stormwater to be retained at the cell surface before it infiltrates through an underlying bioretention media layer. Figure 1 illustrates the general design principles of a bioretention cell. Cells are typically not transport paths for stormwa-



Figure 1. Principles of bioretention cell design. A drainage layer and a drain pipe are necessary in case the local soils are not well drained.

ter (in contrast to bioswales or swales) nor do they have a permanent water surface (in contrast to constructed wetlands).

Since the terms bioretention and raingarden first originated in Prince George County, Maryland, USA, in the early 1990s, bioretention has become a popular practice for stormwater management in the U.S, Canada and Australia (PGC, 1993). For example, there are cities in the U.S. and Australia that aim to build 10,000 raingardens (Melbourne Water Corporation, 2009, SPAWN, 2010). These ambitious goals relate to the practice's capacity to reduce peak flows, retain the water in urban areas, remove contaminants from stormwater, and its flexible design. The use of bioretention cells will additionally increase biodiversity, improve the aesthetic impression of an urban area, protect streams from erosion, recharge the groundwater, and last but not least, help to create a general public awareness for solution-orientated behavior. Furthermore, experiences from case studies in the U.S. show that bioretention cells can be more costeffective than conventional practices for stormwater management (PGC, 2007).

The use of bioretention cells, however, is also associated with some concerns. First, the practice demands a relatively large surface area compared to conventional stormwater management practices (e.g., pipes). Secondly, if the local soils are not well drained (e.g., clay soils), the cell must be drained using drain pipes and the existing soils must be completely replaced. Third, bioretention cells require maintenance. Finally, there are concerns about how the bioretention cell will function during cold conditions (e.g., low temperature, frozen bioretention media, inputs of road salts and abrasives).

This paper covers the design of bioretention cells for Nordic conditions. Our suggestions are based on the experience gained when designing, constructing, monitoring and conducting field tests on four pilot bioretention cells in Norway. Our recommendations also build upon design manuals from Minnesota, USA (MPCA, 2008), Wisconsin, USA (WDNR, 2010) Maryland, USA (PGC, 2007), and Melbourne, Australia (FAWB, 2009). The paper neither aims to be a complete comparison nor a final recommendation. Bioretention technology is a relatively new field in Nordic countries and we expect that the knowledge will increase in the future.

In addition to the hydrological benefits, it is important to note that the use of bioretention cells will also remove a wide range of contaminants from stormwater. Research related to the use of bioretention for the removal of stormwater contaminants under typical Nordic climate conditions has been conducted at the Luleå University of Technology, Sweden (Blecken et al., 2007, Blecken et al., 2011; Søberg et al., 2014), the Norwegian University of Science and Technology (Muthanna et al., 2007a; 2007b), and the University of Minnesota, USA (Paus et al., 2014c). This paper, however, focuses on the design of bioretention cells to manage stormwater on a hydrological basis and discusses the following topics: Conditions in the catchment area, facility location and sizing, bioretention media, vegetation, winter function, maintenance, and future research needs.

2 Pilot Bioretention Cells in Norway

Four pilot bioretention cells were built between 2006 and 2010 in Norway (Table 1 and Figure 2): Langmyrgrenda 34b (L34B) and Nils Bays vei 21 (NB21) in Oslo, Hammondsvei 8 (H8) in Melhus, and Risvollan borettslag (RIS) in Trondheim. The local soils in the cells designed with drain pipes were partly or completely replaced with an engineered bioretention media

Table 1. Descriptions of the four pilot bioretention cells in Norway (L34B, NB21, H8, and RIS). The design principles for each cell are shown in Figure 3.

Location	L34B	NB21	H8	RIS
Year constructed	2006	2009	2009	2010
Surface area [m ²]	5.9	10.3	5.1	40.0
Maximum ponding height, h_{max} [cr	n] 6.5	20	19	16
Media bed depth [cm]	Local soil	80	100	75
Media saturated hydraulic conductivity, K_{at} [cm/h] ^a	52.5	31.5	8.0	5.6
Media composition	Existing soil; moraine	50% sand, 45% compost (Oslo kompost ®) and 5% local topsoil	20 cm of loamy sand (top), local topsoil (middle), and sand (bottom)	70 % sand, 25 % leaf compost (Forseth Grus AS), and 5 % local topsoil
Clay	6%	6%	1 % / 16 % ^c	3%
Loam	20%	17%	12%/62% ^c	21%
Sand	74%	77%	87 % / 22 % ^c	75%
Organic matter	8 %	8%	Not measured	4%
Drain	Not drained	100 mm ^b	100 mm	2 x 100 mm
Drainage area type	Asphalt, gravel and lawn	Roof	Roof	Asphalt and grass
Drainage area [m ²]	291	139	107	8 300

^a Saturated hydraulic conductivity measured using MPD infiltrometers during the summer of 2012 (L34B, NB21, RIS) and synthetic runoff dosage during the summer of 2011 (H8). – ^b The drain pipe is partly blocked to allow a maximum discharge of 36 L/min. – ^c Topsoil and bottom soil / local topsoil.



Figure 2. The four pilot bioretention cells: L34B, NB21, H8, and RIS (Photo: B.C. Braskerud, R.A. Grande and A. Ekle).

(Figure 3). Descriptions of the bioretention cell performances are given in Dalen (2012) and Dalen et al. (2012) for RIS, and Saksæther and Kihlgren (2012), Braskerud et al. (2012) for L34B, NB21 and H8. Further descriptions of building and design of the cells are available in Braskerud et al. (2013).

3 Catchment Area

3.1 Catchment Area Size

Bioretention cells are typically suitable for small catchment areas. Based on design guidelines from the U.S., it is recommended that the catchment area should not be greater than 0.8 ha. Large catchment areas can result in high runoff discharge with increased risk of erosion and a permanent water surface in the cell, which increases the risk of mosquito breeding. Large catchments can typically be divided into smaller watersheds by building multiple cells. If the water supply is more continuous, other practices, such as constructed wetlands, are more suited (Braskerud, 2002).

3.2 Cell Location

Bioretention cells can be located along roads, streets, parking lots, dense urban areas, as a part of a park, in private gardens, in vicinity of new buildings, or refitted during rehabilitation projects. Mapping the topography and determining waterways are important when determining the location of the cell. As bioretention cells do not aim to manage rain events with a particularly high return period, it is essential to make a plan for where excessive or bypassed water will be conveyed. Bioretention cells should not be placed under the canopy of trees if this can inhibit vegetation growth.

3.3 Distance to Other Constructions

Bioretention cells must be located at a proper distance from basements to prevent water damage on constructions below ground. Recommendations from the U.S. are at least 8 m from basements and 1.5 m from building foundations (PGC, 2007). We do not have any specific recommendations on distance other than that infiltrated water must not damage below-ground structures. Controlling the movement of water below ground is usually possible when the bioretention cell is drained. Because the water can follow unknown systems of cracks, care should be taken when the cell is not drained (Figure 4).

3.4 Slope

It is recommended that the slope of the terrain in close proximity to the cell is not too steep (5%) (PGC, 2007). Steep slopes can result in high water velocity which increases the risk of erosion in the cell. In steep terrain, it is possible to build bioretention cells in terraces. In such cases, it is important to be aware that the vegetation will receive varying amounts of water, depending on the distance from the inlet. The cell surface should be fairly level to ensure an even distribution of water.

3.5 Ground Conditions

Infiltration characteristics in the local soils determine if the bioretention cell must be drained and/or if the local soil can be used as bioretention media. Clay soil is gener-



Figure 3. Design principles of the four pilot bioretention cells (L34B, NB21, H8, and RIS).



Figure 4. L34B is located near a garage. The infiltration rate in the surrounding soils is good.

ally unsuitable for infiltration and cells constructed on clay ground should always be drained. If the soil has a low clay content, infiltration capacity can be estimated using: 1) Infiltrometer, where water is supplied to a buried foam with a constant water height (Jensen, 1990), 2) drain test, where water is filled in a shallow excavated hole, and the time when water is no longer visible is recorded, and 3) Modified Philip-Dunne (MPD) infiltrometer, a method developed for measuring surface infiltration rates in stormwater best management practice. MPD infiltrometer tests are conducted quickly at multiple locations over the surface with a minimal equipment requirement (Braskerud et al., 2013).

3.6 Sources of Stormwater Pollutants

When constructing a bioretention cell the anticipated stormwater quality and possible sources of pollution in the catchment should be considered together with the quality of potential recipients. Bioretention cells are generally well suited to handle the first runoff after rainfall (i.e., first flush) and will typically retain a wide range of contaminants from the water (Muthanna, 2007; Davis et al., 2009; LeFevre et al., 2014). In Nordic countries, bioretention cells are likely associated with areas where road salt (i.e., NaCl) is used. NaCl can cause previously retained metals to be released from the bioretention media (Paus et al., 2014c; Søberg et al., 2014) potentially also impair vegetation (Amundsen et al., 2008) and change the soil structure resulting in reduced infiltration capacity (Amrhein et al., 1992; Kakuturu and Clark, 2012).

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4 Sizing Bioretention Cells

Norwegian Water BA (Norsk vann BA) recommends the use of a three-part-strategy for stormwater management (Lindholm et al., 2008): 1) collect and infiltrate runoff from small rain events, 2) retain runoff from moderate rain events, and 3) ensure safe conveyance of runoff from large events. This strategy is getting widely accepted in Norway. The amount of precipitation (in terms of mm), and the storm duration (in terms of hours) that define the three scenarios must be decided locally. Bioretention cells are typically suited to manage stormwater from no. 1 and 2 of the three-part-strategy.

4.1 Bioretention Surface Area

Bioretention guidelines recommend that the bioretention cell area should be between 5 and 10% of the size of the catchment area (MPCA, 2008). This ratio is considered somewhat conservative and in some cases it may be desirable to design the cell with respect to specific requirements, for example values for precipitation amounts and storm durations in the three-part strategy. By assuming that the precipitation falls at a relatively constant intensity over a given duration, it is possible to make the following consideration: The total water volume a cell can manage is equal to the sum of water volumes that can be (1) stored on the surface and (2) infiltrated during the storm duration. We suggest that this relationship can be used to determine the necessary cell surface area according to Equation 1:

$$A_{bio} = \frac{A \cdot c \cdot P}{h_{max} + K_{sat} \cdot t_r} \tag{1}$$

where A_{bio} is the bioretention cell surface area [m²], A is the size of the catchment area [m²], c is the average runoff coefficient of the catchment area [-], P is the amount of precipitation that the cell must be able to manage [m], h_{max} is the maximum water level at the cell surface [m], K_{sat} is the saturated hydraulic conductivity of the bioretention media [m/h], and t_r is the duration of stormwater flow into the cell [h].

In small watersheds, the time lag between the rainfall and the runoff is typically small. Hence, the t_r value can be assumed to be equal to the rainfall duration. Using Equation 1 one can calculate the bioretention cell surface area given values of P and t_r determined from the three-part strategy. Also other requirements for retention (e.g., 100% management of a rainfall with a specific return period) can be used as a basis for choosing the P and t_r values.

The h_{max} value is particularly important for the cell's capacity to manage runoff from rainfall with a high intensity, and also in cases where infiltration capacity is reduced by frozen bioretention media and/or ice covering the cell surface. For example, the NB21 site was functioning well during winter due to a high h_{max} value (Braskerud et al., 2012). Typically, the h_{max} value is between 15 to 30 cm. Bioretention media saturated hydraulic conductivity (K_{sat}) is a measure of the hydraulic capacity of the cell and will affect the cell's ability to remove the surface water before the next rainfall event, and also the management of long lasting precipitation events with low intensity. When selecting the K_{sat} value, previously reported values from field bioretention cells can be used (e.g. Table 1).

A conservative approach often used to size the bioretention cell is to disregard the contribution of infiltration in Equation 1 (i.e., $K_{sat} \cdot t_r$). In this case, the required surface area is determined from the surface storage volume (h_{max}) alone. In dense urban areas, where there is competition for space, it is possible to use equation 1 to size a smaller bioretention cell than would be the case using the conservative approach. For example, if a cell is to be sized for a rainfall of 20 mm (0.02 m) that falls with a constant intensity for two hours, and given other characteristics ($h_{max} = 0.20$ m, $K_{sat} = 0.10$ m/h and c = 1), the ratio between the cell surface area and the catchment area (A_{bio}/A) is 5% using Equation 1. By ignoring the contribution of infiltration, the A_{bio}/A ratio will be 10%. However, this cell will be able to capture all runoff regardless of the rainfall duration. All bioretention cells will in general help reduce runoff regardless of their size. Hence, also cells with a low A_{bio}/A ratio will have an effect on the management of stormwater runoff. In cases where there is a need to determine the hydrologic performance of bioretention cell in more detail, this is possible by using free design software such as RECARGA (WDNR, 2012).

5 Designing Bioretention Cells

One of the main reasons why bioretention cells have become popular in the United States is their aesthetic appeal, if such considerations are included in their design and construction. Use of landscape architects can therefore be beneficial in terms of cell location in the catchment area, geometric shape, and plant selection.

5.1 Inlet

The velocity of the water flowing into the bioretention cell should be as small as possible to avoid erosion. This can be achieved by using stone blocks at the inlet to dissipate energy (Figure 4). Stones will often also be a decorative element in the inlet structure of bioretention cells. If the water enters the cell from pipes, a slab of slate can be placed at the inlet to prevent erosion (Figure 5). In our pilot bioretention cells we used slate slabs with good results. In regions with cold climates, bioretention cells can be operated in areas where large amounts of sand and gravel are used as abrasives during winter. High particle transport into the bioretention cell can result in clogged bioretention media over time. To reduce the risk of clogging and ease the maintenance, it is recommended to build a small sedimentation basin at the cell inlet. The same effect may be achieved by constructing swales or filter strips that direct the water from the catchment area into the cell. Both of these solutions have been used at the RIS site where a 20 m long grassed swale directs the water into a sedimentation basin of 1 m² before the water reaches the bioretention surface (Figure 9).

5.2 Outlet

In some bioretention cells the inlet also functions as an outlet. Alternatively, the drain pipe can be used as an overflow weir. At NB21, the perforated top lid of the drain pipe is placed 15 cm above the surface and functions as an overflow weir in cases of heavy precipitation events or when ice covers the bioretention surface (Figure 5). As for the inlet, also the outlet must be protected against erosion. If the outlet is placed at a large distance from the inlet, this will increase the retention time of the water and thereby promote sedimentation of particulate matter in the water. In case of cell overflow (i.e., the inflow volume excess the volume that can be managed via surface storage and infiltration), safe flood routes or areas that can withstand excess water must be planned (cf. the three-part strategy).



Figure 5. Bioretention cell before vegetation is established (NB21). Slate slabs are placed at the inlet and outlet to prevent erosion. Note the (short) drainage pipe to the right, which serves as an overflow weir (see Figure 8). The two pipes to the left are for loggers.

6 Engineered Bioretention Media

The engineered bioretention media is an important part of the bioretention cell. The properties of the bioretention media affect the cell's capacity to infiltrate water, retain moisture in dry periods, conditions for vegetation growth, and remove contaminants from the water. With respect to the hydrological function of the bioretention cell, there are two factors that are important for the composition of the bioretention media. First, it must have a sufficiently high infiltration capacity or permeability to be able to manage runoff effectively. Second, it must have a sufficiently high organic matter content to facilitate vegetation and microbial activity. As shown in Table 1, various combinations and stratification of the bioretention media were tested in the pilot bioretention cells. The bioretention media in RIS and NB21 are classified as loamy sand, while the media at L34B is classified as sandy loam according to the USDA triangle.

6.1 Composition

If the ground is well drained and has a high infiltration capacity (e.g., > 10 cm/h) the existing soil may be used as bioretention media (i.e., L34B). Where the ground has a low infiltration capacity, it may be necessary to replace the existing soils with an engineered bioretention media and install drain pipes (Figure 6). The engineered bioretention media must have a sufficiently high organic matter content to promote vegetation growth as well as a high infiltration capacity. Bioretention guidelines from Wisconsin and Minnesota recommend using a mix of 50 to 85% sand and 15 to 50% leaf compost by volume (MPCA, 2008; WDNR, 2010). The infiltration capacity of the media will generally increase with increasing amounts of sand (Paus et al., 2014a). Addition of topsoil to the bioretention media may also be possible even where the infiltration capacity of the existing soils is low. In this case, the topsoil should be of good quality (e.g., presence of aggregates and earthworms) and be homogeneously mixed into the bioretention media. Native topsoil was added to the bioretention media at the RIS site. The mixing, however, was difficult as the topsoil contained clay of low quality and became lumpy. At NB21 however, 5% lawn topsoil of clay with good quality was



Figure 6. Because the bioretention cell at H8 was excavated and filled manually, only part of the media was replaced. (Photo: R.A. Grande).

successfully mixed homogenously into the engineered bioretention media. The possibility of using local topsoil should always be assessed, as this will help reduce costs.

6.2 Infiltration Capacity

In the United States, the recommended infiltration capacity (Ksat) of the bioretention media is typically 2.54 cm/h. This value may seem too low for our conditions. Because K_{sat} is not only a function of the permeability of the bioretention media, but also of water density and viscosity, K_{sat} will decrease with decreasing temperature. By using the relationship between permeability and K_{sat} (Hillel, 1998), together with table values for water density and viscosity at various temperatures (Crowe et al., 2005), one can calculate that a K_{sat} measured at 22.5°C will be reduced by 25% at 12°C, and further 50 % at 0°C. Hence, K_{sat} values under field conditions can be much lower than those measured at room temperature. At RIS, the temperature 5 cm below the surface, during the period when the bulk of the precipitation is expected (i.e., September and October), was below 10°C for about two-thirds of the time, and lower than 5°C about one-fifth of the time. To prevent temperature from constraining the infiltration capacity of a bioretention cell, we recommend that the bioretention media should have a K_{sat} value of at least 10 cm/h (i.e., at 25°C). This value coincides with recommendations from Australia (FAWB, 2009), and should provide sufficiently rapid drainage of the bioretention cell throughout the year. Measurements from L34B and NB21 (Table 1) indicate that the bioretention media can have a K_{sat} value far higher than the minimum of 10 cm/h, while simultaneously having vegetation well established.

Based on our experience, it is challenging to recommend a specific composition of clay, silt and sand that result in a sufficiently large K_{sat} value. For example, the bioretention media at RIS has the lowest content of clay, but the K_{sat} values are still about one-tenth of the K_{sat} values for L34B and NB21. Based on results from infiltration tests conducted in bioretention cells in the U.S. (Paus et al., 2014b), it seems that when vegetation is well established in the cell, infiltration is also good. Plant roots and the biological processes that takes place around the roots may provide a more porous soil than soil without plants (Rachman et al., 2004). A positive relationship between vegetation and the K_{sat} value also seems to correspond with our experiences of the Norwegian bioretention cells; the cells L34B and NB21 are older and have higher plant densities than RIS has. Our recommendation is therefore: The infiltration capacity of the bioretention cell will be sufficient if (1) the bioretention media is dominated by sand, (2) the establishment of vegetation is emphasized, and (3) compaction of the bioretention media is prevented (see chapter 7).

6.3 Freezing

To what extent a frozen bioretention cell is able to manage runoff depends on the type of frost formed in the bioretention media. A porous type of frost is formed when the media has a low water content at time of freezing, while a concrete type of frost is formed when the media is saturated at time of freezing. In porous frost, pores are filled with air and infiltration is possible even at freezing temperatures. In concrete frost, infiltration is not possible and only the surface storage volume (i.e., h_{max} multiplied with A_{bio}) is available for water management. To promote the formation of porous frost, the bioretention cell should be sufficiently drained before the water freezes. Hence, this further supports the importance of having a high infiltration capacity of the bioretention media in cold climates. However, even with a high infiltration capacity, a layer of ice is likely to form when the cell is covered with snow for a long time. This is due to the freeze and thaw processes occurring near the surface (French and Binley, 2004). Shifts from porous to concrete frost during winter have been observed at sites L34B, RIS and NB21.

7 Layering of the Bioretention Media

7.1 Complete or Partial Replacement When existing soils do not have the recommended infil-

when existing sons do not have the recommended mintration capacity, the soils need to be either partially or completely replaced. By partial replacement of the soils, only a broad trench for placement of drain pipes is needed. Partial replacement is applicable to large facilities were costs must be reduced, and/or where an excavator cannot access the site (e.g., the site at H8 was dug out manually using a shovel; Figure 6). If one uses an excavator for the construction of a small cell (e.g., NB21), complete replacement of the soil is not likely to give significant additional costs. The low K_{sat} value of H8 is likely due to the light clay loam texture of the native soils, which were refilled over the drainage layer of sand (Table 1 and Figure 3). In case of partial replacement, a media without clay should be used to refill the trench.

7.2 Media Depth

The optimal bioretention media depth depends on ground conditions, the expected depths of roots, and the purpose of the cell. Guidelines recommend depths of 40 to 80 cm. The media depth together with h_{max} and the effective porosity of the bioretention media determine the water volume that at any given time can be retained in the bioretention cell (Equation 1). The bioretention media at sites NB21, H8 and RIS, constitute about half

of the cells' total retention capacity. However, efficient retention of water in the pore volume below the surface requires a sufficiently high K_{sat} value.

7.3 Layering

As shown in Figure 1, the bioretention media typically has an underlying drainage layer with depth > 30 cm. The drainage layer consists of well-sorted coarse material to prevent clogging of the drain pipe. The bioretention media layer and drainage layer may be separated by geotextiles (e.g., H8 and NB21), but it is uncertain whether this is required when grain sizes are relatively uniform. Bioretention design manuals recommend that the bioretention media layer and the drainage layer are horizontally stratified. Although this may be convenient when constructing a cell, a horizontal stratification can be vulnerable if the properties of the bioretention media are not optimal. For example, at RIS, where the same media was used in the entire depth (Figure 3), the low K_{sat} value limits hydraulic performance (Table 1). An alternative to a horizontal stratification is to slope the drainage layer so a part of it is visible at the surface of the cell (e.g., NB21; Figure 3). Such layering can ensure adequate hydraulic capacity in the cell even if the K_{sat} value in the bioretention media is low. Based on observations from site NB21, the growth conditions may be poor where the drainage layer goes up the surface. It is therefore recommended that the drainage layer goes up to the surface in the middle of the cell when a sloped stratification is applied.

During the mixing and layering of the bioretention media it is very important to prevent compaction of the media. This is because compaction can have dramatic effects on permeability, and thus the infiltration capacity of the bioretention media. Compaction of the media was carried out to ensure an even surface during the construction of RIS. The compaction of the media is probably the predominant factor causing the low K_{sat} value. The weight of people during construction, snow and water is likely to even out the surface of the bioretention cell over time.

8 Drainage

8.1 Drain Pipes

The installation of drain pipes is necessary in case the local soils do not have a sufficient infiltration capacity. It is recommended to use one or more perforated drain pipes with a minimum diameter of 100 mm. The slope of the drain pipe should be such that standing water will not freeze during winter. In our pilot cells, we have used perforated drain pipes with a diameter of 100 mm. To obtain control of the effluent discharge (e.g., if a maxi-

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Figure 7. The end of the drain pipe at NB21. The pipe is partly blocked to allow a maximum of 36 L/min to be conveyed to the municipal storm sewer system.

mum discharge is allowed to be conveyed to the municipal storm sewer system), it is possible to partly block the drain pipe or use a smaller diameter at the end of the pipe (Figure 7).

8.2 Assisted Infiltration Using Drain Pipes

The water flowing into the cell during extreme rain events may exceed the hydraulic capacity of the cell. This may result in a situation where the cell overflows before the below-surface storage volume (*i.e.*, media pores) is utilized. To promote the utilization of bioretention media pore volume at all depths, it is possible to direct the excess water into the drain pipe via a vertical perforated pipe. Such a design approach was used at site NB21, where the top of the drain pipe (i.e., perforated lid; Figure 8) was placed 5 cm below the outflow weir.



Figure 8. The perforated lid on the drain pipe located on the surface of NB21.

The first meter of the vertical drain pipe was without slots. During winter operation, when the surface was covered with a 5 cm thick ice layer, the design was observed to effectively saturate the bioretention media from within, hence providing extra capacity (Braskerud et al., 2012). An additional benefit of this design is that the drain pipes are easily accessed and maintained.

9 Vegetation

9.1 Planting Strategies

In principle there are two possible planting strategies. First, a traditional park design strategy using ornamental plants and garden plants which require maintenance. Secondly, a natural design using local vegetation that is adapted to local conditions and climate, and which typically requires minimal maintenance. In our pilot bioretention cells the use of ornamental plants was chosen to increase the aesthetic values of the local environments (Figure 9).

9.2 Plant Species

Species that are suitable for use in bioretention cells must tolerate alternating wet and dry conditions. These species are typically between those that thrive in a wetland environment, and those which require more dry conditions. The selected plant species must be adapted to the local climate zone, and the use of local species is generally recommended. Overall, the options are many and suggestions on planting plans and species are available (Shaw and Schmidt, 2003, Wallace, 2009). Based on the experiences from our pilot cells we recommend perennial species. Traditional wetland species (e.g., *Typha*) did not get sufficient moisture and they are thus not so suitable for use in bioretention cells.

9.3 Establishment and Maintenance of Vegetation

During and in the first years after construction, it is important to ensure that the vegetation gets well established and covers the bioretention cell surface as soon as possible. Irrigation during the first years may be required during drought. U.S. design manuals state that fertilization is unnecessary because the runoff from developed areas is likely to contain sufficient amount of nutrients. Adding fertilizers during the first period may, however, be necessary to establish vegetation in case the runoff has a particular low content of nutrients (e.g., roof water). In such case, we recommend that the addition of fertilizer is distributed over the growing season in several small doses hence ensuring the best utilization by plants. In general, the use of fertilizers should always be at a minimum to prevent the potential eutrophication and impairment of downstream water bodies.

Further maintenance of vegetation consists of irrigation during dry periods and mechanical weed control. When the desired vegetation is well established, there will be less space and light for weeds and thus less maintenance. We observed this at L34B where relatively tall species are used. In L34B we also observed that species with a robust stem (e.g., *Iris pseudacorus*) form holes in the ice during spring and thus promote infiltration through the ice layer. The stems should therefore not be cut lower than approximately 5 - 10 cm when biomass is removed during fall.



Figure 9. The bioretention cell at RIS contains a variety of plant species adapted to the local climate (photo: A. Ekle).

9.4 Covering

U.S. design guidelines commonly recommend to apply organic mulch as a top layer on the bioretention cell surface. The mulch layer will improve the retention of soil moisture, prevent weeds from germinating, and make the bioretention cell more aesthetically appealing in periods when vegetation does not cover the surface. The mulch must however occasionally be replenished, thus more maintenance is required when using a mulch layer. In addition, large quantities of water can easily redistribute the mulch. On NB21 we added compost on the surface instead of mulch shortly after construction. As the bioretention cell is relatively small, weeds have not been a challenge and compost has thus not been refilled.

10 Research Needs

Although the current international experiences with bioretention cells are good, this is a relatively new technology in the Nordic countries. Based on our knowledge, we propose the following topics for further research on bioretention technology for Nordic conditions:

- What criteria for the composition of bioretention media should be set to ensure both adequate infiltration capacity and vegetation growth?
- Are geotextiles needed for mass separation when both the bioretention media and the drainage layers are dominated by sand? Will geotextiles reduce infiltration and root development?
- How can costs be reduced when vegetation is established in new bioretention cells?
- Can cell design, choice of plant species, operation and maintenance help reduce the formation and consequences of ice at the bioretention cell surface?
- How is the long-term infiltration capacity affected by the influx of sand and gravel used as abrasives, and road salt used for deicing?
- Will vegetation prevent the negative effects of clogging and reduced infiltration capacity over time?
- How do the effectiveness, costs, maintenance, and social acceptance of bioretention cells compare with other stormwater management practices? How can the cost-effectiveness of bioretention cells be increased?

11 Conclusions

On the basis of this review, the following check list is suggested for bioretention cell design and construction for Nordic conditions:

 Map waterways to find suitable locations. Ensure sufficient distance to buildings and below-ground structures.

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- 2. Determine the size of the catchment area and estimate an average runoff coefficient. Choose a design rainfall event (amount and duration).
- Determine the maximum water level above the surface, assume a value of saturated hydraulic conductivity and calculate the bioretention cell surface area.
- 4. Determine if the local soils have sufficient infiltration capacity. If not, the local soils should be replaced by an engineered bioretention media and drain pipes should be installed.
- Apply a bioretention media with sufficient infiltration capacity in order to promote adequate stormwater management year-around. Consider if the drainage layer and/or the drain pipe should be in contact with surface.
- Choose a surface area shape that promotes water to be distributed evenly over the surface. Consider if pretreatment is necessary.
- 7. Decide on a planting strategy. Use plant species adapted to the local climate.
- 8. Ensure that vegetation is well established. Consider watering, weeding, and the possible use of fertilizers.
- 9. Maintain the bioretention cell as needed.

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References

- Amrhein, C., Strong, J.E. and Mosher, P.A. (1992) Effect of Deicing Salts on Metal and Organic Matter Mobilization in Roadside Soils. Environmental Science & Technology, 26 (4), 703–709.
- Amundsen, C.E., French, H., Haaland, S., Pedersen, P.A., Riise, G. and Roseth, R. (2008) Salt SMART – Miljøkonsekvenser ved salting av veger – en litteraturgjennomgang, Statens Vegvesen rapport 2535.
- Blecken, G.-T., Marsalek, J. and Viklander, M. (2011) Laboratory Study of Stormwater Biofiltration in Low Temperatures: Total and Dissolved Metal Removals and Fates. Water, Air, and Soil Pollution, 219 (1–4), 303–317.

- Blecken, G.-T., Zinger, Y., Muthanna, T., Deletic, A., Fletcher, T. and Viklander, M. (2007) The Influence of Temperature on Nutrient Treatment Efficiency in Stormwater Biofilter Systems. Water Science and Technology, 56 (10), 83–91.
- Braskerud, B.C. (2002) Fangdammer/konstruerte våtmarker som et tiltak i restaurering av vassdrag. Vann, 3, 256–259.
- Braskerud, B.C., Kihlgren, K.S., Saksæther, V. and Bjerkholt, J.T. (2012) Hydrologisk testing av regnbed for bruk som LOD-tiltak i småhusbebyggelse. Vann, 4 (47), 490–503.
- Braskerud, B.C., Paus, K.H. and Ekle, A. (2013) Constructing Raingardens. Photographies of 4 constructed raingardens (In Norwegian with extended English summary), NVE rapport nr. 3/2013.
- Crowe, C.T., Elger, D.F. and Roberson, J. A. (2005) Engineering Fluid Mechanics. John Wiley & Sons, (8th edition),
- Dalen, T. (2012) Hydrologisk dimensjonering av regnbed i kaldt klima. Masteroppgave, NTNU.
- Davis, A.P., Hunt, W.F., Traver, R.G. and Clar, M. (2009) Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering, 135 (3), 109–117.
- Facility for Advancing Water Biofiltration (FAWB) (2009) Stormwater Bioinfiltration Systems. Adorption Guidelines. Melbourne, Australia.
- French, H. and Binley, A. (2004) Snowmelt Infiltration: Monitoring Temporal and Spatial Variability using Time-lapse Electrical Resistivity. Journal of Hydrology, 297 (1–4), 174–186.
- Hillel, D. (1998) Environmental Soil Physics. Academic Press, San Diego, USA.
- Jensen, P.D. (1990) Methods for Measuring the Saturated Hydraulic Conductivity of Tills. Nordic Hydrology, 21 (2), 95–106.
- Kakuturu, S. and Clark, S.E. (2012) Impacts of Deicing Salts on Soil Structure and Infiltration Rate. 9th Urban Watershed Management Symposium, Albuquerque, New Mexico, USA. May 20–24, 2012.
- LeFevre, G., Paus, K., Natarajan, P., Gulliver, J., Novak, P., and Hozalski, R. (2014) Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. Journal of Environmental Engineering, (in press)
- Lindholm, O., Endresen, S., Thorolfsson, S., Sægrov, S., Jakobsen, G. and Aaby, L. (2008) Veiledning i klimatilpasset overvannshåndtering, Norsk Vann rapport, 162/2008.
- Melbourne Water Corporation (2009). Healthy Waterways Raingardens. Be part of building 10,000 raingardens to help your local waterways., Melbourne Water's 10,000 Raingardens Program, Melbourne, Australia.
- Minnesota Pollution Control Agency (MPCA) (2008) Minnesota Stormwater Manual. St.Paul, Minnesota, USA. http://www.pca.state.mn.us/index.php/water/water-typesand-programs/stormwater/stormwater-management/minnesotas-stormwater-manual.html
- Muthanna, T.M. (2007) Bioretention as a Sustainable Stormwater Management Option in Cold Climate. Dr.gradsavhandling, NTNU.

- Muthanna, T.M., Viklander, M., Blecken, G. and Thorolfsson, S.T. (2007a) Snowmelt Pollutant Removal in Bioretention Areas. Water Research, 41 (18), 4061–4072.
- Muthanna, T.M., Viklander, M., Gjesdahl, N. and Thorolfsson, S.T. (2007b) Heavy Metal Removal in Cold Climate Bioretention. Water, Air, and Soil Pollution, 183 (1), 391– 402.
- Paus, K.H., Morgan, J., Gulliver, J.S. and Hozalski, R.M. (2014a) Effects of Bioretention Media Compost Volume Fraction on Toxic Metals Removal, Hydraulic Conductivity, and Phosphorous Release. Journal of Environmental Engineering, In press.
- Paus, K.H., Morgan, J., Gulliver, J.S., Leiknes, T. and Hozalski, R.M. (2014b) Assessment of the Hydraulic and Toxic Metal Removal Capacities of Bioretention Cells After 2 to 8 Years of Service. Water, Air, and Soil Pollution, 225 (1).
- Paus, K.H., Morgan, J., Gulliver, J.S., Leiknes, T. and Hozalski, R.M. (2014c) Effects of Temperature and NaCl on Toxic Metal Retention in Bioretention Media. Journal of Environmental Engineering, In press.
- Prince George's County (PGC) (1993) Design Manual for Use of Bioretention in Stormwater Management. Technical Report, Maryland, USA.
- Prince George's County (PGC) (2007) Bioretention Manual. Environmental Service Division. Department of Environmental Resources, Maryland. http://www.princegeorgescountymd.gov/Government/AgencyIndex/DER/ESG/Bioretention/pdf/Bioretention%20Manual_2009%20Version.pdf
- Rachman, A., Anderson, S.H., Gantzer, C.J. and Thompson, A.L. (2004) Influence of stiff-stemmed grass hedge systems on infiltration. Soil Science Society of America Journal, 68 (6), 2000–2006.
- Saksæther, V. and Kihlgren, K.S. (2012) Regnbed som tiltak for overvannshåndtering i småhusbebyggelse. M.Sc. Thesis, Institutt for matematiske realfag og teknologi, Universitet for miljø- og biovitenskap.
- Shaw, D. and Schmidt, R. (2003) Stormwater Design: Species Selection for the Upper Midwest, Minnesota Pollution Control Agency, St.Paul, Minnesota, USA.
- SPAWN (2010) 10,000 Rain Gardens Project 2010, Report to the Marin Municipal Water District, Salmon Protection and Watershed Network.
- Søberg, L., Blecken, G.-T. and Viklander, M. (2014) The influence of temperature and salt on metal and sediment removal in stormwater biofilters. Water Science and Technology, 69 (11), 2295–2304.
- Wallace, T. (2009) The Rain Garden Planner. Schiffer Publishing Ltd,
- Wisconsin Department of Natural Resources (WDNR) (2010). Conservation Practice Standard 1004: Bioretention for infiltration. Madison, Wisconsin, USA.
- Wisconsin Department of Natural Resources (WDNR) (2012) Recarga Model v. 2.3 – Infiltration Basins, Bioretention Devices. http://dnr.wi.gov/topic/stormwater/standards/recarga.html (01.01.2013).