Seasonal variations in infiltration in cold climate raingardens – a case study from Norway

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Summary

Winter infiltration in cold climate raingardens is a key function for proper year-round function. The Modified Phillip-Dunne Infiltrometers (MPD) procedure was used for measuring the infiltration capacity. The research was based on a case study approach, combining field measurements and simulations. The results were compared to results from the literature about raingardens in cold climates. Saturated hydraulic conductivity (K_{sat}) provides a measure of infiltration capacity and is recommended to be >10 cm/h in cold climate raingardens. The results show a seasonal variation in K_{sat}, from 1 cm/h (October) to 0.05 cm/h (November-April). Simulation of a raingarden in Trondheim, show a decrease in infiltrated inflow from 75 % to 25 % in the raingarden when K_{sat} goes from 1 cm/h to 0.05 cm/h. This paper presents a winter adaptation of the MPD-method.

Sammendrag

Sesongvariasjoner i infiltrasjon i regnbed i kaldt klima – en case studie fra Norge

Infiltrasjonsbaserte overvannsløsninger som regnbed er avhengige av tilstrekkelig infiltrasjonskapasitet. Høy infiltrasjonskapasitet er spesielt viktig for regnbed i kaldt klima, da vinterforhold byr på særlige utfordringer for deres funksjon. Denne studien har undersøkt variasjonen i et regnbeds vinterinfiltrasjon og dens påvirkning på design av regnbed i kaldt klima. Mettet hydraulisk konduktivitet (K_{sat}) er brukt som mål på infiltrasjonskapasitet og er anbefalt å være høyere enn 10 cm/t for regnbed i kaldt klima. Resultatene viser en sesong variasjon i K_{sat}, fra 1 cm/t (oktober) til ca. 0.05 cm/t (November-April). Simuleringer viser at andelen av vinter avrenningen som infiltreres/dreneres i et regnbed i Trondheim synker fra 75 % til 25 % når K_{sat} synker fra 1 cm/t til 0.05 cm/t. Det er i forbindelse med studien utviklet en vinter modifisert versjon av MPD-metoden.

Introduction

The use of raingardens for handling stormwater has recently become a popular stormwater management option in Norway. A lack of knowledge about design and practical experience in cold climates among consultants, architects and developers might explain this. A main concern for the performance of raingardens is their winter infiltration capacity, where only limited experimental data exists. A few research projects

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on raingardens located in Norway has been carried out (Dalen, 2012; Paus, 2016). Paus et al. (2015) evaluated the hydrological performance of three raingardens in Norway using saturated hydraulic conductivity (K_{sat}). Dalen (2012) carried out a similar research. Both Dalen (2012) and Paus et al. (2015) used a raingarden located at Risvollan, Trondheim.

The objective of this research was to document a raingarden's infiltration capacity in the winter months. The expectation is that these results on winter infiltration can help develop better standards for designing cold climate raingardens. The raingarden at the newly built Åsveien school in Trondheim was used for field observations.

The research questions:

1) How does winter conditions influence infiltration capacity in the raingarden?
2) What modifications to the MPD-method are necessary for measuring the K_{sat} of frozen winter soils?
3) What are the design implications of seasonal variations in infiltration capacity?

Theoretical framework – state of the art

Infiltration

The Three-step-strategy described by Lindholm et al. (2008), is a stepwise approach for handling stormwater. The first step focuses on infiltrating the runoff from small rain events. The next step being retaining and delaying water from medium to larger rain events. The last step being securing safe floodways for the excess runoff from large events, exceeding the design rain events. Raingardens are typically designed as part of step 1 and 2.

Pitt et al. (2008) found that compaction of the soil greatly reduced the steady-state infiltration rate. The K_{sat} value can be seen as a conservative minimum measure of the actual infiltration rate (Dingman, 2002; Paus, 2016).

According to Hillel (1971), the infiltration rate in the vertical direction is expected to settle down to a steady state driven by the earth's gravity and this is practically equal to the K_{sat}. Braga et al. (2007) observed a seasonal variation in the infiltration rate and based their study on a calibrated model and field measurements of an infiltration basin. They observed that the infiltration rate decreased with decreasing temperature.

Raingardens

Raingardens are vegetated depressions in the soil, to which stormwater is lead during rainfalls (figure 1). Raingardens typically consist of plants that tolerate wet and dry conditions (Paus & Braskerud, 2013). Typically, raingardens are designed to infiltrate and retain water before gradually releasing it into the stormwater network or receiving water. The capacity of raingardens depends mainly on infiltration capacity and storage area (Medina, D. & Pomeroy C., 2012). In urban area – where there often is limited surface area – the storage area can be the limiting factor for raingardens' capacity.

Paus and Braskerud (2013) suggest using Equation 1 for sizing of raingardens. The equation presents the relationship between the surface stored and infiltrated water in the raingarden.

$$A_{raingarden} = \frac{A \times c \times P}{h_{max} + (K_{sat} \times t_r)} \quad (1)$$

Where: $A_{raingarden}$ [m^2] is the surface area of the raingarden, P [m] is the design precipitation, A [m^2] is the area of the catchment, c [-] is the runoff coefficient of the catchment, h_{max} [m] is the maximum ponding depth, and t_r [h] is the duration of inflow into the raingarden.

Raingardens in cold climate

Measurements in the last years (1985-2014) has shown an increase in annual rain (4 %), autumn runoff (3%), winter runoff (6 %) and spring runoff (6 %) in Norway (Hanssen-Bauer et al., 2015). The temperature during winter has increased with 0.4 °C. Peel et al. (2007) has classified the climate in Trondheim as a cold climate without dry season, with cold summer.

Figure 1 Åsveien Raingarden during field measurements in October 2016.

Measuring infiltration with Modified Philip-Dunne Infiltrometers

The Modified Philip-Dunne Infiltrometers (MPD) was developed at the University of Minnesota, as a low water need simplified method for measuring infiltration capacity (Ahmed et al., 2014). It is a modified version of the Philip-Dunne borehole permeameter. The MPD-method carries out measurements of K_{sat} based on surface infiltration. Whereas the Philip-Dunne method is based on measurements of K_{sat} in a borehole. Both the MPD-method and the Philip-Dunne method is based on assumptions of the Green-Ampt model (Philip, 1993; Ahmed et al., 2014). Ahmed et al. (2014) presented both the MPD-method and procedures for calculating K_{sat}. Blom (2017) assessed different in-situ methods for measuring infiltration rate. Blom (2017) concluded that the MPD-method had the highest infiltration rate estimates.

Simulations of raingardens using the RECARGA model

The RECARGA model is an raingarden performance model developed by the University of Wisconsin-Madison (Dussaillant et al., 2005). The input it needs are precipitation data (mm per hour), the soils K_{sat}, raingarden design parameters and catchment data. Dalen et al. (2012a) used RECARGA to investigate the importance of a raingardens area as the percentage of the impervious catchment area.

Materials and methods

Field measurements of infiltration capacity

The raingarden at Åsvein school is located in a cold climate zone (Peel et al., 2007). The research on the raingardens performance was based on a case study approach (Yin, 2003), combining technical (field measurements), experimental (simulations) and qualitative approaches. A scoping literature review on cold climates infiltration based stormwater systems was carried out (Arksey & O`Malley, 2005), alongside a content analysis of drawings and technical specifications (Weber et al., 1990).

K_{sat} was measured with MPDs through the winter and spring 2016-17, (October- May). The MPDs were constructed of a plastic column of 50 cm length and approximately 10 cm inner diameter. The columns were inserted 5 cm in the soil and filled with water. The water level in the column was measured with regular intervals. The water level and time were recorded. For test with very low infiltration rates the tests were limited to approximately one hour due to practicalities. The soil mass water content, (θ) [gram water/gram undried soil], [%] before and after test, were obtained with soil samples taken during field test. Where the samples weight was measured before and after drying. The samples were dried in a stove for at least 48 hours at 105 ˚C. The K_{sat} values calculated with the Matlab code from Paus (2016) were compared with results from similar studies. The cold condition of the test site made measuring the change in θ further difficult than anticipated. When the increase in θ was calculated to be negative, due to ice content, the increase was set to 1 %.

Winter modifications on the MPD-method

The in-situ conditions of the research necessitated some modifications to the original methodological approach. Modifications on the MPDs rendered measurements on frozen ground impossible. A cast iron pipe (inner diameter 10 cm) was hammered down in the frozen soil. The cast iron pipe and the original MPD plastic column was connected with the help of an interior gasket. This modification of the MPD-method was developed with experimental testing through February and March 2017. The winter modified MPDs are further called Balstad Modified Philip-Dunne Infiltrometers (BMPD).

Figure 2 Picture of the Balstad Modified Philip-Dunne Infiltrometers (BMPD) column during field measurements in Mars 2016.

Simulations of seasonal variation in K_{sat}

To investigate the design implications of seasonal variations in infiltration capacity, simulations of a typical raingarden located in Trondheim was carried out in RECARGA. It was distinguished between winter and summer season. The winter season was defined as October 1st – April 31st. The summer season was defined as May 1st – September 30th. Precipitation data from Voll station in Trondheim was imported from Eklima (met.no) for the period October 1st 2012 to April 31st 2015. The data were manually divided into seasons as follows: Winter 2012/2013, Summer 2013, Winter 2013/2014, Summer 2014 and Winter 2014/2015. The raingarden was chosen to have a depression zone of 18 cm depth, a root layer of 60 cm loamy sand, a storage layer of 20 cm sand and an underlying native soil layer of clay. The model of the raingarden included an underdrain pipe with diameter of 100 mm. The size of the catchment was set to 10 000 m^2. The imperviousness of the catchment was set to 100 %. This results in a simulation independent of a catchments imperviousness and therefore usable for similar raingardens with different catchment imperviousness.

The ratio between the Raingardens area and the Impervious Catchment area (RIC ratio) was simulated for the following values: 0.5 %, 1%, 2%, 4%, 6% and 10%. The K_{sat} value of the root layer and storage layer were kept equal. The soils K_{sat} value was simulated for the following values: 0.05cm/h (winter only) 0.1 cm/h, 0.5 cm/h, 1.4 cm/h, 2.5 cm/h, 5 cm/h and 10 cm/h. The K_{sat} value of the native soil layer was set fixed to the programs standard for clay (0.18 cm/h).

This paper adds seasonality to Dalen (2012)'s procedure, as described above. Dalen (2012) investigated the percentage of the annual precipitation that the raingarden infiltrated, while the presented study in this paper distinguished between summer and winter season. Additionally a lower range of K_{sat} values were used, corresponding with presented field measurements of K_{sat} when simulating winter conditions.

Results and discussion

Field measurements of infiltration capacity

The results presented in this paper indicates large seasonal variations in infiltration capacity (Figure 3). The seasonal variations are larger than what were presented in previous studies (Figure 4) (Dalen, 2012; Paus et al., 2015). The mean K_{sat} value from the results of Paus et al. (2015), through the whole period of testing (36 months) was 5.0 ± 5.7 cm/h. The large standard deviation clearly indicates seasonal variations. It shows that the winter conditions (low temperature) negatively influences the saturated hydraulic conductivity (K_{sat}) by decreasing it. Therefore, also negatively influences the infiltration capacity in the raingarden.

The results from field measurements of K_{sat} is lower than the reported values from Dalen (2012) and Paus et al. (2015) (except for in October and May) (Figure 4). Paus et al. (2015) presented values of K_{sat} estimated from observed infiltration rate (OIR) including the months of November, March and April. As previous reported Paus et al. (2015) conducted this part of his study on the raingarden at Risvollan. Dissimilarities in the raingardens (degree of compaction, organic matter in the soil etc.) could be part of the explanation, or that the OIR method measures higher values than the MPD-method. However, this is contradictory to Paus et al. (2015) where it was concluded that the MPD-method measured higher values than the OIR method.

Paus (2016) hypothesized that K_{sat} would decrease with increasing change in soil mass water content, θ. However, results from field measurements of K_{sat}, showed that this relationship was often illogical and seemingly random. To further investigate this, it was created a Matlab code that looped the code presented by Paus

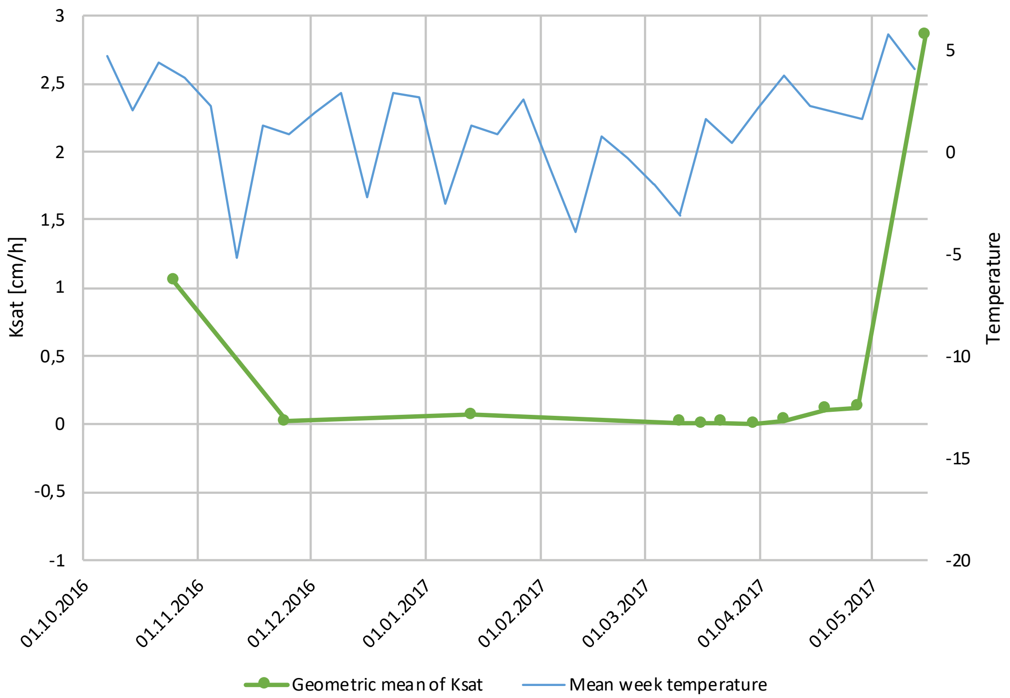

Figure 3 The variation in the geometric mean of the K_{sat} field measurements and temperature in the period of field measurements. The markers on "the geometric mean of K_{sat}" represents the geometric mean of every usable field measurement of K_{sat} on that specified day.

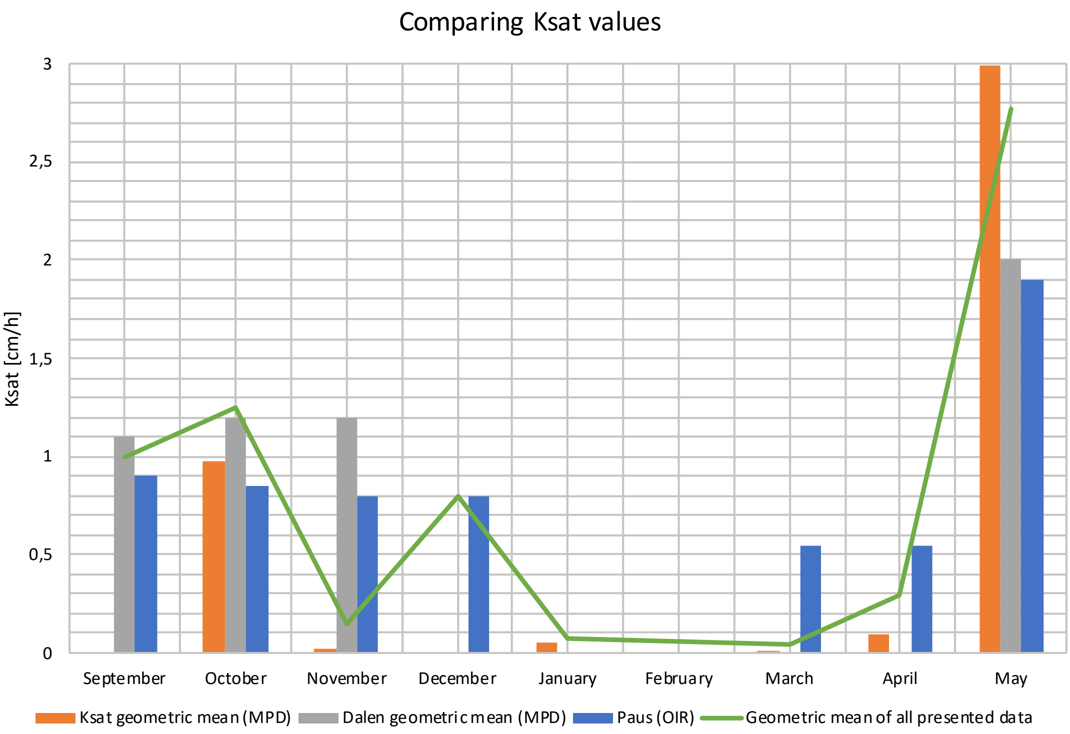

Figure 4 Comparison of this study's geometric mean K_{sat} field measurements with MPD against the geometric mean K_{sat} field measurements with MPD of Dalen (2012) and the mean K_{sat} values estimated by Paus et al. (2015) from observed infiltration rate (OIR).

(2016) with step-wise change in θ. This revealed that the calculated K_{sat} was dependent on the last recorded value of water level.

In measurements with last water level above zero, i.e. the field test was terminated before the column was empty, K_{sat} as function of change in θ was illogical. However, in measurements where the last water level equal to zero, the K_{sat} as function of change in θ was logical and in line with the hypothesis. As an adjustment field measurements with the last recorded water level above zero, were linearly extrapolated back to a zero level.

The results also showed that the K_{sat} value only depends on the change in θ if its maximum value, independent of change in θ is above 0.1 cm/hour. Below 0.1 cm/hour the change in θ have no real implication on the K_{sat} (Figure 5). This implies that under winter conditions with high frozen water content in the soil, it might not be necessary to measure change in soil mass water content.

Experience from winter modifying the MPD-method

Use of the MDP-method during periods with frozen soils showed to be challenging. Frozen soils had two main challenges; (1) Not possible to get the MDP tube inserted 5-cm into the soil due to a very hard frozen ground; (2) Difficult to avoid large air gaps around the tube inserted into the soil, which will result in water rapidly leaking laterally out of the tube. To overcome these challenges the modified MPD-method described in the "Winter Modifications to the MPD-method" was implemented. The modification proved to be an easy low cost modification. It was used successfully for field measurements in March.

The choice of gasket ended on an interval gasket, because the external gasket could not properly seal the joint between PVC column and cast iron pipe. However, the internal gasket have a smaller internal diameter (9 cm) than the PVC column and the cast iron pipe. This could

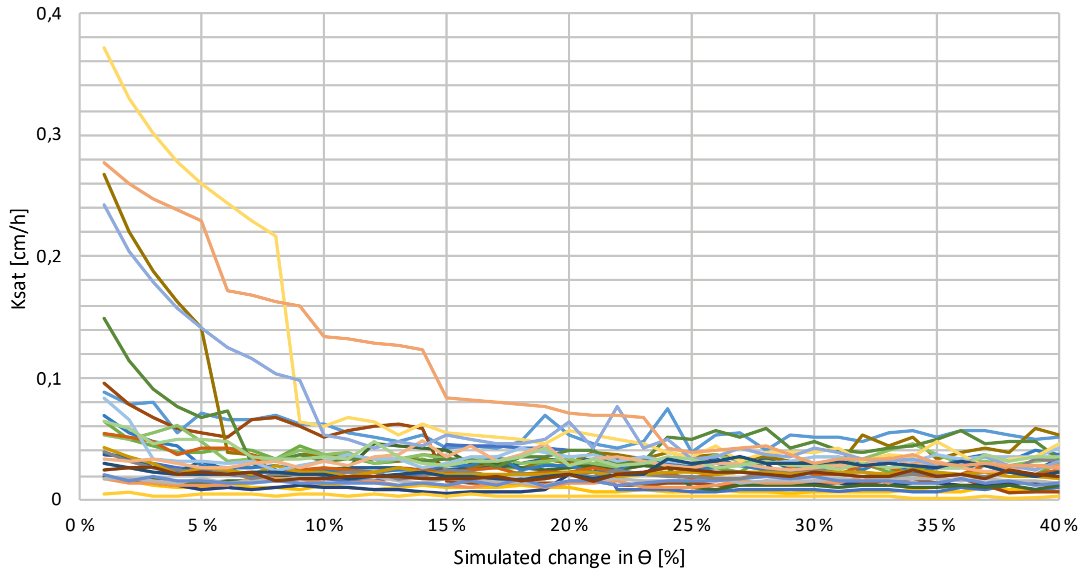

Figure 5 Simulated effect of increased change in mass water content (θ) during testing on field measurements of K_{sat} with theoretical highest K_{sat} above and below 0.1 cm/h.

have resulted in slightly lower K_{sat} then presented in this paper. However, this was assumed to be a very minor effect and not further accounted for in the results.

Simulations of the design implications of seasonal variations in K_{sat}

Figure 6 and 7 show the relationship between seasonal inflow infiltrated, RIC ratio and K_{sat}. The percentage of winter inflow infiltrated is the mean value from simulating the three winters. The percentage of summer inflow infiltrated is the mean value from simulating the two summers. The inflow infiltrated is defined as the sum of inflow infiltrated to nearby soils and inflow drained by underdrain pipe.

Data on evaporation and runoff from snowmelt were not used in the simulations. Evaporation is a negligible process in the winter season. However, it would increase the consumed water in the summer season, which would have resulted in increased % infiltrated. Nevertheless, it can be seen as a conservative summer estimate. Data on runoff from snowmelt could have resulted in a higher volume of inflow to the raingarden in the end of winter season and in the beginning of summer season (spring). It is unclear to what extent this would have reduce the values of percentage inflow infiltrated.

The results (Figure 6 & 7) show that the design implications of seasonal variations in a raingardens infiltration capacity (K_{sat}) are a reduction in its performance to infiltrate inflow during winter season. The RECARGA simulation showed that a raingarden similar to the Åsveien raingarden (2.8 % RIC ratio) might experience a change in its winter performance from 75 % to 25 %, when the K_{sat} value goes from 1 cm/h to 0.05 cm/h (Figure 6).

Conclusions

The results presented in this study clearly show that the low temperature during winter decreases the infiltration capacity (K_{sat}) in the raingarden. The infiltration capacity changed from 1 cm/h in October too close to 0.05 cm/h in November-April and up to 3 cm/h in May. This shows reduced infiltration during winter, with values much lower than the recommended level of 10 cm/h (Paus et al., 2015).

A winter modification to the MPD column was proposed to measure infiltration in frozen

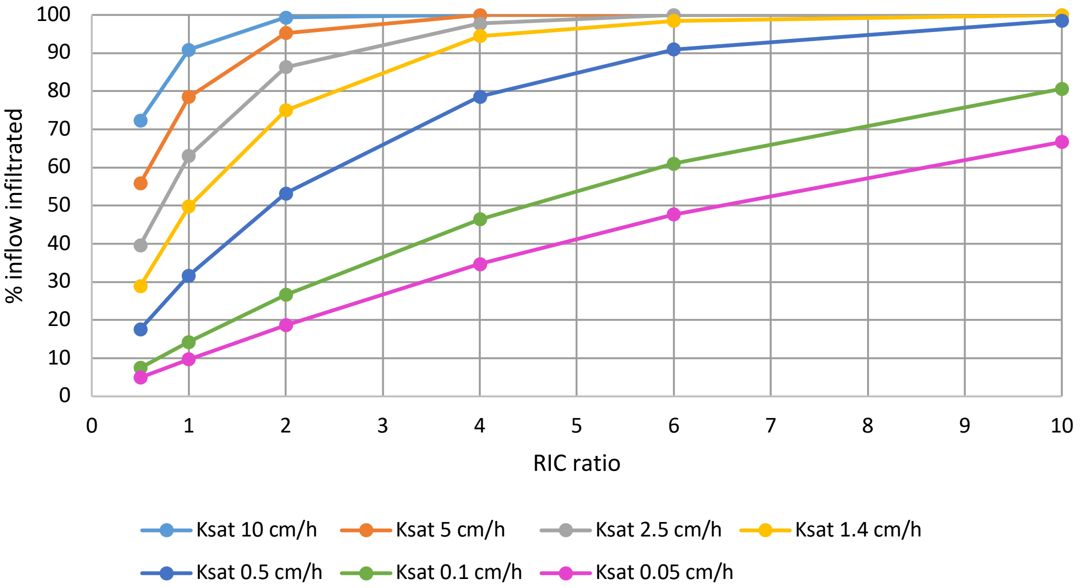

Figure 6. The effect of the raingardens infiltration capacity (Ksat) and the raingarden area to impervious catchment area (RIC) ratio on the percentage of winter season inflow infiltrated. The arrow shows change in percentage of winter season inflow infiltrated, when Ksat changes from 1 cm/h to 0.05 cm/h.

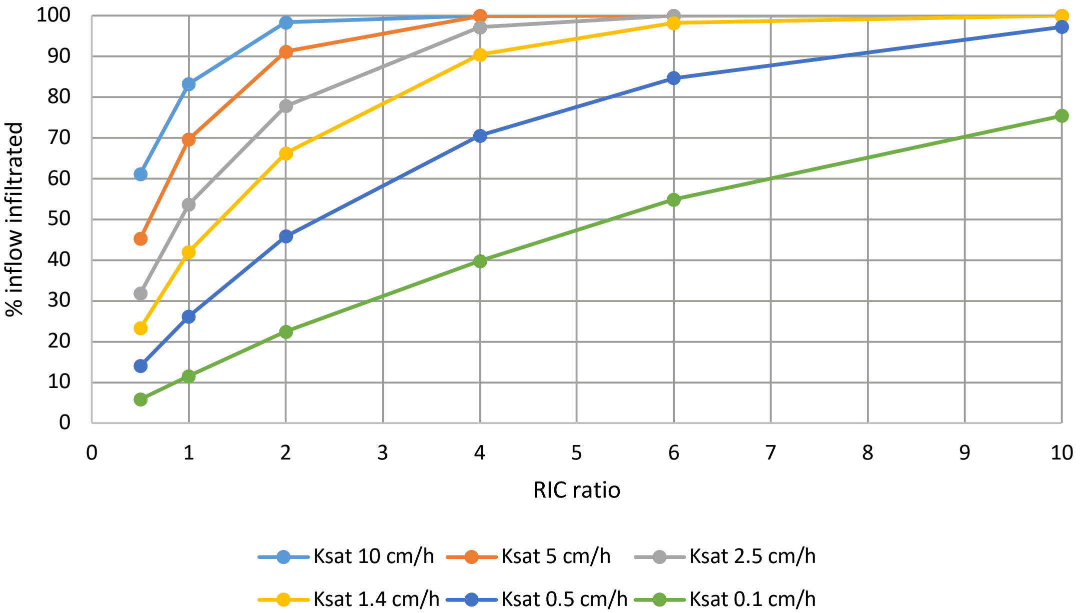

Figure 7. The effect of the raingardens infiltration capacity (Ksat) and the raingarden area impervious catchment area (RIC) ratio on the percentage of summer season inflow infiltrated.

soils. This new modification of the method is called Balstad modified Phillip-Dunne (BMPD).

The design implications of seasonal variations in a raingardens infiltration capacity is a performance reduction in the winter season. For a raingarden with a RIC ratio of 2.8 %, the percentage winter inflow infiltrated will decrease from 75 % to 25 % when the K_{sat} decrease from

1 cm/h to 0.05 cm/h. Winter infiltration should be part of the design guidelines to ensure year-round performance.

Few studies on raingardens in cold climates have been carried out. Of these, few have included full-scale tests on seasonal variation in infiltration capacity. This study add important knowledge, however additional research on the infiltration capacity of cold climate raingardens in winter months could further improve design and function of infiltration based stormwater management solutions.

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