Infiltration capacity in grass swales during frequent freeze-thaw cycles and intermittent snowmelt in a cold maritime climate

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Highlights

- Frost reduces soil porosity and infiltration capacity in grass swales.
- Intermittent snow and freeze-thaw cycles lead frost formation soil destabilization.
- Sparsely vegetated surfaces are prone to heave, cracks and deep frost formation

Introduction

The rapid increase in urbanization, along with the expected rise in temperatures and extreme rainfall events, has stressed the conventional urban drainage systems leading to more frequent and detrimental floods (Houston et al., 2011). In recent years, sustainable urban drainage systems (SuDS) have gained increasing popularity among planners as a low-impact, cost-effective approach to reduce runoff peaks and volumes (Caraco & Claytor, 1997). Despite the known advantages of using grass swales as stormwater control measures, their implementation and effectiveness are subject to local meteorological and pedological conditions. As infiltration-based systems, the performance of grass swales is dependent on their ability to infiltrate runoffs at a high rate. In cold climates, soil infiltration capacity is reduced due to low temperatures and soil frost formation (Paus et al., 2016). Depending on the extent and type of the formed frost, infiltration can be completely impeded, often referred to as concrete frost (Khan et al., 2012; Muthanna et al., 2008). Whereas porous or granular frost permits or enhances infiltration capacity. One of the complications associated with cold coastal regions, is the mid-winter snowmelts, rain-on-snow events, and freeze-thaw cycles experienced each winter (Andradóttir et al., 2021; Muthanna et al., 2008). Thus, the soil becomes more susceptible to frequent frost formation due to the increase in soil water content and the absence of the insulating snow cover. As such, frost type is highly dependent on the antecedent water content prior to the onset of freezing (Fach et al., 2011; Roseen et al., 2009). To determine the efficiency of SuDS under such cyclic frost conditions, the infiltration capacity of grass swales in a residential area as well as open undisturbed areas was evaluated over 28-month. To that end, synthetic runoff experiments, infiltration measurements, and long-term monitoring of soil moisture and temperature monitoring in a Gardabaer, Iceland.

Methodology

Site description

Urridaholt is the first BREEAM (Building Research Establishment's Environmental Assessment Method) certified neighborhood in Iceland. Sited on a hill in the Gardabaer municipality in the greater capital area. Grass swales are a part of a large network of SuDS elements designed to preserve the quality and level of a nearby shallow lake. The swales have been constructed using local material and without an underdrain. The undisturbed areas surrounding the swale have different vegetation covers (*Lupinus nootkatensis*, dwarf shrub heath, and barren areas).

Synthetic runoff experiments

Water was delivered from the tank into a smaller upstream reservoir equipped with a 45° V-notch weir using a submersible pump. The overflow from the inflow weir box was distributed evenly over the bottom channel of the swale (Figure 1; left). The runoff simulations were performed using constant inflow rates ranging from 0.65 to 4.2 l/s for 20-30 minutes. On each day, two to three experiments were conducted consecutively with a 30 to 45-minute resting period in between to allow for all water in the depressions to infiltrate. Details of the experimental setup are given in (Zaqout & Andradóttir, 2021).

Ring infiltrometers

A total of 12 single-ring infiltrometers have been installed in the study site (six in the swale, two in each of the other terrains i.e., lupine field, barren area, and heath). The rings were 22.5 cm in diameter and 40 cm in height and were gently hammered down to 15–17 cm depths perpendicular to the slope of the soil surface (Figure 1; centre). Constant head infiltration measurements were conducted once every three to four weeks (Zaqout et al., In preparation). The added volume was recorded every 5 minutes and each experiment was run for 45-60 minutes until the infiltration rate became constant for at least three iterations (15 minutes).

Soil moisture and temperature monitoring

The swale was equipped with five water content reflectometers that continuously measured volumetric water content and temperature installed at the middle of a swale section at depths of 5, 15, 25, 35, and 45 cm, placed horizontally from top to bottom; the top is located just below the 5 cm thick turf layer (Figure 1; right). Readings were logged using a data logger (Campbell Scientific Inc.) every 1 minute.

Figure 1. Synthetic runoff experiment in winter (left), infiltrometers in grass swale (center), and soil temperature and water content probes (right).

Results and discussion

A total of 63 synthetic runoff experiments were conducted from March 2019 to August 2020. During summer, the average peak flow reduction was 38%, which was significantly higher than spring and winter averages of 26 and 13%, respectively. The flow attenuation in the swale was highly dependent on the inflow rate used, decreasing with the increase in event intensity (correlation coefficient = -0.37). The average measured flow reduction for high flow (4.2 ± 0.3 l/s) in all seasons was 16% and 29% for low inflows (0.65 l/s). During winter, the swale's infiltration capacity was significantly reduced due to lower temperatures and frost formation. This can be attributed to the fact that pore ice was present, reducing the soil horizon's porosity and the swale infiltration capacity, reflected in the very low peak flow reduction measured (*Peak flow reduction* = 5%; a seasonal low). Nevertheless, infiltration to the deeper soil layers still occurred, indicating the presence of preferential flow paths or cracks that allows for water to short-circuit, which was indicated by the change in moisture content and soil temperature. It can also be explained by the formation of porous or granular frost as opposed to concrete frost that completely impedes infiltration (Muthanna et al., 2008). The repeated freeze-thaw cycles can also contribute to destabilizing soil aggregates and cause volume changes in the filtering media, permitting infiltration to occur despite frost presence (Flerchinger et al., 2013).

In total, 28 infiltration measurements campaigns were conducted. The results from the infiltration tests also suggested a reduction in infiltration capacity in all terrains during winter. In winter, the average infiltration rate in the swale was significantly lower compared with summer averages ($p < 0.05$). Infiltration during winter 2018/2019 dropped to half that of the antecedent summer in the bare ground (Fig. 2b) and the less densely vegetation cover lupine (Fig. 3c). In the heath location, however, infiltration doubled after the first winter and again at the beginning of the second, indicating porous frost formation and structural changes have occurred. During the following winter, characterized by intermittent snow and frequent freeze-thaw, infiltration inhibiting frost was formed in all terrains. The sites covered with the dense grass turf remained infiltrative during the freezing period. The sparsely vegetated areas exhibited both a reduction and a subsequent increase in infiltration around mid-winter in the lupine field (Fig. 3c), and late winter in the barren soil terrain (Fig. 3b). The high infiltration rates coincided with structural deformations observed at the surface.

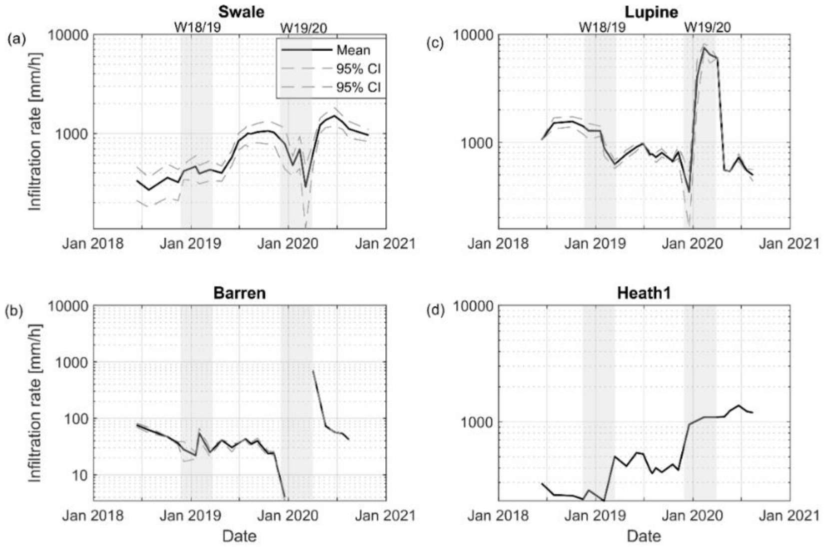

Figure 2. Averages and 95% confidence intervals of infiltration rates measured during the study period (summer 2018 - Fall 2020). a) Swale, b) lupine, c) barren, and d) heath location no. 1. Shaded area is the winter period.

Conclusions and future work

The reduction in infiltration capacity was intermittent, a characteristic of cold coastal regions experiencing multiple freeze-thaw cycles each winter, which was more prevalent in less vegetated surfaces than in the grass swale, leading to both the formation of infiltration inhibiting frost and structural deformation in the soil. The results indicate that bare grounds were more susceptible to increased flooding risk in urban areas, and therefore, sustainable urban development should aim to minimize non-vegetated or impermeable areas and promote the integration of green surfaces. In order to better understand frost formation processes, we aim to model soil moisture and heat transfer in grass swales which can provide more accurate estimations of their hydrologic performance in cold climatic regions.

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