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Pédogenèse des milieux de biorétention dans les bassins versants urbains du Midwest, aux États-Unis : comprendre l'évolution des sols pour guider l'entretien

Pedogenesis of bioretention media in urban watersheds of the Midwestern United States : Understanding soil evolution to guide maintenance

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RÉSUMÉ

Lorsque les cellules de biorétention filtrent le ruissellement des eaux pluviales, les polluants s'accumulent et modifient l'hydraulique du milieu du sol. Cette étude mesure l'accumulation de particules et de matière organique dans 50 cellules de biorétention (de moins d'un à 16 ans) dans le Midwest des États-Unis avec diverses utilisations contributives des terres. De plus, les effets de ces facteurs sur l'hydraulique des sols ont été quantifiés. Des essais d'infiltration de la tête tombante ont été effectués à trois endroits (entrée, milieu, sortie) dans chaque cellule de biorétention. L'échantillonnage de l'huile S a eu lieu à une profondeur (0-5 cm, 10-15 cm et 35-50 cm) à ces endroits et à l'avant-bassin, le cas échéant, pour un total de 553 échantillons. L'analyse granulométrique a été effectuée par tamisage humide (sables et graviers) et diffraction laser (limons et argiles); la teneur en matière organique a été mesurée par perte au feu. La taille des particules variait selon la profondeur et l'emplacement – des particules plus grosses à l'avant-bassin / entrée et des particules plus petites au milieu / à la sortie. Le taux moyen d'admission en surface était le plus faible à l'entrée (777,2 mm/h), suivi du milieu et de la sortie (825,5 et 1389,4 mm/h, respectivement). Les résultats préliminaires suggèrent que la matière organique de surface, l'utilisation des terres, la salinité et l'âge sont des facteurs importants dans la pédogenèse des milieux de biorétention du sol.

ABSTRACT

Bioretention cells are engineered stormwater controls designed to abate some of the harmful effects of urbanization; however, they require maintenance to ensure their hydraulic function. As bioretention cells filter stormwater runoff, pollutants collect and alter the hydraulics of the soil media. This study measures the accumulation of particulates and organic matter in 50 bioretention cells (from less than one- to 16-years-old) in the Midwestern United States with various contributing land uses. Further, the effects of these factors on soil hydraulics were quantified. Falling head infiltration tests were conducted at three locations (inlet, middle, outlet) in each bioretention cell. Soil sampling occurred with depth (0-5cm, 10-15cm, and 35-50cm) at these locations and at the forebay when applicable for a total of 553 samples. Particle size analysis was conducted using wet sieving (sands and gravels) and laser diffraction (silts and clays); organic matter content was measured by loss on ignition. Mean particle size varied with depth and location – larger particles at the forebay/inlet and smaller particles at the middle/outlet. Mean surface intake rate was lowest at the inlet (777.2 mm/hr), followed by the middle and outlet (825.5 and 1389.4 mm/hr, respectively). Preliminary findings suggest surface-level organic matter, land use, salinity, and age are important factors in bioretention soil media pedogenesis. Further data analysis will result in improved maintenance guidance for bioretention.

KEYWORDS

hydraulics, organic matter, particle size analysis, soil science, urban ecology, infiltration

1 INTRODUCTION

Sediment, organics, and other pollutants become incorporated into bioretention soil media (BSM) through adsorption, filtration, biological transformation, and sedimentation. This can cause the hydraulic conductivity of BSM to change, either through the formation of preferential flow paths, compaction, or changes in particle size distribution. Pedogenesis is the study of soil change over time; applying this concept to BSM is important because the development of distinct soil horizons may affect BRC hydraulics (Ayers & Kangas, 2018). Previous research has shown that sands and gravels trapped in BSM improve hydraulic conductivity; meanwhile, smaller particles and organics limit infiltration (Vijayaraghavan et al., 2021). Native soil type in the watersheds, high intensity rainfall, construction runoff, or unstable watersheds all may factor into potential clogging of bioretention filters. This process – known as siltation – alters the particle size distribution (PSD), and thereby the soil texture, of the surface-layer BSM (Ayers & Kangas, 2018). PSD is the most important physical property of BSM because it is directly related to bulk density, clogging potential, hydraulic conductivity, pore size, and other vital properties for BRC function (Tirpak et al., 2021).

Ayers & Kangas (2018) found that the fraction of fines increased with increasing BRC age, the uppermost BSM layers were enriched with organic matter, and biota (e.g., earthworms and other macroscopic invertebrates) play an important role in maintaining BRC functionality. Spraakman and Drake (2021) found that saturated hydraulic conductivity (K_{sat}) was only moderately negatively correlated with age, and where data existed on soil K_{sat} immediately after construction, K_{sat} improved for six out of nine sites. Wardynski & Hunt (2012) found that 71% of samples collected at 3 depths (0-5cm, 5-10cm, and 10-20cm) from 43 BRCs in North Carolina, USA with ≤ 10 years of service did not meet PSD specifications of the state design guidance, the percentage of fines in BSM had decreased in recent years with better design guidance, and that infiltration rates remained adequate despite the high percentages of fines.

Current standards recommend a design life of 20-25 years for BRCs (Spraakman & Drake, 2021). Since the oldest BRCs in the Midwestern USA are nearing this age, a retrospective analysis of the accumulation of particles and organic matter in BSM was performed to guide bioretention design and maintenance. The research objectives of this study are to 1) describe how highly organic BSM evolves with time and affects the hydraulics of BRCs with watersheds of varying land use and land cover, 2) determine qualitative and quantitative variables that explain the accumulation of fines and organic matter accumulation in BRCs, and 3) provide BRC design and maintenance recommendations.

2 METHODS

Sampling occurred in November 2019, November 2021, and March 2022 across 50 BRCs in Ohio, northern Kentucky, and Southern Michigan, USA. Some BRCs were visited twice for a total of 62 independent visits to BRCs. BRC ages ranged from less than one- to 16-years-old and contributing watershed areas ranged from residential to downtown (ultra-urban). Single ring (28-cm infiltrometer), falling head infiltration tests were conducted at three locations (inlet, middle, outlet) at each BRC. Soil sampling occurred with depth (0-5cm, 10-15cm, and 35-50cm; Figure 4) at the same locations and at the forebay when applicable for a total of 553 soil samples. 'Surface intake rate' is used to describe the rate of water entering the soil for the single ring, falling head infiltration test.

Oven-dried samples were passed through a 2-mm sieve to remove the gravel fraction. Samples were combusted in a muffle furnace at 550°C for 24-hours to burn off organic matter. Percent organic matter was checked against that measured using a Carbon analyzer. The remaining mineral fraction was passed through a #270 (53 μ m) sieve to determine the percent sand. The fines that passed through the sieve were further analyzed by laser diffraction (Faé et al., 2019). This method was found to be preferable to the hydrometer method as sandy BSM settles quickly; a direct gravimetric measurement of sand was needed.

Field notes and infiltration data were aggregated. Summary statistics of soil texture and organic matter were determined using laboratory-reported values. Pedotransfer functions were used to convert textural classification and organic matter to K_{sat} . All data analysis was completed using R statistical software version 3.4.2 (R Core Team, 2021). A criterion of 95% confidence ($\alpha = 0.05$) was used.

3 RESULTS AND DISCUSSION

Mean surface intake rate was lowest at the inlet (777.2 mm/hr), followed by the middle and outlet (825.5 and 1389.4 mm/hr, respectively). The surface intake rate of BRCs <5 years of age was significantly greater than those of older BRCs (Figure 1).

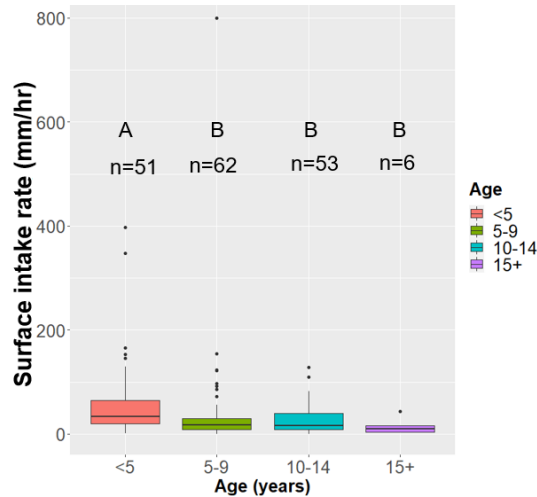


Figure 1: The surface intake rate of BRCs by age

Younger BRCs (less than 10 years old) had more homogeneous textural classifications with location and depth. Older BRCs (10 years and older), however, showed variation in textural classification with location, particularly within the 0-5cm surface layer (Figure 2). These changes in textural classification at the surface were consistent with Stokes' Law, with larger particles at the forebay/inlet of the BRC and fines settling at the middle/outlet. Significant changes in surface layer textural classification with location, but no significant differences in hydraulics with location suggests plant roots and microbes aid in maintenance of infiltration capacity of BRCs. Older BRCs still had homogeneous textural classifications at deeper depths (10-15 cm and 35-50 cm).

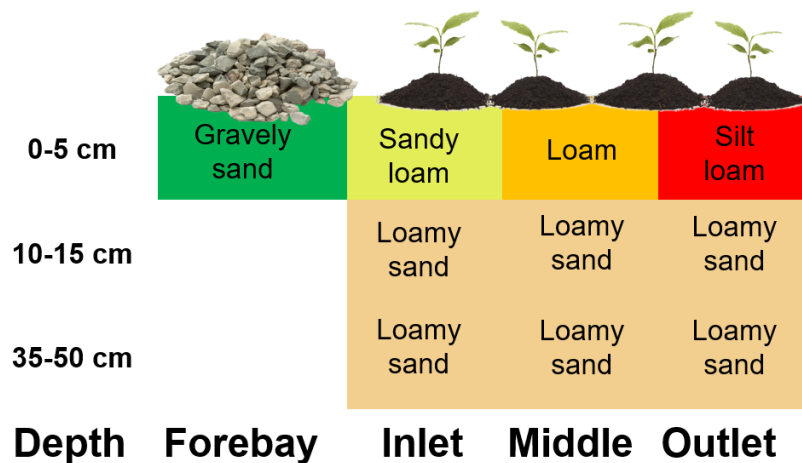


Figure 2: Textural classification of BRCs changing at the surface layer of older BRCs. Younger BRCs remained homogeneous.

Organic matter accumulated at the surface from the addition of mulch, organics washing off from the watershed, and the senesce of plants. Surface (0-5cm) percent organic matter is 2- to 2.5-times higher than deeper layers, indicating that organic matter accumulates naturally in BRCs (Figure 3). There was no significant difference in organic matter by location (forebay, inlet, middle, outlet).

Average % Organic Matter by Depth

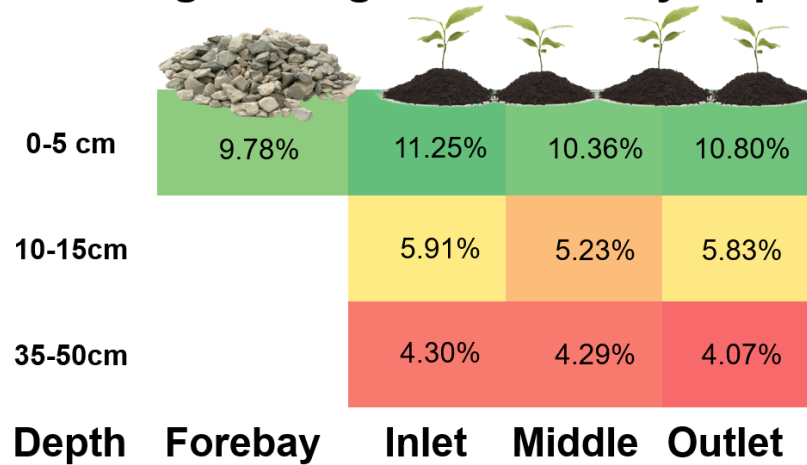


Figure 3: The average percent organic matter with depth and location for all sites. Dark green indicates high percent organic matter, yellow moderate percent organic matter, dark red low percent organic matter

4 FUTURE WORK

Textural classification can be converted to a K_{sat} using the soil water characteristic calculator and pedotransfer functions, such as $K_{sat} = 60.96 \times 10^{0.0126 \times \text{sand} - 0.0064 \times \text{clay} - 0.6}$ found in Zhang & Schapp (2019). We plan to relate the textural classifications of our 553 samples to a K_{sat} using these tools – using field surface intake rates for verification. Then, we plan to recommend BRC ages, depths, and contributing land use and land cover that most require maintenance. We have done this analysis on data presented in Ayers & Kangas (2018 ; Figure 4a) and Spraakman & Drake (2021 ; Figure 4b), which suggest that BRCs require maintenance after 16.6- and 15.0 years, respectively.

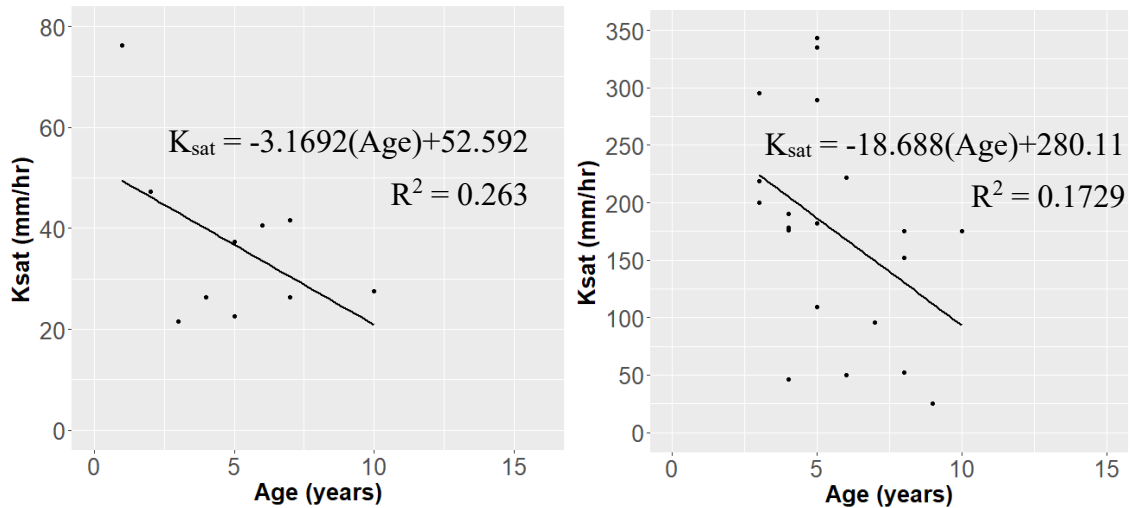


Figure 4a and b: Derived Ksat values (mm/hr) with age from Ayers & Kangas (2018; left) and Spraakman & Drake (2021; right)

5 CONCLUSIONS

Siltation, sedimentation, and the accumulation of organic matter are key processes that influence the evolution of BSM. Younger BRCs retain soil textural homogeneity and high hydraulic conductivity. In older BRCs (10 years and older), particles accumulate at the surface layer. Larger particles were present at the forebay/inlet, smaller particles at the surface layer of the middle/outlet. The hydraulic conductivity of BRCs decreases with age. Surface layer organic matter is double to triple the design standard ; organic matter washes off from the watershed and accumulates at the surface of BSM. As we did with the data from other studies in section 4, we plan to relate textural classifications to K_{sat} before the conference to inform BRC design and maintenance recommendations.

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