Measuring infiltration rates for stormwater biofilters: Comparing emerging technologies and traditional methods

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ABSTRACT: Stormwater runoff is an increasing problem in urban areas. The development of biofilters is one possible control measure. Measuring stormwater runoff and saturated hydraulic conductivity provide the ability to monitor existing soil and plant species for better preservation. The saturated hydraulic conductivity can be measured both offsite and onsite, so it acts as a parameter in determining whether the established biofilter is still effective post construction. The use of saturated hydraulic conductivity can also be used to investigate prior to the design and construction takes place to ensure that any issues can be addressed. There are numerous factors that influence the measuring of saturated hydraulic conductivity in biofilters such as the accumulation of pollutants over time, the original vegetation and soil types selected during the construction phase (native vegetation is preferred) and meteorological effects. An emerging technology being the SATURO dual head infiltrometer will be used to compare to measure for field saturated hydraulic conductivity (K_{fs}) compared to three other infiltrometers; The single-ring, double-ring and the Modified Philip-Dunne (MPD) which are all infiltrometers that have been researched extensively in the past. As there is still limited research in the field about measuring infiltration rates in biofilters using emerging technologies such as the SATURO infiltrometer, a comparative analysis using sandy dunes will form the basis of the research to compare the SATURO infiltrometer to other traditional methods of measuring saturated hydraulic conductivity. The MPD and SATURO infiltrometer both showing promising results for measuring infiltration rates in stormwater biofilters based on the calibrations obtained from fieldwork in Melbourne, Australia.

1 INTRODUCTION

Biofilters (also known as rain gardens, biofiltration systems or Bioretention systems) are a treatment method that allows for the filtering of stormwater pollutants in urban areas and reduces the peak flows of runoff (Le Coustumer et al. 2009). The reason why stormwater biofilters are essential is that they are used to prevent harmful pollutants damaging the soil and can maximise the water quality of the region (Chaudhary et al. 2003). They can be used in a variety of soil, climate and groundwater conditions meaning that their flexible nature allows them to be fitted into a variety of settings (Le Coustumer et al. 2009).

The biofilter or rain garden is a long term solution in which the pollutants from the runoff are reduced to several processes such as “of filtration, sedimentation, plant root uptake, biodegradation by microorganisms in soil, and sorption on soil layers”. (Singh 2020, p. 147). This allows for the reduction of numerous potentially hazardous materials such as phosphorus, pathogens, heavy metals, and suspended solids. However, there are some concerns in general for the construction and implementation of said biofilters (Singh 2020). Inexperienced contractors may build biofilters incorrectly or poorly due to the improper vegetation used, poor soil quality or not site-specific or ineffective placement of the biofilter (Singh 2020). Therefore, it is crucial to gain an in-depth understanding of how to better measure saturated hydraulic conductivity (K_{fs}) in the field to ensure that the design process of the biofilters that are being established meet its intended aims. This includes being able to maintain the infiltration capacity for years after establishment. Saturated hydraulic conductivity is an important measure because it helps to accurately assess both soil and water movement in soils (Wang, Wedin & Zlotnik 2009). However, K_{fs} values have longed been deemed as a sensitive measure when analysing infiltration in the field (Rienzner & Gandolfi 2014). This means it is vital to find a way to analyse K_{fs} in a way that provides less variability to produce more meaningful results.

Infiltrometers are a tool used to measure K_{fs} in the field and are used in various spatial settings and provides information regarding saturated hydraulic conductivity (Chaudhary et al. 2003). The uses and types of infiltrometers have changed over with manual and automated infiltrometers now available. Single ring infiltrometers is one type that has issues, as there is an overestimation of field saturated hydraulic conductivity (K_{fs}), due to ponding and the “capillarity of unsaturated soil” (Bouwer 1986). The double-ring infiltrometer helps to reduce flow divergence as the outer ring prevents build up in the inner ring. However, the lateral flow remains a problem

(Swartzendruber & Olson 1961). The dual head infiltrometer was created to overcome lateral flow, soil capillarity, inner ring ponding, and more straightforward calculations, (Cobos, Rivera & Campbell 2015). Dual head infiltrometers, e.g. the SATURO is a new type of infiltrometer which uses this model with slight modifications. Using the infiltrometer, soil macroscopic capillary length does not need to be estimated because using two different pressure heads; it measures infiltration rates considering three-dimensional flow (METER Environment 2017). As there is a direct link between infiltration and the soil structure, it is integral that there is routine analysis of the infiltration rates under different soil structures to understand how water flow impacts soil quality and the rate in which it occurs. The SATURO shows promising results, although it is yet to be critically reviewed extensively to confirm accuracy and repeatability in results (Shevade, Alizadehtazi & Montalto 2018).

The issue with using traditional methods of measuring infiltration capacity is that it can yield inconsistent or unpredictable results as human error during post-research and setup is commonplace with inexperienced researchers (Cobos, Rivera & Campbell 2015). Human error can add significant costs to the testing process when results need to be repeated for further clarity in the data. As time and cost are inhibiting factors of testing, it is essential to determine which infiltrometers effectively mitigate these issues so the right one can be selected from the initial data collection point (Yolcubal et al. 2004).

1.1 *Infiltration characteristics*

Infiltration types may vary due to different factors. Land cover and soil characteristics may differ between sites, and this plays an important role in infiltration rates (Rieu & Sposito 1991). The measuring of infiltration rates can depend on numerous environmental factors such as the soil characteristics, such as porosity and soil water content (Báťková, Miháliková & Matula 2020). Porosity has significant impacts on the infiltration capacity of soils. Soils like clay have small pores; sands are an example of soils with large pores. Large pores have higher infiltration capacity (Rieu & Sposito 1991) This may require extensive testing to produce reliable results (Rieu & Sposito 1991) The soil-surface itself differs between soil types such as the vegetative cover or slope of the land (Tindall, Kunkel & Anderson 1999). Rainfall characteristics such as the intensity and duration can also play a role (Báťková, Miháliková & Matula 2020)

Even with emerging technologies, little is known about infiltration in urban settings or size dependency on the rings of the infiltrometer (Lai & Ren 2007). This means that there is no one set way of measuring infiltration rates that can cover all field conditions. In addition to the unpredictable results, expenses vary from each test, and there may be special conditions at the field that are being measured apart from saturated hydraulic conductivity. The availability of the equipment used may cause issues.

The focus of this paper is to critically review the literature concerning using different infiltrometers to measure K_{fs} in biofilters. The research also seeks to compare both emerging and traditional methods in measuring hydraulic conductivity in biofiltration media with high infiltration rates. As there is still limited research on the infiltration of biofilters in practice, this research helps frame the measure of infiltration in other types of systems being sandy soils and sandy dunes as a comparative measure. The use of emerging technologies in measuring saturated hydraulic conductivity in biofilters can help to address existing gaps in the literature regarding infiltration characteristics of biofilters and what can be done in the future to produce more repeatable and accurate results.

2 METHODOLOGY

2.1 *Infiltrometers and method of instruction*

A literature review was undertaken on infiltrometer technologies in sandy soils to evaluate the appropriate methods for measuring infiltration rates in local stormwater biofilters. The focus was on aeolian landforms such as sandy dunes. Using the information from existing literature about the common characteristics of stormwater biofilters, a better understanding of the most appropriate methods for measuring K_{fs} is achievable.

A range of sources has been adopted to develop the understanding behind the topic. Both SCOPUS and the Monash Library are essentials tools used to refine the results and search criteria. As there is limited research in the field comparing biofilters against other landforms, separate searches were conducted to gather research about measurements of which infiltrometer is more appropriate in measuring K_{fs} values in the field. This means searching for information about biofilters, and sandy dunes concurrently were not possible. The most useful search terms that brought results regarding biofilters included saturated hydraulic conductivity, biofilters, K_{fs} and rain gardens (as biofilters are known as in other parts in the world). The most useful search terms to include when searching for sandy dunes were sand, dunes, infiltrometer, saturated hydraulic conductivity and K_{fs}. It is important that when literature reviews are undertaken on topics similar to this that key words like unsaturated hydraulic conductivity be excluded from the search terms as in sandy dunes often research is design to test both saturated and unsaturated hydraulic conductivity where mini-disk infiltrometers are employed.

The field data collection obtained helped to explain the two more promising methods that were measuring infiltration rates in stormwater biofilters.

This is the MPD infiltrometer and the dual head infiltrometer (commonly known as the SATURO) respectively. Data collection occurred in Semester Two of 2019 at Monash University, Clayton, Australia.

However, due to laboratory closures, the data obtained from the field was unable to be verified. COVID-19 has prevented the ability to gather field data during the entirely of Semester One 2020. The calibration data which has been presented in this report as an analysis tool. The intended process was to undertake several more field measurements and then contrast these results in the laboratory.

Figure 1 shows an example like the MPD that was used in the research project. The MPD used was constructed manually (although an automated version can be produced) and organised by Dr Brandon Winfrey. The dual head infiltrometer being the SATURO used is an automated infiltrometer, and therefore no self-construction was used for the infiltrometer.

The saturated hydraulic conductivity rate that would be expected of a typical Melbourne biofilter would be somewhere between 100-300 mm/hr (Payne et al. 2015). This estimate is based on the typical Melbourne topography, soils, and infiltration capacity rates (Payne et al. 2015).

The method used for the MPD involves inserting the infiltrometer ring compacted 5cm into the soil (Ahmed, Gulliver & Nieber 2011). The infiltrometer is then pumped with water, and then the recordings are made using a stopwatch at the required intervals. Figure 1 demonstrates the infiltrometer that was created for this experiment.

Figure 1. Revised Modified Philip-Dunne infiltrometer

Figure 2 demonstrates the setup of the dual head infiltrometer being the SATURO. As can be seen in the photograph, the setup process is simplified, and inexperienced researchers can perform the infiltration measurements. The ring is required to be installed in the soil profile to be measured with the hoses connected to start the infiltrometer and to initiate the process. The SATURO also has an insertion ring of 5cm similar to the MPD. There is also a second ring of 10cm which is available for sites that have significant fluctuations in the flux values due to the macropores present in the soil, deep disturbances to the soil or soils that have a deep organic layer present. However, in this research, only the 5cm was required as these characteristics were not present in the biofilter measured at Monash University. To ensure that the dual head infiltrometer was configured to the soak time and pressure head configurations in line with the soil type, the settings were mirrored as per the SATURO manual, which can be seen in Table 1. The intention of making adjustments to the settings it to ensure to account for the significant differences in spatial and temporal variability as it is important to consider using infiltrometers that can better record reliable data (Báťková, Miháliková & Matula 2020).

Table 1. Soak time and pressure head configurations for dry loamy sands for a dual head infiltrometer

Pressure Head 1 (cm)	5.0
Pressure Head 2 (cm)	10.0
Soak Time (min)	25
Pressure Cycles	3
Hold Time (min)	15
Insertion Depth (cm)	5
Run Time (min)	115

Figure 2. SATURO infiltrometer set up at a biofilter in Monash University, Clayton

2.2 *Measurement process*

2.2.1 *Measurement setup*

The infiltration rate can be measured using numerous types of infiltrometers at a biofilter. Figure 3 demonstrates the setup of the different infiltrometers being the single-ring, the double-ring, MPD and the SATURO infiltrometer set up in a biofilter. The data processing that was produced for this report uses single-ring and double-ring infiltrometers as a literary comparison only.

The field measurements that were conducted were performed at Monash University, Clayton, Australia, over three separate days at two field locations. The two locations were chosen for their unique features and proximity to where the equipment was held. Location one had a variety of vegetative cover surrounding the testing soil. This is useful as the vegetative cover is likely to play a role in the K_{fs} values recorded. Location two was selected as there was more open space around the soil and less vegetative cover. This allows a better understanding to be gained about how the soil properties play a role in measuring K_{fs}. To understand the values that could theoretically be produced when using the SATURO; a test was performed using the baseline settings as per the manual on the 15th of November 2019. This was to establish what values for K_{fs} and K_{fs} errors may be potentially produced if results were repeated in the same biofilter later. At this stage, there was no access to an MPD infiltrometer, so only the SATURO values were recorded. On the 27th of November 2019 once, there was access to both infiltrometers a test in the same biofilter was able to be performed.

The MPD infiltrometer is mostly used for calculating unsaturated hydraulic conductivity. The raw data has been provided in Table 5. Multiple runs were performed using both infiltrometers in to ensure the infiltrometers were calibrated correctly to the settings inputted and to verify if any data points had any significant anomalies which would indicate some kind of error (most likely human).

Figure 3. The methods of measuring infiltration rates in a biofilter (a) double-ring infiltrometer, (b) single-ring infiltrometer, (c) MPD infiltrometer, and (d) automated SATURO infiltrometer (Ebrahimian et al. 2020)

2.2.2 *Data Processing*

The methodologies for the MPD and SATURO infiltrometers that were conducted onsite at Monash University differ. The SATURO allows for K_{fs} values to be produced in real-time due to it being automated. The MPD requires the data to be extracted and analysed more intensely post-experiment due to it being manually measured. The data that is presented in this report is used as a calibration tool because of the closures of laboratories of COVID-19 preventing the repetition of more measurements in the field and comparing them to the results in the laboratory.

3 RESULTS AND DISCUSSION

3.1 *Factors that influence infiltration rates:*

Numerous factors influence infiltration rates of a biofilter. This is because biofilters come in different types, and the physical characteristics of the biofilter are dependent on the area that it has been established in. Firstly, the quality of infiltrating water is a factor that may influence the infiltration rates of the soil and this compromise the effectiveness of the biofilter in filtering out pollutants. For example, the use of deicing practices can cause issues such as flocculation of particles resulting in reduced infiltration rates due to the clogged soils or clays (Kakuturu & Clark 2015). The sodium ions enter the soil and displace other types of ions, which can have long-lasting negative impacts because of the harmful pollutants that enter the soil as well making it more challenging to record accurate data of infiltration rates. Clogging often occurs in biofilters in the years after installation and slows down the infiltration rate of the biofilter (Guo & Luu 2015). The clogging effect occurs when there is the accumulation of runoff pollutants in the void spaces of the soil profile or when the plasticity of the soil increases resulting in a reduction in K_{fs} values recorded and adding which adds to the clogging effect. A redesign of the biofilter, including installation of a cap orifice where there is any damage to underdrain pipes, allows for the free flow of water in a controlled manner (Guo & Luu 2015). Water flow that occurs then can be in line with the stage the biofilter is at in terms of lifespan.

Water freezing plays a big part in being able to accurately measure the K_{fs} values in both sandy soils and biofilters. In areas such as France Regional park, there are considerable differences between the years because of seasonal impacts such as thawing and freezing where the water table increases make changes in soil permeability for sandy soils (Olson et al. 2013). This impact on biofilters in the unthawing process can cause the soil to increase in K_{fs} (Emerson & Traver 2008). The impact of raindrops on bare soil and significant volumes of rainfall can also affect the measured K_{fs} values because the soil experiences breakage and then forms a seal which then reduces the K_{fs} of the soil (Ebrahimian et al. 2020).

Soil compaction plays a significant role in developed urban land (Ahmed, Gulliver & Nieber 2011). Rapid changes to the soil quality due to compaction means that there is an increase in runoff and the infiltration rates are affected. These are all the factors that show how biofilters can have varying saturated hydraulic conductivity.

3.1.1 *Sand Dunes – Physical characteristics and saturated hydraulic conductivity in the field:* Analysing the physical characteristics and saturated hydraulic conductivity of sand dunes is useful because there are still gaps in the knowledge regarding measuring infiltration rates in biofilters. This allows for a comparative point for understanding how the current methods of measuring saturated hydraulic conductivity against biofilters. The general properties that are seen in typical sand dunes are that they generally have significant homogeneity when analysed at face value (Ritsema & Dekker 1994). However, its research has found that there are significant differences between the K_{fs} values in sand dunes because of the soil moisture variations (Ritsema & Dekker 1994). This means that even in dry conditions, there can be different moisture patterns found, and when significant rain events occur, it may amplify the differences between these systems. Sand dunes generally have saturated hydraulic conductivity much higher compared to a biofilter. The reason why is because sand dunes generally have a high infiltration rate due to the texture of the soil as the pores of the sand allows for more effortless flow due to the large pores of the sandy soil (Sweeney & Loope 2001).

Another factor that can significantly affect the infiltration rate of the dunes and the ability to use an infiltrometer meaningfully to measure the K_{fs} is the topography and climate of the dune. The Tengger Desert which is located in the Inner Mongolia Autonomous Region of China has a range of sand dunes with soil crust layers that range from non-biological crusts, crust with mosses, and crusts that are overrun by vegetation (mosses, algae and liverworts) (Li et al. 2002). In this desert, there are multiple variations of infiltration depth because of the different vegetation apparent and soil composition along the sand dunes, as seen in Table 3. It is apparent that the crust soil type has the lowest saturated hydraulic conductivity due to the elevates levels of organic matter, number of soil microorganisms and an increase in the saturated soil water content. This contrasts with the shifting sand where the opposite was apparent in which there was significantly high levels of saturated hydraulic conductivity and lower levels of saturated soil water content, number of soil microorganisms and the organic matter in the soil. Other considerable differences between the saturated hydraulic conductivity within the sand dunes are due to the presence of leeward slopes, inter-dune depressions, windward slopes and dune tops (Li et al. 2002). This relates to the topographical nature of the dunes, which makes it more difficult to measure K_{fs} in these areas because of the numerous factors that need to be accounted for.

In the cause of stabilised dunes at the Nebraska Sand Hills in periods where there is intense summer rainfall, the K_{fs} of the sand dune is so significant that it is unable to allow for Horton overland flow (Sweeney & Loope 2001). This means that the water flows across the ground surface level because depression storage capacity and infiltration capacity have both been reached (Horton 1945).

There are differences in saturated hydraulic conductivity in sand dunes depending on its current state (Ly & Ramirez-Avila 2018). For example, between an active state and a stabilised dune in a 2010 study in Saskatchewan, Canada showed that from 25cm depth until 500cm below ground surface level showed that the moisture and hydraulic conductivity for the stabilised dune were significantly lower than the active dune (Ly & Ramirez-Avila 2018). At the stabilised dune that there is an increase in material such as silt and clay, which reduces the infiltration capacity of the dune. When a dune becomes stabilised because of the changes in the vegetation profile (a proliferation of vegetation that can undergo transpiration) and the changes in the soil structure due to the increase in vegetation (Ly & Ramirez-Avila 2018).

Table 2. Comparison of Infiltrometers according to previously reviewed literature (adapted from Ebrahimian et al. 2020)

Criteria\Methods	Double ring	Single ring	MPD	SATURO
Installation	Time-consuming/not easy	Quick/easy	Quick/easy	Quick/easy
Test speed	<4 hr	<4 hr	30-60 min	1-3 hr
Ease of operation	Not easy	Easy	Easy Fully automated version is available	Fully automated
Automatic/manual K_{fs} calculation	Manual	Manual (with potential to be automated)	Both manual and automatic versions are available	Automatic
Accuracy	Fair	Low	Adequate like the double ring	Comparable to MPD but still under evaluation
ASTM standard	D3385-18	Not available	D8152-18	Not available

Table 3. Saturated Hydraulic Conductivity in Tengger Desert measured against physical characteristics (from Li et al. 2002)

Soil type:	Organic matter (g kg^{-1} soil)	Number of soil microorganism (10^6 kg^{-1} soil)	Saturated soil water content (cm^3 cm^{-3})	Saturated hydraulic conductivity (cm day^{-1})
Crust	9.47	6226.38	0.6267	89.87
Subsurface soil	5.59	2565.7	0.4996	257.35
Shifting sand	0.54	71.35	0.3835	924.64

3.2 *Biofilter characteristics that affect the measuring of K_{fs} values*

A biofilter (Ahmed, Gulliver & Nieber 2011) should not have significant variation between slope profile compared to sandy dunes. However, recent research that has been conducted shows that in biofilters, there is also an impact caused by the slope of the biofilter, as seen in Figure 4. All the rain gardens are 1m x 1m, rain garden 1 is a flat rain garden whereas rain gardens 2 and 3 have the slope dimensions of 1H:0.3V slope 1H:0.6V. The water was filtered through at a stable pace at the same volume to measure the infiltration rate, as seen in Figure 4 below. All the biofilters used the same native vegetation being couch grass (*Cynodon dactylon*). Figure 4's information is based on the results produced in Table 4. The different observation points were recorded on different dates, and this is why there are different temperature points, although the mean discharge of water was the same. Figure 4 demonstrates that has temperature decreases, so does the infiltration capacity of the biofilter. This is in line with other research that has been found that shows that during the colder months, there is a general decrease in K_{fs} values recorded (Ebrahimian et al. 2020). K_{fs} values tend to increase during the warmer months of the year due to the viscosity of the soil decreasing (Emerson & Traver 2008). It is theorised that 'there could be a 40% difference in infiltration rates between summer and winter months due to a change in viscosity' (Ebrahimian et al. 2020, p. 1024) The free movement of water is a direct result in this reduction in viscosity. There are many suggested reasons for this link between temperate variation in K_{fs} values in biofilters. For example, there may be surface tension changes in the soil and temperature may cause structural changes to the soil profile of the biofilter such as changing the thickness of the soil layer.

Native vegetation is necessary to be used during the design process of a biofilter as it assists in reducing the effects of evaporation and transpiration and stops standing water from accumulating (Singh 2020). Standing water can cause the compounding of mosquitos as well as looking aesthetically unpleasing to humans once the rain event has ceased. Figure 4 shows that Rain garden 1 was the most efficient at all points during the different analysis points as at no point during the observation points were any of the other rain gardens performing more efficiently. Effective planning is therefore required to ensure that the construction of the biofilters efforts does not hamper efforts due to the topography.

The use of native (in-situ) soils should be encouraged in the process of establishing a new biofilter. This is because when native soils are used, they can maintain sufficient infiltration rates because of the reduction in contamination and being a stable soil profile (Ebrahimian et al. 2020). Native soils, when used in biofilters significantly reduce the cost of the biofilter because the amount of soil that is required to be excavated from outside of the area to be transported to the biofilter site is minimised. Native vegetation is uplifted by the presence of native soils because the ongoing maintenance efforts and costs are reduced. The infiltration capacity of the biofilter is complimented by both native vegetation and soils because this reduction in maintenance efforts means decreasing K_{fs} values over time are less likely to be present. It is important that before a biofilter is constructed that significant analysis is performed on the soils introduced. It accounts for issues such as plasticity and the particle size as previously discussed to ensure that the soils used compliment the design and expected infiltration rates expected. This helps address the knowledge gap regarding the lack of understanding of the characteristics and construction methods for biofilters, so future studies that focus on this specific field will benefit (Singh 2020).

Table 4. The relationship between temperature and infiltration rates measured at different observation points (adapted from Singh 2020)

Observation	Temperature	Mean discharge (litre/min)	Rain garden 1 (seconds)	Rain garden 2 (seconds)	Rain garden 3 (seconds)
Observation 1	$36^{O}C$	4.54	600	1320	2700
Observation 2	$33^{O}C$	4.54	610	1365	2852
Observation 3	$25^{O}C$	4.54	730	1450	3000
Observation 4	$22^{O}C$	4.54	794	1550	3327
Observation 5	$12^{O}C$	4.54	880	1630	3590

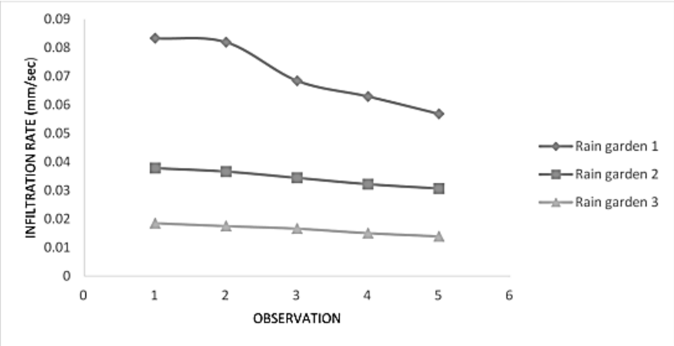

Figure 4. "Comparison of infiltration rate of rain gardens and effect of temperature on infiltration rate" (from Singh 2020)

3.3 *Infiltrometers used in measuring K_{fs} values in biofilters – Which one is most optimal for a typical biofilter?*

Table 2 shows the difference between traditional methods of measuring K_{fs} rates compared to the MPD and SATURO models. The most common method of measuring K_{fs} values in the field for biofilters is by using the double-ring infiltrometer as there is a low-moderate cost, and ability to control the one-dimensional flow of the water because of the two rings. This means that there is an improvement in terms of 'the vertical movement of water through the soil' (Ebrahimian et al. 2020, p. 1030). The double-ring infiltrometer is the most selected infiltrometer due to its cost and fair accuracy in measuring K_{fs} values. The MPD infiltrometer if used manually, does not account for one-dimensional flow similarly to the single ring infiltrometer. The relative cost of the manual infiltrometers for the double ring, single and ring and the manual MPD is low. However, the cost of the SATURO is cheaper than the automated version of MPD, which can provide some benefits in its selection.

Both the MPD (when automated) and SATURO infiltrometers tend to be easier to install, use less water and can capture the results faster. However, one negative factor about the SATURO is that it has yet to receive an ASTM standard rating due to being newer on the market. This compares to the MPD and double-ring infiltrometers that both have established ratings. Despite this, while the SATURO is a reasonably new instrument in measuring saturated hydraulic conductivity, literature is beginning to emerge that corroborates the claim that it may be beneficial in measuring high K_{fs} values (Ebrahimian et al. 2020). As sand dunes also have temporal and spatial variabilities like biofilters, there may be some cases where the use of automated dual head infiltrometers are inappropriate. For example, in hotter months of the year, the sand surface/air temperature may exceed 50°C which the SATURO will no longer be able to be operated at this exceeds this value (METER Environment 2017). The infiltrometer that is used most in sandy dunes is the double-ring infiltrometer or mini-disk infiltrometer (as often unsaturated hydraulic conductivity is analysed during the analysis stages of sandy dunes concurrently) (Ankeny et al. 1991; Báťková, Miháliková & Matula 2020). The reason why this infiltrometer is more commonly used is because each infiltrometer serves different purposes and differences in topography in sandy dunes compared to biofilters.

The double-ring infiltrometer requires a significant amount of water to conduct the testing compared to the other three common types of infiltrometers (Ebrahimian et al. 2020). This makes it challenging to use the infiltrometer in remote sites as the transportation of the water vessel may be unachievable. Due to amount of time that is required to conduct the test (according to Table 2 it is denoted as the infiltration method which is the most time consuming), it may limit the number of tests that can be performed in one sitting. Therefore, developing an understanding of the potential cross-directional or longitudinal differences with a biofilter may be difficult using a double-ring infiltrometer.

The single ring-infiltrometer is a cheap method of determining K_{fs} values in biofilter systems. Difficulties in measuring one-dimensional vertical flow mean that the accuracy of the results may be skewed. It is not recommended for the use of a single-ring infiltrometer for detailed research projects because of this inhibiting factor. There is also no ASTM standard for the single-ring infiltrometer like the SATURO infiltrometer.

It is difficult to compare all four of the infiltrometers currently because of the lack of research regarding the use of dual head infiltrometers generally. Minimal research comparing all four infiltrometers simultaneously is difficult to locate irrespective of soil profile being analysed (Ebrahimian et al. 2020).

3.4 *Infiltrometer measurements based on fieldwork – MPD versus SATURO: The challenges*

The field measurements that were performed have different results as can be seen from the test results at the two separate locations, which highlights that the average results produced can be different within the same biofilter. This could be because the biofilter may have cross-directional and longitudinal differences. Human error when recording the data values can also occur as this was test is not automated as the dual head infiltrometer.

As seen in Table 6, test three, which was only done using the SATURO displayed significantly different results from any other attempts or tests when hold time was adjusted, but other value points remained the same. These results demonstrate that when significant deviations from the ideal value points cause inaccurate results and unrepeatable data. This means that when using a dual head infiltrometer in the field such as the SATURO, there should be extensive testing undertaken first to understand the profile of the biofilter before undertaking measurements to ensure the accuracy and repeatability of the experiment can be measured post-experiment.

Test two, as per Table 6 shows the use of the SATURO with adjustments to the soak time is reduced in the experiment that the K_{fs} error values also increase. This exemplifies that when significant deviations are made from the operating guide. It should be noted that when there are biofilters that have unique soil profiles, there should be some thought in determining what infiltrometer is the most appropriate to be used.

For both methods of testing, the first run in each test is performed to ensure that the data were calibrated to their specific requirements and to collect thee starting data. For example, there are differences between the two locations for the separate runs using the MPD infiltrometer. It is assumed that the infiltration capacity of the soil in both locations recorded in the second run is lower because the soil was already saturated after the first run. However, because the data was unable to contrast against measurements made in the laboratory, it cannot be verified. As the data could not be calibrated for the MPD infiltrometer, the flux average of the SATURO can be contrasted to the MPD infiltration rates recorded as a more comparative measure. The results show similar results in the testing phases, for example, the MPD (Location one and two in the first run) compared to Test-2-R1 of the SATURO. This means that although the data was not calibrated in the laboratory, initial results were promising that the use of the SATURO was providing repeatable results that were in line with established methods of measuring K_{fs} such as the MPD.

Table 5. Infiltration capacity rates recorded using the MPD infiltrometer on the 27th of November 2019

Level (cm)	Location 1		Location 2	
	1st run	2nd run	1st run	2nd run
50	0	0	0	0
40	0.104166667	0.080645161	0.133333333	0.083333333
30	0.042918455	0.032154341	0.055865922	0.041493776
25	0.015923567	0.012468828	0.017921147	0.015873016
20	0.012285012	0.009823183	0.015974441	0.012886598
15	0.009708738	0.00798722	0.012755102	0.010351967
10	0.007911392	0.006896552	0.010330579	0.008474576
5	0.006451613	0.005382131	0.008333333	0.006877579
0	0.005668934	0.004995005	0.007256894	0.006535948
Average (cm/s)	0.025629297	0.020044053	0.032721344	0.023228349

Table 6. K_{fs} tests using the SATURO infiltrometer

Test Settings							
Name	TEST-1	TEST-2-R1	TEST-2--R2	TEST-2-R3	TEST-3-R1	TEST-3-R2	TEST-3-R3
Date	15/11/19	27/11/19			05/12/19		
Pressure Head 1 (cm)	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Pressure Head 2 (cm)	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Soak Time (min)	25	25	15	5	25	25	25
Pressure Cycles	3	3	3	3	3	3	3
Hold Time (min)	15	15	15	15	10	5	15
Insertion Depth (cm)	5	5	5	5	5	5	5
Run Time (min)	115	115	105	95	85	55	115
Results							
K_{fs} (cm/s)	0.007884	0.007153	0.008669	0.00848	0.00585	0.002549	0.009029
K_{fs} Error (cm/s)	0.0006594	0.0004317	0.01084	0.001282	0.0003296	0.0003727	0.0004264
Flux Average (cm/s)	0.033663	0.029286	0.034012	0.029934	0.032964	0.035720	0.037497

4 CONCLUSION

Based on this research that there are significant challenges in measuring infiltration rates in biofilters. Past literature has analysed the problems in biofilter construction, meaning that the analysis of K_{fs} values using the right kind of infiltrometer can be complicated. There has been literature presented in the past that proves that the use of biofilters as a measure for controlling issues such a stormwater runoff is effective. However, more could be done to understand the long-term impacts associated with the hydraulic behaviour of the biofilters established.

Due to the specialised nature of biofilters, a tailored approach is required when using infiltrometers to measure K_{fs} because of the unique setup compared to sandy soils in sand dunes. This research has helped to clarify what the typical methods for measuring K_{fs} are in the different soil types for biofilters in contrast to sand dunes and what research should look out for in the future.

The results that can be inferred from the uncalibrated data presented in this research is to use caution when using a dual head infiltrometer without a firm understanding of the biofilter that is being analysed. Significant deviations from the default settings for the soil type being measured increased the K_{fs} error values produced meaning that if the experiment was to be repeated in the future, the results might be inaccurate or unable to be replicated. This means that while emerging technologies such as the SATURO are promising in measuring

However, in the future infiltrometers such as the SATURO that automate the process for measuring saturated hydraulic conductivity will become more frequently used compared to the traditional methods of measuring K_{fs} such as the single-ring and double-ring infiltrometer. This is because it is easier to use, easier to install and minimise the damage to the soil (through compaction) due to the use of infiltrometers such as the double-ring infiltrometer. However, once an ASTM standard and further literature verify the use of the SATURO infiltrometer, a suspected increase in the use of the infiltrometer in testing environments for K_{fs} measurements is expected to become commonplace.

5 RECOMMENDATIONS

- More peer-reviewed research is needed in the field of newer technologies such as the SATURO to better measure its effectiveness in measuring saturated soil conductivity despite its potential because of its lack of ASTM standards and being relatively new in the market.
- In the design process of biofilters, there needs to be more care taken when selecting the soils and vegetation that comprises the biofilter. Research looking into the effects of local biofilters where the setup of one biofilter with native soils and vegetation compared to non-native soils and vegetation may have profound effects for the construction process in the future.
- Biofilter systems are complex so they should not be constructed with a set or constant value in mind when referring to K_{fs}. This neglects the general winter decrease of K_{fs} values and other conditions such as soil and vegetation used. If the K_{fs} value is estimated to be set during the construction period, there may be a perceived reduced cost estimate of the biofilter due to the 'smaller' footprint of the biofilter. However, due to the complex spatial and temporal variability of biofilters, it is not useful to model based on this set value.
- It is recommended that more research is undertaken into where the best measurements to take are in the biofilter as there may be cross-sectional or longitudinal differences that impact the optimum location for measuring K_{fs} values.

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7 REFERENCES

Ahmed, F, Gulliver, JS & Nieber, JL 2011, 'Performance of low impact development practices on stormwater pollutant load abatement'.

Ankeny, MD, Ahmed, M, Kaspar, TC & Horton, R 1991, 'Simple field method for determining unsaturated hydraulic conductivity', *Soil Science Society of America Journal*, vol. 55, no. 2, pp. 467-70.

Báťková, K, Miháliková, M & Matula, S 2020, 'Hydraulic Properties of a Cultivated Soil in Temperate Continental Climate Determined by Mini Disk Infiltrometer', *Water*, vol. 12, no. 3, p. 843.

Bouwer, H 1986, 'Intake rate: cylinder infiltrometer', *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*, vol. 5, pp. 825-44.

Chaudhary, DS, Vigneswaran, S, Ngo, H-H, Shim, WG & Moon, H 2003, 'Biofilter in water and wastewater treatment', *Korean Journal of Chemical Engineering*, vol. 20, no. 6, p. 1054.

Cobos, D, Rivera, L & Campbell, G 2015, 'Automated Dual-Head Infiltrometer for Measuring Field Saturated Hydraulic Conductivity (Kfs)', in *EGU General Assembly Conference Abstracts*, vol. 17.

Ebrahimian, A, Sample-Lord, K, Wadzuk, B & Traver, R 2020, 'Temporal and spatial variation of infiltration in urban green infrastructure', *Hydrological Processes*, vol. 34, no. 4, pp. 1016-34.

Emerson, CH & Traver, RG 2008, 'Multiyear and seasonal variation of infiltration from storm-water best management practices', *Journal of irrigation and drainage Engineering*, vol. 134, no. 5, pp. 598-605.

Guo, JC & Luu, TM 2015, 'Operation of cap orifice in a rain garden', *Journal of Hydrologic Engineering*, vol. 20, no. 10, pp. 1-6.
Horton, RE 1945, 'Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology', *Geological society of America bulletin*, vol. 56, no. 3, pp. 275-370.
Kakuturu, SP & Clark, SE 2015, 'Clogging mechanism of stormwater filter media by NaCl as a deicing salt', *Environmental Engineering Science*, vol. 32, no. 2, pp. 141-52.
Lai, J & Ren, L 2007, 'Assessing the size dependency of measured hydraulic conductivity using double-ring infiltrometers and numerical simulation', *Soil Science Society of America Journal*, vol. 71, no. 6, pp. 1667-75.
Le Coustumer, S, Fletcher, TD, Deletic, A, Barraud, S & Lewis, JF 2009, 'Hydraulic performance of biofilter systems for stormwater management: Influences of design and operation', *Journal of Hydrology*, vol. 376, no. 1-2, pp. 16-23.
Li, X-R, Wang, X-P, Li, T & Zhang, J-G 2002, 'Microbiotic soil crust and its effect on vegetation and habitat on artificially stabilized desert dunes in Tengger Desert, North China', *Biology and Fertility of Soils*, vol. 35, no. 3, pp. 147-54.
Ly, P & Ramirez-Avila, JJ 2018, 'Hydrologic and Nutrient Removal Performance of Rain Gardens', in *World Environmental and Water Resources Congress 2018: International Perspectives, History and Heritage, Emerging Technologies, and Student Papers*, pp. 348-54.
METER Environment 2017, *SATURO Manual*, viewed 30 April 2020, <https://www.edaphic.com.au/wp-content/uploads/2018/01/SATURO_Manual_Dec_2017.pdf>.
Olson, NC, Gulliver, JS, Nieber, JL & Kayhanian, M 2013, 'Remediation to improve infiltration into compact soils', *Journal of environmental management*, vol. 117, pp. 85-95.
Payne, E, Hatt, B, Deletic, A, Dobbie, M, McCarthy, D & Chandrasena, G 2015, 'Adoption guidelines for stormwater biofiltration systems—Summary report', *Cooperative Research Centre for Water Sensitive Cities: Melbourne, Australia*.
Rienzner, M & Gandolfi, C 2014, 'Investigation of spatial and temporal variability of saturated soil hydraulic conductivity at the field-scale', *Soil and Tillage Research*, vol. 135, pp. 28-40.
Rieu, M & Sposito, G 1991, 'Fractal fragmentation, soil porosity, and soil water properties: I. Theory', *Soil Science Society of America Journal*, vol. 55, no. 5, pp. 1231-8.
Ritsema, CJ & Dekker, LW 1994, 'Soil moisture and dry bulk density patterns in bare dune sands', *Journal of Hydrology*, vol. 154, no. 1, pp. 107-31.
Shevade, L, Alizadehtazi, B & Montalto, FA 2018, 'Statistical differences of field saturated hydraulic conductivity measurements due to plant roots in urban rain gardens', in *AGU Fall Meeting Abstracts*.
Singh, KK 2020, 'The Influence of Slope Profile on Rain Gardens' Hydrological Performance', in *American Society of Civil Engineers*.
Swartzendruber, D & Olson, TC 1961, 'Model study of the double-ring infiltrometer as affected by depth of wetting and particle size', *Soil Science*, vol. 92, no. 4, pp. 219-25.
Sweeney, MR & Loope, DB 2001, 'Holocene dune-sourced alluvial fans in the Nebraska Sand Hills', *Geomorphology*, vol. 38, no. 1-2, pp. 31-46.
Tindall, JA, Kunkel, JR & Anderson, DE 1999, *Unsaturated zone hydrology for scientists and engineers*, vol. 3, Prentice Hall Upper Saddle River, NJ.
Wang, T, Wedin, D & Zlotnik, VA 2009, 'Field evidence of a negative correlation between saturated hydraulic conductivity and soil carbon in a sandy soil', *Water Resources Research*, vol. 45, no. 7.
Yolcubal, I, Brusseau, ML, Artiola, JF, Wierenga, PJ & Wilson, LG 2004, 'Environmental physical properties and processes', in *Environmental monitoring and characterization*, Elsevier Inc., pp. 207-39.

Project Management Statement:

The undertaking of this research has been an illuminating educational experience and has provided a lot of useful skills in the final year for me as an undergraduate, completing a Bachelor of Environmental Engineering (Honours). However, the change from a structured environment where it was very formulaic of how the unit would be run to undertaking a unit where there is so much freedom for an individual approach was quite nerve-wracking. This is because it meant that my time management skills needed to be strong to ensure that I did not lose focus during this semester.

Dr Brandon Winfrey was so encouraging and supportive throughout this process, and I cannot thank him enough for being so supportive and encouraging during this process. From Semester two of 2019 until the end of the submission he was always available for help, and we had weekly meetings (apart from the odd occasion of fortnightly meetings), and we always were able to work together to find times that matched. The routine meetings met that I was able to keep on track with my research and made sure I did not leave a significant amount to the end of semester one of 2020. Before each meeting, I would send across what I had been working on for the week with annotated notes/highlights advising what I had achieved in the week. Brandon taught me many skills throughout this time that will help me outside of this unit, such as the ability to cross-reference in Microsoft Word and gave me a lengthy demonstration of how to use SCOPUS effectively. This is invaluable knowledge that I appreciate that he was able to teach me. Once I had a better understanding of some useful resources, I was able to better plan and more effective research about the topic. One way that I was able to do this was by using SCOPUS. SCOPUS allowed me to refine my results to exclude literature that was not entirely relevant to the topic and refine it directly to what I wanted to find. I was then able to export the information to an excel spreadsheet from SCOPUS, and then by reading the abstracts in an organised manner, I was able to compare literature to understand what was the most relevant to the topic and determine where there were linkages.

Overall, I feel that my time management skills were good in that I was able to complete this promptly. Choosing a twelve-credit point for the research proposal has had its benefits and limitations. The benefits are that I was able to continuously refresh my ideas to ensure I had a firm grasp of the topic and that I was able to more efficiently research about the topic due to the extra time available. However, I do feel like I could have done more during the summer break leading into semester one of 2020 to be more prepared now that I think about it retrospectively. Due to numerous external issues, I had previously been doing less than four subjects in previous semesters, so this was the first time I was doing four subjects in one semester in some time which at times tended to be overwhelming.

One of the significant challenges that I experienced during the development of this research proposal was the disruptions caused by COVID-19. COVID-19 completely changed the way that I had to approach the research. Initially, there was going to be significant amounts of fieldwork conducted to measure the infiltration rates in different biofilters around Melbourne. The tests would have been replicated in the field using the SATURO infiltrometer on dry loamy sands. This meant that the focus of the research needed to be switched to an extensive literature review on infiltration methods used in both biofilters and sandy dunes as a comparison. Some data was captured in the forms of preliminary tests. However, the amount of data was not recorded to the extent required to make fully realised deductions. The data presented in the results and discussion are uncalibrated; they are simply used as a reference to point to explain how deviations from the ideal soak time and pressure head configurations using the infiltrometers (specifically the dual head infiltrometer being the SATURO) made a significant impact to the K_{fs} error values recorded.

This was the first time writing a research proposal was very daunting for me. Throughout my time at university, the formatting guidelines of other units were not as strict compared to this research proposal. Adhering to the formatting and page limits by also being able to convey the information in a meaningful way but also by being concise was challenging. However, I do appreciate that I was able to undertake this research proposal because I am now able to apply the technical skills, I have learnt about reporting writing beyond just this unit and post-university.