CHARACTERISING CONTAMINANT LOADS, TREATMENT, AND MONITORING AS SOURCES OF VARIABILITY IN STORMWATER TREATMENT SYSTEMS

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ABSTRACT (500 WORDS MAXIMUM)

In an effort to remove contaminants from urban runoff, stormwater treatment systems are gradually being integrated into the built environment. These include detention basins, treatment wetlands, rain gardens, and commercial manufactured devices. They have been installed with an expectation that they will improve stormwater as it moves through them, and in some cases are part of an overarching, catchment-wide water quality improvement plan. Frequently, these stormwater treatment systems do not meet the upper contaminant removal efficiencies due to an incomplete understanding of the dynamic variables that affect their performance. Contaminant removal performance within various stormwater treatment systems shows a high variability between different systems, between systems of the same type at different locations, and even within an individual system between different storm events. Variables affecting performance range from human-derived factors such as lack of maintenance, improper installation, or poor design, to the physical environment, such as climatic conditions affecting rainfall intensity, frequency and duration as well as catchment impervious surface types and speciation of contaminants.

Sources of variation in stormwater treatment system efficiency can be expressed as three broad categories: (1) contaminant load variables, (2) treatment system variables, and (3) monitoring technique variables. Contaminant load variables are influenced by local climate and catchment land use and surface materials, treatment variables depend on a stormwater treatment system's specific design, installation and maintenance history and operational mechanisms, while differing monitoring techniques likely contribute to variation in globally available data. This paper outlines and qualifies the key sources of performance variation within stormwater treatment systems. A better understanding of these variables will help improve choice of treatment system type, placement, and management.

KEYWORDS

Urban waterway, stormwater treatment, stormwater contaminant

PRESENTER PROFILE

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1 INTRODUCTION

Urban stormwater drainage systems have historically been designed and developed for the sole purpose of conveying runoff as efficiently as possible away from impervious surfaces, with little thought for the receiving water quality (Fletcher et al., 2015). This has mostly been achieved by directing untreated runoff into urban streams, which has led to high concentrations of urban contaminants such as suspended solids, heavy metals, nutrients, and hydrocarbons (Walsh et al., 2005; Jefferson et al., 2017). Drainage of most cities around New Zealand is achieved in this way; in Christchurch, for example, the majority of urban runoff flows directly into pipes which ultimately discharge, for the most part, into the Avon and Heathcote Rivers (Christchurch City Council, 2009; Marshall and Burrell, 2017; Golder Associates (NZ) Limited, 2018).

In an effort to remove contaminants from stormwater runoff and reduce the hydrologic effects downstream of flooding from impervious surfaces, stormwater treatment systems have been slowly integrated into the built environment. These include systems such as detention basins, treatment wetlands and rain gardens, as well as commercially manufactured structures and devices (Fletcher et al., 2015).

Stormwater treatment systems have been referred to in many different ways around the world. Frequently used terms include: low impact development (LID), sustainable urban drainage system (SUDS), stormwater control measure (SCM), green infrastructure (GI), water sensitive urban design (WSUD), stormwater quality improvement device (SQUID), nature based solutions (NBSs) and most recently, best management practices (BMPs). It is important to consider that in many cases, the term may not refer to a singular water treatment process, but an incorporation of the presence and reduction of the damaging effects of stormwater volume and quality in urban design. The term 'BMP,' which originated as methodology for sustainable land management in North America, has evolved into a term referring to physical structures that remove contaminants from urban stormwater, predominantly used in the USA and Canada (Fletcher et al., 2015). In their review, Fletcher et al., (2015) point out the vagueness of the term, BMP, as the word "best" can be misconstrued, and it may be understood to refer to a general land management practice rather than a singular treatment system. For clarification, the term "stormwater treatment system" is used in this paper intending to refer to a singular treatment process.

Depending on the receiving water body, many local authorities in New Zealand require stormwater treatment. These include: Northland, Auckland, Waikato, Bay of Plenty, Hawkes Bay, Canterbury, Otago, and some parts of Southland. Globally, in the National Pollutant Discharge Elimination System (NPDES), the United States has set total maximum daily loads of contaminants for certain water bodies or municipalities (USEPA, 2018). Contaminant generation and removal can be controlled by low impact development, or through the installation of stormwater treatment systems.

Some local authorities require strict studies undertaken to approve the sale and installation of proprietary stormwater treatment systems, also known as manufactured devices (MDs) within a municipality (Washington State Department of Ecology, 2011; The State of New Jersey, 2013; Ansen et al., 2014). Guidelines set out the process for a MD to be used in development projects, beginning with laboratory evaluations all the way through to field scale evaluations in natural conditions. Following a field evaluation by industry developers that shows suitable contaminant removal rates, MDs are listed as approved stormwater treatment systems and can be used in development to meet regulatory controls. Subsequent development practice is to utilize an approved stormwater treatment system based on the best practical approach (i.e. hydrologic load, size, price etc.) to treat a location's runoff. This does not signify, however, that MDs will always perform as they did during field trials, due to an array of variables (Sage et al., 2015; Liu et al., 2017).

In spite of the required monitoring and knowledge of treatment system function prior to installation, stormwater treatment performance still remains in a grey realm and is reported to range widely between systems of the same type, and even within the same system between different storm events (Clary et al., 2017). In an effort to conglomerate treatment system monitoring data reported widely, to provide a better idea of what removal to expect from different system types, the International Stormwater BMP Database (BMPdb) was developed. This database serves as a repository for large amount of data including influent and effluent contaminant concentrations from various treatment systems, as well as some metadata including treatment system location, and storm details in different spatial and temporal dimensions around the world. Performance is reported as the concentration of key contaminants (metals, suspended sediment, nutrients etc.) in the influent and effluent of treatment systems. However, within the reported monitoring metadata there is a general lack of data related to treatment system and storm details. These details include specific vs. pre-fabricated design, quality of installation and as-built drawings, maintenance regimes, age of system, current state of the system at the time of monitoring, total runoff and pollutant loads treated, storm characteristics, and watershed characteristics such as slope, vegetation, and land cover (Liu et al., 2017).

At an individual scale, the impact of a treatment system with a high degree of removal variability has precluded the ability for models to accurately predict the downstream effects of stormwater treatment (Ahiablame et al., 2012). The variability has been blamed for catchment restoration projects not meeting their goals (Liu et al., 2017). While Jefferson et al., (2017) suggested in a review that performance variation is largely dependent on variables that change from catchment to catchment, others indicate variations within stormwater treatment systems themselves as sources of uncertainty (Hunt et al., 2006; Ahiablame et al., 2012; Liu et al., 2017).

This paper discusses the key variables that affect variability in contaminant removal efficiency during a stormwater treatment system's lifetime. The paper involves an analysis of the performance of treatment systems around the world and the variables affecting the performance of those systems. Knowledge of the contaminant loading, treatment specific, and monitoring variables that affect stormwater treatment system performance will help in the selection and installation of more effective and resilient stormwater treatment systems in the future.

2 METHODOLOGY

A review of international literature and an analysis of the BMPdb was initially undertaken. Available literature included a detailed review of case studies published in journals, conference proceedings, governmental reports and individual studies on treatment system performance and function. The BMPdb analysis examined internationally available monitoring data of treatment systems. Observations of local treatment systems within Christchurch provided local examples of treatment system function. It is important to note that the BMPdb lacks full monitoring records of treatment systems with respect to a system's condition at the time of monitoring, maintenance activities, and other metadata information (Liu et al., 2017). This metadata lies at the basis of variability within treatment performance. The lack of metadata was supplemented with reviews of individual studies when available.

3 RESULTS AND DISCUSSION

Variation in contaminant removal performance was seen across stormwater treatment system types throughout the literature and within the BMPdb (Clary et al., 2017). As an example, total zinc removal efficiencies varied across system types reported in the BMPdb is summarized in Figure 1.

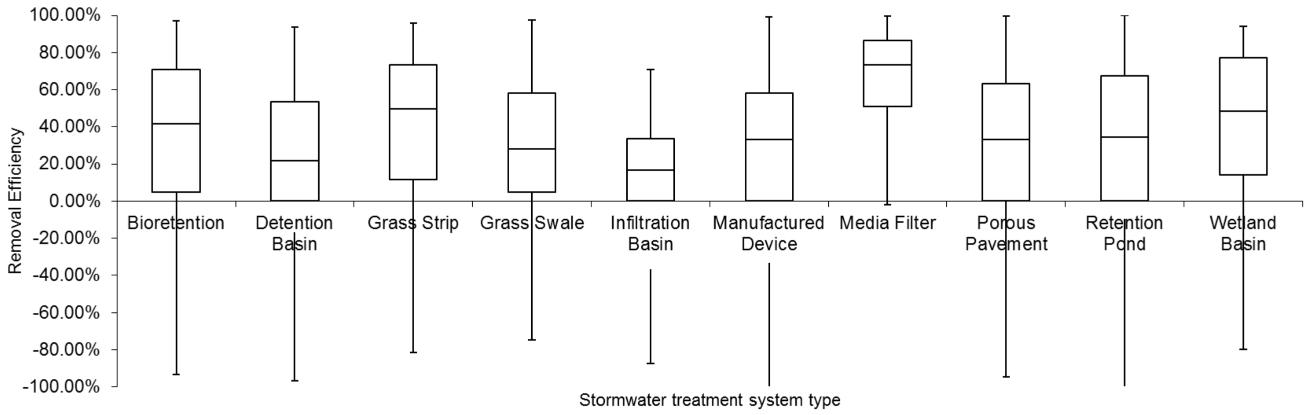

Figure 1: Variability in total zinc removal across stormwater treatment system types with removal efficiency on the y-axis. Data sourced from the BMPdb (2019).

In general, nutrient loading within the effluent is the greatest source of variation seen in stormwater treatment (Hunt et al., 2006; Dietz, 2007; Stander et al., 2010). Liu et al., (2017) found total phosphorus contributes the greatest variability to stormwater treatment systems, with removal efficiencies ranging from net export (-240%) to removal (87%). The authors also encountered negative removal rates of TSS, TN, TKN, and NH3-N. In another investigation of bioretention basins for hydrologic and contaminant removal performance, NO_3^- removal efficiencies varied between 13%-75%. If the bioretention cells weren't reducing outflow through infiltration, they would have also been net exporters of nutrient mass (Hunt et al., 2006). In the context of Christchurch, contaminants of concern include dissolved metals, TSS, BOD_5, DRP, and E. coli (Marshall and Burrell, 2017). As such, a focus has been given on several of these contaminants.

When making judgements based on expected treatment performance alone, influential variables can be grouped into 3 broad categories: contaminant load variables, treatment variables, and monitoring technique (Figure 2). Contaminant load variables include the attributes of each rainfall event – from the antecedent dry days before rain, to the intensity and duration of rainfall, to the pH of the rain itself – as well as the hydrology and land use within the contributing catchment. These factors determine the expected flow rate and volume of runoff to be treated, as well as contaminant speciation signature, and loads to be treated. Water quality is affected by specific treatment variables, which range from the type of treatment system in place and whether it has been specifically designed for the specified location and expected contaminant load, to the maintenance regime and current physical state of the system. The quantity of contaminants (either one or more types) that has been treated and any changes to the runoff flow rate brought about by the treatment system may also affect the overall efficiency. Discrepancies may also exist within the monitoring techniques used to collect water quality data. From the location used to obtain a representative sample, to the temporal discrepancies that result between first flush and steady state conditions, to the number of aliquots per sample, these discrepancies may have a large impact on the overall rating of efficiency.

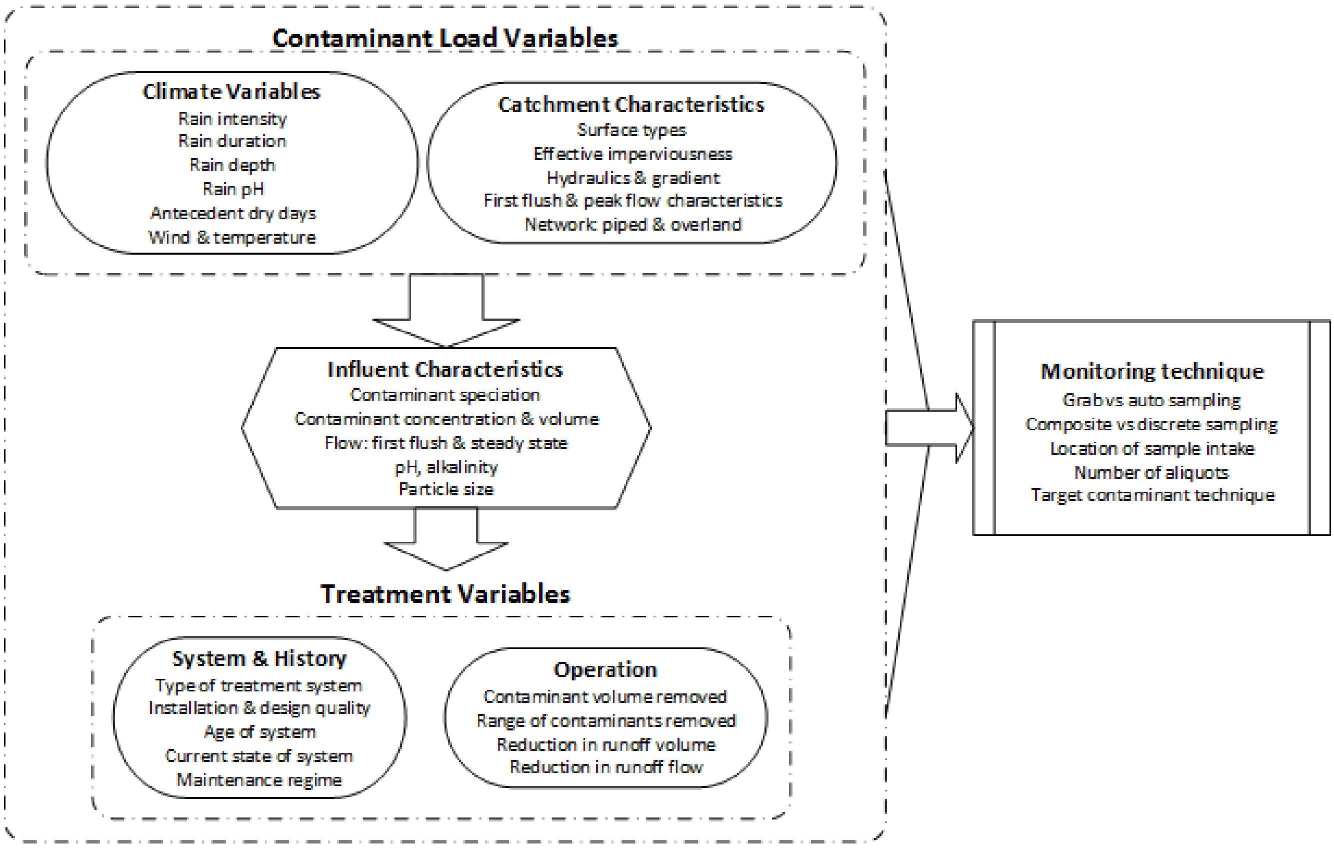

Figure 2 Proposed treatment variables relating to the efficiency of a stormwater treatment system

3.1 LOAD VARIABILITY

Each catchment has its own contaminant and hydraulic loading signature, dependent on many factors including the amount and layout of impervious surfaces and land use activities (Liu et al., 2013; Charters et al., 2015). The load generated for a stormwater treatment system is dependent on these surface characteristics, as well as the catchment's unique climate and individual storm characteristics (Jefferson et al., 2017).

3.1.1 CLIMATE AND STORM CHARACTERISTICS

A variety of storm characteristics influence contaminant generation in stormwater. Both the duration and the intensity of storms generate different contaminant loads (Charters et al., 2015) which can vary throughout a rain event. It is generally understood that a short intense rainfall will mobilise more sediment than a long light rainfall with a similar volume. The amount of contaminants available for transport depends on build-up processes which are less understood than wash-off processes (Wijesiri et al., 2016a). Antecedent dry days (the amount of dry days before a storm) have been indicated to have a large influence on contaminant generation, allowing for longer periods of contaminant build-up (Moore et al., 2017). Contaminant build-up and wash-off models that accurately predict the concentration of metals in runoff, dependent on rainfall pH, intensity and duration, are rare but are slowly being developed and may help better undertand the natural variability in contamint loading (Auckland Regional Council, 2010; Fraga et al., 2016; Wijesiri et al., 2016b).

Removal of different size sediment is critical for not only TSS reduction, but removal of other contaminants – such as metals, bacteria and nutrients – that bind to small particles with large surface area (Marla and Kim, 2016).

Site specific climate has an impact on the functioning of a treatment system. In North Carolina, USA, researchers found a high variation between winter and summer hydraulic infiltration rates of bioretention cells, with summer conditions capturing and infiltrating significantly more runoff than in winter for the same amount of input runoff (Hunt et al., 2006). In contrast, researchers in Wisconsin and Minnesota, USA, found no statistical difference between seasonal infiltration rates in a grassed swale in spring and autumn (Ahmed et al., 2015). Results from a similar study in south-eastern Pennsylvania, USA, suggest that variation in seasonal infiltration rate had more to do with the dynamic viscosity of water than the vegetated state of the treatment systems, with the viscosity of water doubling during the colder winter months and subsequently slowing infiltration (Emerson and Traver, 2008).

Similar seasonal variability was found with nutrient, metal and sediment removal rates. Higher removal rates of NO_x occurred during summer months in Melbourne due to high denitrification rates (Hatt et al., 2009). Copper removal was dependent on the time of year, with the spring showing higher removal rates than the autumn (Cates et al., 2009). Stormwater treatment systems such as bioretention systems that rely on vegetation to slow water and allow for sedimentation of TSS, are affected by seasonally induced growth rates. A lush, vegetated garden in the summer months can contrast significantly in the winter and have large impacts on removal efficiency (Emerson and Traver, 2008).

Climate and storm characteristics can have a large influence on the contaminant load generated and transported within a catchment and the subsequent performance of treatment systems. Seasonal and atmospheric characteristics are not consistent geographically, which suggestes that these factors alone do not influence treatment system performance. The different surfaces that rain falls on further exemplifies the dynamic nature of stormwater characteristics.

3.1.2 CATCHMENT SURFACE CHARACTERISTICS

Each catchment generates its own unique contaminant load, dependent on the type and quantity of surfaces in the catchment (Fraga et al., 2016). Atmospheric depositional processes during both dry and wet weather periods also impact the speciation of contaminants within stormwater (Kabir et al., 2014). Depending on both atmospheric conditions at the time of a storm event, as well as runoff flow rate and transport characteristics, metal contaminants in runoff can be found in various ionic forms (Violante et al., 2010; Kabir et al., 2014). Metal removal from stormwater is thus depended on its chemical speciation entering a treatment system (Kabir et al., 2014) or the size of particle that it is bound to (Marla and Kim, 2016).

Particulate load generation within catchments varies as a function of surface type and catchment hydrology (Charters et al., 2016; Poudyal et al., 2016). Fine particulate matter generated from roofs, roads, carparks, and pervious surfaces often acts as vectors for contaminant transport within runoff. The finer the suspended sediment and particle size, the more surface area available for contaminant bonding (Marla and Kim, 2016). Particles less than 250 μm have been shown to absorb the majority of heavy metals (Haile et al., 2015). Both the storm size and hydrology of the catchment determine a critical flow for which TSS loads are transported to and through treatment systems (Tiefenthaler et al., 2000). For effective stormwater treatment, treatment systems must be designed with an expected particulate size in mind and focus on removal of fine sediment (Charters et al., 2015). If the contaminant sources, quantity and concentrations of expected contaminants are not correctly identified, the treatment systems may become quickly overloaded and clogged, and require more maintenance than expected; or the reverse, they may not treat the actual contaminant load at all (Liu et al., 2017).

A catchment’s ability to infiltrate runoff has a large impact on when and how much load is generated during a storm. The variation in contaminant concentrations between the first flush and steady state will vary throughout the duration of a storm event. A highly impervious catchment will generate more runoff with a higher concentration of contaminants during the first flush (Kayhanian and Stenstrom, 2005) than a catchment of higher capacitance (ability to infiltrate runoff) (Miles and Band, 2015; Jefferson et al., 2017). Similarly, catchments with a developed, piped stormwater network, also known as a high effective imperviousness (Hatt et al., 2004), will transport contaminant loads more quickly and effectively than overland runoff. With different hydrologic and contaminant loading and treatment, removal performance and effluent concentrations should be expected to change throughout a storm.

Any changes in a catchment's surface characteristics (site development, construction, land use change, etc.) will result in changes in loading and thus result in potential variability in downstream treatment. For example, a dry and hot summer would decrease the capacitance of a catchment to infiltrate runoff and result in additional suspended sediment and hydrologic load on a downstream treatment system, while new construction or transformation of pervious surfaces due to development would have a similar effect.

Together, climate and catchment make up influent load characteristics that act upon stormwater treatment systems. A catchment's contaminant generation is determined by the previous climate and individual storm characteristics acting on the specific surfaces. Each catchment generates a unique particle size distribution, and contributes a unique chemical makeup of dissolved metals and other contaminants, dependent on its land use and surface types. Catchments generate more contaminant and hydrologic load with increasing imperviousness, which varies with the seasons and development choices. Imperviousness also affects the hydrological impacts of the first flush and steady state conditions which leads to performance variability within an individual treatment system.

3.2 TREATMENT VARIABILITY

Looking at discrepancies within individual treatment systems presents a plethora of potential for variability. The design, construction, and installation of treatment systems is made more complicated by the complexities involved in modelling stormwater (Ahiablame et al., 2012; Fraga et al., 2016). Generally, the installation of treatment systems is undertaken by contractors who may be more likely to make localized variations to the design, resulting in critical effects on treatment efficiency (Lucke and Nichols, 2015). Additionally, maintenance is a critical area in which stormwater treatment systems have been known to suffer complete neglect following installation (Blecken et al., 2017). Furthermore, the physical condition of a treatment system at the time of a storm event has a great effect on the expected contaminant removal during the particular storm.

3.2.1 DESIGN, CONSTRUCTION AND INSTALLATION

Making good initial design choices based on the expected contaminant and hydraulic loads is the difference between function and failure of a treatment system. Municipalities generally have manuals for building bioretention basins which have recommendations for ponding times, recommended media (sand, compost, topsoil, pH, salt, fertility, membrane or filter fabric), and sizing guidelines dependent on the impervious area to filter (Dietz, 2007). Identification of site conditions such as sunlight and rainfall patterns, surrounding land use and human activities, underlying soil type and water table, is critical to the functional performance of a treatment system (Eckart et al., 2017). A disregard for specific design in an individual catchment and mistakes during construction and installation, may have long lasting outcomes on the ability of a treatment system to treat unique hydrologic and contaminant loads.

The design of treatment systems is a difficult task, which can only be correctly undertaken with prior knowledge of an expected contaminant load and character. In a review, Ahiablame et al., (2012) summarized the critical nature of sizing and installing stormwater treatment systems, especially of bioretention systems. Undersized systems will yield more overflow/bypass of untreated runoff during larger events and greatly reduce performance (Davis et al., 2003; Cates et al., 2009). Accurate sizing of sedimentation ponds saves money on unnecessarily large designs, and ensures a large enough retention time to allow for sedimentation of a target particle size, which is critical for removal of particulate bonded metals (Selbig et al., 2016). While it is not possible to accurately design a treatment system to obtain a specific removal (Currier et al., 2006), undersized and oversized retention basins are common. In the study of a pre-existing bioretention basin in Auckland the authors found that it had most likely been undersized for the contaminant loads it was treating. As can be the case with treatment system design, the authors had difficulty calculating the contributing area to the basin, combining methods of opening/following manholes up the catchment, calculating area based on recorded inflows, and using old aerial imagery (Trowsdale and Simcock, 2011).

Knowledge of a catchment's expected loads plays a key role in media selection. For example, the selection of media with a buffering capacity means contaminant removal can continue even in the event of changes in stormwater pH (Davis et al., 2003). Even in lab settings where contaminant removal efficiencies are idealized by removing natural variation, removal rates of Zn varied between 75 – 96% with different media combinations of sand, compost, and other specialty media (Seelsaen et al., 2006). Inappropriate design for the expected contaminant loading will result in performance efficiencies below expectation and the potential for large variations in performance.

Not only is sizing important, but for vegetated systems, the type of vegetation is fundamental to a treatment system's success (Ahiablame et al., 2012). The selection of appropriate grass species in a swale, for example, is critical for maintaining expected contaminant removal rates, as different species of grass have been shown to benefit different removal mechanisms, from infiltration to removal of metals (Leroy et al., 2017). The flow rate across the surface of a swale, which affects its contaminant removal rates, is regulated by its length, slope, check dams, and the type of vegetation on the surface. Those design factors were attributed to the variation found in removal rates of grass swales in Virginia, USA and an agricultural test farm in Taiwan, which varied between 14% to 99% for TSS, COD, TN and TP (Yu et al., 2001).

Within infiltration systems the critical design parameter is residence time to obtain sufficient treatment, and hydraulic conductivity to avoid overflow/bypass events (Kluge et al., 2018). The frequency and volume of overflow events decreases the overall performance of an infiltration system as untreated water passes downstream. Locating treatment systems at the source of contamination is recommended (Zahmatkesh et al., 2015); when distances increase, runoff becomes overloaded with contaminants, resulting in relatively high effluent levels and more potential for bypass.

In some cases, the design and installation of a system is responsible for heightened contaminant loads within the effluent. Trowsdale & Simcock, (2011), for example, suggested that higher dissolved Cu concentrations in the effluent of a bioretention system (net exportation of dissolved Cu) may have originated from fungicides used in a soil potting mix, or formerly applied to plants in the nursery prior to planting in the bioretention cell.

Flaws in installation are common in stormwater treatment systems. In one study, a clogged and un-functioning patch of porous asphalt was scraped and the top 2.5 cm was removed. This returned the pavement to near new infiltration conditions. However, this same maintenance strategy was performed on other patches of asphalt to no avail. The blame was pointed at flaws in installation (Winston et al., 2016). Manufacturers of permeable pavement insist that with proper design and installation of subsurface soils, and good maintenance and care, infiltration rates can be maintained no matter the season (Dietz, 2007). Similar flaws in installation quality were found recently at the University of

Canterbury which resulted in variability of performance. A commercial treatment system was discovered to be leaking at the influent manifold to the extent of no flow through the system, rather, all flow through the system was infiltrated to the gravelly undersoil (author's observations).

Proper design, construction and installation is critical for functionality of a stormwater treatment system. Site specific conditions can have a large effect on factors such as vegetative growth and infiltration rates. An understanding of expected contaminant loads is critical for correct media selection while varying hydrologic loads impact the residence time in retention basins. Mistakes during construction and installation are common and have the potential to render a treatment system useless, or worse, turn them into contaminant exporters.

3.2.2 MAINTENANCE

A lack of maintenance is a common example of a treatment system not functioning as expected (Erickson et al., 2010; Li, 2015). In a review, Blecken et al., (2017) noted that common practice when implementing a stormwater treatment system is installation followed by neglect. This is especially common in areas where regulatory consent requires the use of a best management practice, rather than consented stormwater discharges managed by total maximum daily loads.

In a review of treatment system effectiveness, Ahiablame et al., (2012) noted that clogging of permeable pavement systems is common. Provided they are constructed correctly, these systems require regular maintenance to maintain their capacity for filtration and infiltration (Winston et al., 2016). Furthermore, permeable asphalt, concrete, and pavers may require specific care and use, such as suction cleaning and avoiding salt application and sanding in the winter to maintain their performance and lifetime (Dietz, 2007).

In many cases treatment systems are left alone after installation, sometimes forgotten about and not maintained, and presumed to be treating the target contaminants. A survey of city stormwater departments in the United States showed that 61% of cities conduct annual maintenance trips (Erickson et al., 2010). A lack of maintenance leads to membrane filters becoming clogged, media becoming overloaded with contaminants, and biofiltration systems becoming clogged. At the University of Canterbury, a commercial filtration system was left, un-maintained, for approximately 2 years. It was not treating runoff at all during a storm prior to maintenance; following the maintenance, it treated stormwater as expected (author's observations). In a study of underground filtration media designed to remove fine particles, the majority of heavy metals were found deposited within the outer layer of the media surface while an accumulation of fine particles had led to the degradation of hydraulic conductivity over time – thus increasing bypass rate and decreasing contaminant removal performance (Haile et al., 2015).

The reliance on vegetation in a stormwater treatment system presents another realm of maintenance factors, affected by seasonal and atmospheric conditions that play a large impact on the efficiency of contaminant removal. In some cases, the height of the vegetation or grass in the swale is responsible for slowing runoff to allow for sedimentation (Yu et al., 2001). Should excessive mowing occur, retention of TSS is expected to decrease. In another study involving hydraulic conductivity of the soils, researchers suggested that roots and the presence of established vegetation creates macropores within the soil structure of a swale that increases the hydraulic conductivity. When vegetation is young and developing, infiltration rates will be lower than when vegetation has matured and formed deep roots (Hatt et al., 2009; Ahmed et al., 2015). Another study found high removal rates of metals within the top layer of the soil following establishment vegetation within a road-side infiltration system. Low removal rates occurred just after installation, when vegetation was young, root systems were not very well established, and vegetative coverage was also inadequate (Leroy et al., 2017).

Efficiencies of treatment systems are likely to change over time, even with regular maintenance activities. In vegetated systems these variables include changes in vegetation species, age and root structure of the plants, while in manufactured systems this could include structural degradation, and accumulation of contaminants (Liu et al., 2017). Natural treatment systems age differently to manufactured systems and are at risk of invasive species taking over (Erickson et al., 2010). In one case, the continued performance of an infiltration pond was attributed to regular maintenance and mulching of the vegetation surrounding the pond, as well as good design and vegetative health. The maintenance regime reduced the amount of suspended sediment entering and potentially slowing infiltration rates (Emerson and Traver, 2008). With proper maintenance and vigilance for invasive vegetation, degradation of the hydraulic conductivity from long-term (over 10 years) operation is not expected within natural systems due to the presence of established root systems that work to break up sediment and maintain a porous bottom (Kluge et al., 2018).

Blecken et al., (2017) suggests the plethora of maintenance activities required for good upkeep of mostly natural stormwater treatment systems (Table 1).

Table 1: Maintenance needs for various stormwater treatment systems (Blecken et al., 2017)

	Maintenance needs					
Practice	Forebay cleanout & disposal	Pruning	Removing / mowing vegetation	Inspect outlet structure	Unclog surface	Mechanic or electric repair
Wet Pond	X		X	X		
Wetland	X		X	X		
Bioretention	(X)	X		X	X	
Infiltration trenches					X	
Permeable pavement					X	
Filter strips & swales			X			
Rainwater harvesting	X[1]					X

Notes:
(1) Rainwater harvesting systems have a first flush diverter to be cleaned out (cognate to a forebay) and a debris screen to be unclogged.

Unmaintained stormwater treatment systems inevitably lead to clogging and poor performance. Maintenance activities differ with different treatment system; natural treatment systems require specific care of the vegetation, while structural systems require regular mechanized inspections. Especially in the case of permeable pavements, specific maintenance considerations and land use activities that degrade a treatment system require all user groups to have an understanding of the system's functionality. In the long run, however, long-term performance of a stormwater treatment system is expected to either increase or decrease depending on the regular maintenance and care it receives.

3.2.3 SYSTEM'S CONDITION DURING STORM

The current condition of a treatment system at the time of monitoring is potentially the most allusive to the system's treatment efficiency during the storm. For example, if there is residual water from a previous storm in a retention basin, overflow of the system will occur sooner than otherwise (Liu et al., 2017), resulting in a lower volume of treated runoff.

A properly designed, dry bioretention unit will treat the majority of the contaminants within the contaminated first flush (Kayhanian and Stenstrom, 2005; Poudyal et al., 2016). This not only generates a higher removal performance for the system, but protects downstream waters from the higher contaminant concentrations of the first flush (Davis et al., 2003). Should any subsequent overflow of the system occur during the steady state of long-duration events, the contaminant load within the influent is comparatively lower. When the system is saturated, the bypass state is reached more quickly resulting in a decrease in performance.

In an infiltration basin, the effect of a previously high groundwater table can lower contaminant removal rates as a result of bypass. Infiltration basins depend on their ability to infiltrate runoff; in one study, high mass removal rates of zinc, copper and lead (98%, 99%, and 81% respectively) were primarily due to hydraulic retention and infiltration (Hunt et al., 2006). Generally, metals to bond to the near-surface sediments as water infiltrates and does not pose a threat to groundwater (Kluge et al., 2018). A decreased ability to infiltrate runoff due to previously wetted soil and a higher groundwater table will result in additional bypass of untreated runoff from the system.

A treatment system's physical condition at the time of a storm event has the most influence on its performance. The condition it's in comes from proper design and a good maintenance regime, as well as previous atmospheric conditions. When monitoring performance of treatment systems, physical condition is a critical component to be recorded as it aids the subsequent investigation in variability of contaminant removal.

3.3 MONITORING TECHNIQUES

Stormwater treatment performance monitoring is a complex study due to the amount of variables that affect it. Stormwater quality on its own varies not only from event to event, but within the duration of a storm itself. Variation in stormwater quality samples from grab sampling is higher than both wastewater and potable water variation (Lee et al., 2007). The variations within individual stormwater treatment systems leads to further complications when monitoring their contaminant removal performance. Because of this, multiple protocols have been suggested and are required by certain authorities (Washington State Department of Ecology, 2011; The State of New Jersey, 2013; Ansen et al., 2014).

Due to the complexity of stormwater itself, monitoring programs must be complete to catch variability. Contaminant concentrations within runoff change during a storm cycle, from the highly contaminated first flush to the more dilute steady state, and peaks in between, depending on rainfall intensity and other factors. In some locations of consistent dry weather, there is a seasonally increased first flush contaminant concentration (Lee et al., 2007). Monitoring programs should include sampling and analysis for a full set of stormwater contaminant speciation, especially as some treatment systems have been reported to remove total metals, but not the dissolved fraction (Trowsdale and Simcock, 2011). Sampling only a portion of stormwater flow may show different contaminant concentrations than sampling the total flow. Sampling the total flow leads to an event mean concentration (EMCs) of a particular contaminant that is used to characterize a storm's contaminant load. Using an auto sampler at regular intervals is the most accurate method of obtaining an event mean concentration, however, individual sampling strategies do exist. McCarthy et al., (2018) found random grab sampling strategies for TSS and TN were most similar to EMCs, while fixed grab sampling strategies led to most similar EMC results for E.coli.

To ensure continuity and comparability with other stormwater treatment systems, monitoring programs should adhere to strict and common practices. A full analysis begins with sampling procedure and the number of aliquots taken during a storm event. This is made easier with the use of an auto-sampler, but further variations can originate from flow proportional vs time sequential sampling regimes. Flow proportional sampling will catch more of high flow periods in a storm when more contaminants may be present, while time based sampling may skew results toward lower flow concentrations (NIWA, 2014). Grab samples can vary drastically based on the time during the event they are taken (Lee et al., 2007). Monitoring flow rate through a treatment system is critical to understand a treatment system's response to hydrologic load and bypass (Washington State Department of Ecology, 2011). Following sampling, an extended holding time of a sample may allow for metamorphosis of contaminants to change form, or precipitate from solution, therefore, strict quality assurance processes must be in place to ensure continuity. There are large differences in stormwater treatment system performance when comparing laboratory experiments, with natural field based settings. Field based studies using synthetic stormwater show higher performance rates than natural conditions.

Influent contaminant concentration is a key indicator of contaminant removal efficiency. Generally, a higher influent concentration of a target contaminant will yield a higher removal efficiency. In spite of the high removal rate, effluent concentrations of the target contaminant are generally still high and when emitted to receiving water bodies, depending on stream/lake size, may result in contaminant concentrations above environmental guidelines (ANZECC, 2018). Conversely, treatment system's efficiency value generally decreases with low influent concentrations (Hatt et al., 2009). As such, the performance of a treatment system cannot be considered based on efficiency alone, but in context with the land use derived, volumetric contaminant loads exerted upon and emitted by it (Clark and Pitt, 2012). While the word 'efficiency' may be used to describe a system's operation, it should not be used as the sole metric to describe a treatment systems contaminant removal performance.

Because accurate investigations of stormwater quality are expensive, the best management practice approach has been adopted. Pre-approved stormwater treatment systems are installed with the intention of treating a catchment's contaminant load, however, the actual performance of the device remains unknown until a monitoring study is undertaken. Industrial sites are different as they may be regulated by a stormwater discharge consent as in the case of the Resource Management Act (NZ), or NPDES.

A consistent monitoring program is critical to maintain comparability between stormwater treatment performance results. Differences in sample collection and processing can lead to un-quantifiable differences in influent and effluent concentrations, and raise unnecessary questions about a treatment system's performance variability. Treatment performance should be assessed by comparing influent and effluent concentrations on a volumetric scale versus removal efficiency. There is no single numerical rating that can be used to compare treatment system performance of different types or locations.

4 CONCLUSIONS

Stormwater treatment systems are affected by a plethora of variables within an urban environment. These variables are responsible for the variation seen in contaminant removal efficiencies and performance. Beginning with surface characteristics and local climate, every urban catchment's stormwater is different than the next, and changes between individual storm events also result in performance variability. The design, construction, and installation within and between different stormwater treatment systems provides an additional source of variability. Understanding this variability is made more complex by the difficulty involved in monitoring stormwater itself. Further research on variability is ongoing and involves a deeper understanding of these variables that affect effluent quality from stormwater treatment systems. It will involve an investigation of influent characteristics, the functions of the individual treatment system and factors that may affect it, and variations in monitoring technique. A deeper understanding of influential variables has the potential to improve treatment system development, and aid in the selection of the best system for a certain location.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support from Callahan Innovation and the University of Canterbury.

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