OUTCOME BASED SIZING OF STORMWATER TREATMENT SYSTEMS

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ABSTRACT

Stormwater treatment devices or 'Best Management Practices' (BMPs), as they are sometimes referred to, can provide both water quantity and water quality benefits. These systems are typically sized using either a water quality volume (WQV) (calculated based on a water quality rainfall depth) or a flow rate (WQF) (calculated based on a water quality rainfall intensity). Although methods for calculating the WQV & WQF can vary across regions and councils within Aotearoa New Zealand, the same volumes or flow rates are typically applied across a range of devices for each locale, regardless of their function. For example, the same WQV may be used to size a raingarden as a wetland. This paper explores the validity of this approach with a focus on achieving a consistent outcome (in this case, in terms of run-off treated), rather than a consistent input (rainfall depth or rainfall intensity). The analysis challenges the status quo by promoting outcome-focused thinking when it comes to stormwater device sizing, based on a comprehensive understanding of system function.

The intended outcome adopted for this analysis was for a benchmark percentage (90% for Auckland and 80% for Christchurch) of annual run-off, on average, to be treated.

To do this, Long Time Series (LTS) rainfall was analysed through each BMP and the input (WQV or WQF) iteratively changed, using automation, until the target outcomes were achieved across all systems assessed. The results illustrate why there is potentially value in using device specific inputs to achieve a more uniform outcome (as opposed to fixed inputs across a range of system types). The methodology used in this study could be replicated for any location, system, or outcome metric, and used to optimise stormwater treatment sizing across Aotearoa New Zealand.

1 OUTCOME BASED DESIGN

Outcome based design is a design approach intended to deliver a consistent result, regardless of the design process adopted. In the context of this paper, the intent is to explore the sizing of stormwater systems using a consistent outcome and reverse engineering the design inputs that would be required to achieve this. Using a consistent outcome as the design target (rather than consistent design input values) may provide scope for innovation and improved cost-effectiveness, reductions in embodied carbon and highlight fundamental differences between treatment systems. It also provides a simplified means of adopting a nationally consistent approach to stormwater treatment sizing irrespective of regional differences such as hydrology. This study has focused on Auckland and Christchurch sizing methodologies and has therefore adopted their specified intended outcomes, i.e., 90% of annual runoff treated for flow-based systems in Auckland (no Auckland specific volume-based systems were assessed) (*B.1.7.2 GD01*) and 80% of annual runoff for volume and flow-based systems in Christchurch (*Christensen & Parsons 2014)*. Whether these metrics are the most appropriate is outside the scope of this study, but the approach could easily be modified to another metric. For example, annual reduction in Total Suspended Solids (TSS) could alternatively be used which would then also include consideration of the device specific treatment efficiencies.

2 CONVENTIONAL SIZING APPROACHES

Conventional BMP sizing approaches are traditionally volume based, i.e., sized based on a first flush volume or rainfall depth. These systems are typically designed to target the 90th percentile rainfall depth of a 24-hour event or 1/3 of the 2 year 24-hour rainfall depth, on the basis that it represents approximately 80% of annual run-off. Hence, in this example, the intended outcome would be to treat 80% of annual runoff.

This outcome was derived from analysis (*TP04*) suggesting the capture of 80% of annual runoff will result in the removal of 75% of TSS on a long-term average basis. Furthermore, *TP10* references *TP04* and states "this study concluded that the removal of 75% TSS is at the marginal point of return for sediment removal versus device sizing, i.e., aiming for a higher degree of removal would require an undue increase in treatment device size and therefore cost".

Some BMPs have little or no storage volume and are therefore typically sized based on a water quality flow rate (determined by the rainfall intensity used). Like volume-based systems, the rainfall intensity used is intended to represent a given percentile of rainfall intensities or percentage of annual run-off treated.

There is a fundamental difference between volume and flow-based systems, however. Volume based systems tend to capture a fixed volume and then bypass once full, whereas flow-based systems treat stormwater up to a determined flow rate (i.e., the water quality flow rate). Flow based systems, once exceeded, will begin to bypass, but may still treat a percentage of the overall flow rate, consequently, flow-based systems can continue providing treatment well after the first flush volume has been exceeded. This analysis accounts for the treatment that still occurs during bypass occurrences.

Auckland Council currently specify approximately 25 mm rainfall depth to represent the 90th percentile rainfall depth and 10 mm/hr for rate-based systems which is intended to represent 90% of annual run-off.

Christchurch City Council currently recommend 25 mm rainfall depth for volume-based systems, with 20 mm applied specifically to rain gardens, and a value of 5 mm/hr for rate-based systems which is intended to represent 80% of annual runoff.

3 METHODOLOGY

For convenience the assessment has been restricted to two rain gauges, Christchurch (Kyle Street EWS) and Auckland (North Shore Albany EWS). The analysis included the following treatment systems:

- Raingarden
- Infiltration Basin
- StormFilter (Proprietary Stormwater360 device)
- Filterra/Bioscape (Proprietary Stormwater360 device)

To determine the outcome, each system is represented by a conceptual hydrological (run-off and routing) and hydraulic model. The catchment was assumed to be 1 hectare with a runoff coefficient of 0.65, the runoff was estimated using the rational method (given the focus is primarily hardstand areas). This is a simplistic rainfall runoff methodology and is likely to over-state the percentage of annual run-off treated due to under-representing pervious run-off in significant events. However, the approach could easily be adapted to use another rainfall run-off model that supports continuous simulation, such as Horton's infiltration model if deemed necessary.

A 5-year period series rainfall is then simulated, and the volume of water treated and bypassing the system totalled to determine the percentage of annual run-off treated. Each model is initialised with a starting water quality depth or rainfall intensity and then iteratively solved until the required outcome is met.

A graphical example of the output of this model is shown below. Figure 1 depicts an approximate 20-hour period of the Christchurch rainfall data during which a storm event was recorded. The flow from this event was routed through a raingarden sized as per Christchurch City Council guidance. The volume of the inflow when the water depth is below the weir level is assumed to be treated, the volume of the inflow exceeding the treatment flow, when the water depth is above the weir level, is assumed to be bypassed. In reality, the water level would not significantly exceed the weir level (as is seen in figure 1), however, this is a symptom of the 10-minute time-step and does not affect the calculations of the % of flow bypassed.

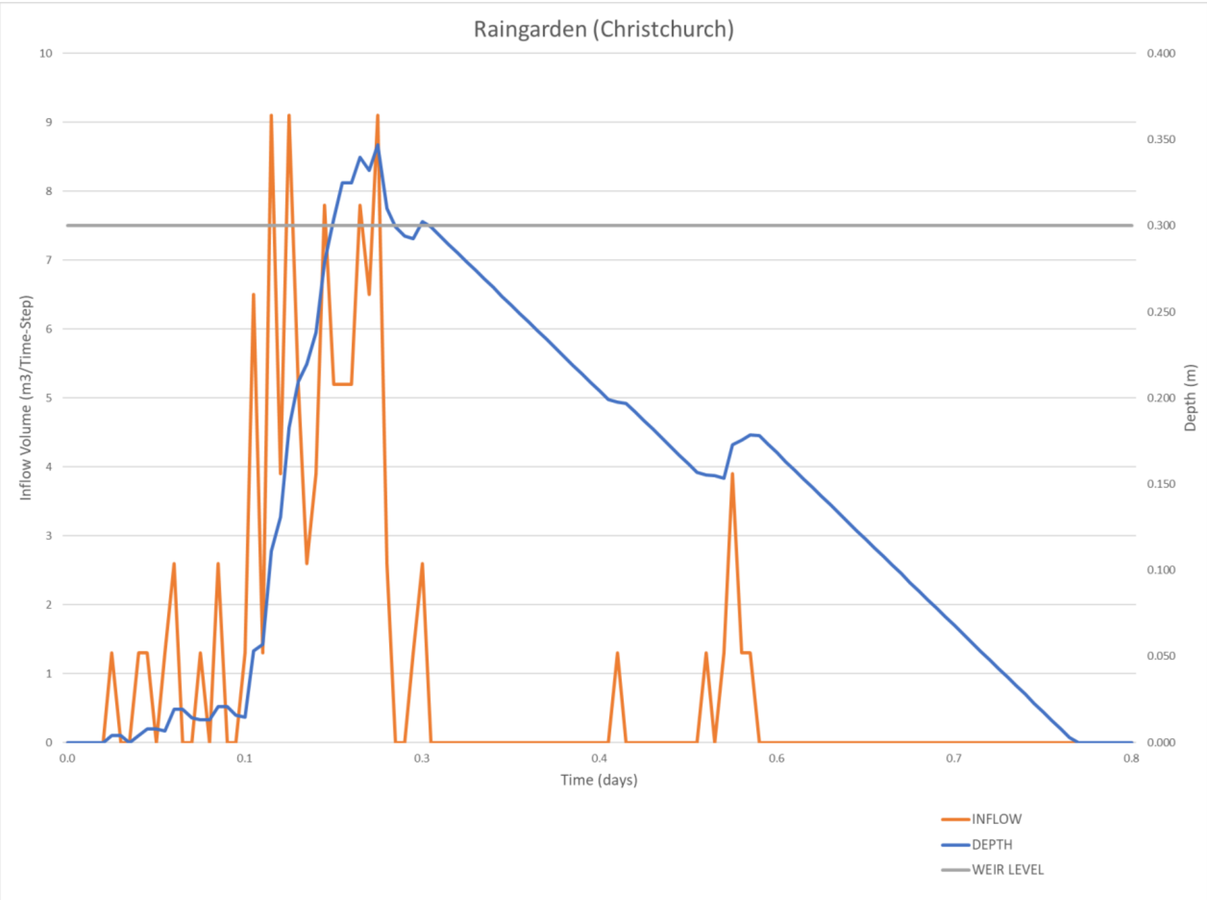

Figure 1 - Inflow & Depth of a Christchurch Raingarden During a Storm Event as per the hydrologic and hydraulic model

Treatment systems were sized following contemporary guidance for the respective locations. A period of 5 years was selected to provide a sufficient timeframe to cover annual variation in rainfall but without undue computational burden.

The outcome targets adopted were derived from local guidance, i.e., to treat 90% of annual runoff in Auckland and 80% of annual runoff in Christchurch. The outcome could easily be changed to a lower or higher value, to cover a longer time period, or even an alternative approach e.g., %TSS removed annually. Whilst %TSS removed would better account for differences between the treatment performance of certain systems, it is beyond the scope of this assessment. However, if this was to be explored in future work, an estimated annual load of TSS (relative to the assumed land-use of the catchment) could be routed through the model, with the load per time-step proportional to the runoff, and the removal of this load dependent on the system used. The sizing of the systems would then be iteratively changed to achieve the intended outcome (e.g., 75% TSS removal). Systems with proven higher TSS removal could consequently be reduced in size to achieve a more consistent outcome. This could extend beyond TSS, if the system is being used to target a specific contaminant of concern (e.g., dissolved zinc) then the same approach could be used to target a desired load reduction. This would just require sufficient system-specific pollutant removal performance data and catchment-specific influent data to ensure an appropriate level of accuracy for such use. To further increase accuracy a relationship between rainfall intensity and contaminant wash off could also be applied.

Ultimately, the concept is the same, in that the methodology can be applied to any pre-determined outcome to determine suitable design input values (e.g., rainfall depth and intensity) for a more consistent output.

3.1 LIMITATIONS OF ANALYSIS

- One of the key limitations of this analysis was the use of 10-minute rainfall data and a corresponding 10-minute computational time-step. Whilst computationally more efficient, under a period of very high intensity rainfall, the time-step did not always have sufficient resolution to fully derive the volume of bypass. However, this was generally an isolated issue and represented <1% of the total flow volume and was therefore not expected to significantly influence results.
- The analysis is specific to a particular rain gauge and would need to be re-run for other rain gauge locations with appropriate inference of values between them if it were applied to a region.
- The outcomes adopted are based on that applied in the Auckland and Christchurch regions and do not necessarily represent the best outcome for any given location and may not represent the best metric as an outcome.
- Losses due to evapotranspiration and media storage were not included in this analysis.
- No specific consideration to climate change was explored, this was considered outside the scope of this analysis.
- Fixed run-off has been used to generate the synthetic inflow hydrographs.

4 RESULT OF ANALYSIS

4.1 AUCKLAND

4.1.1 RAINGARDEN

The Auckland raingardens assessed were water quality only systems sized as per *GD01* guidance (equation 13):

$$A = \frac{WQF}{\left(0.5 \times K_{(media)}\right)} \qquad \textbf{Equation 13}$$

Where	A	-	Area of bioretention media bed at its narrowest point (m^2)
	WQF	-	Water quality flow (m^3/hr)
	$K_{(media)}$	-	Infiltration rate of bioretention media (m/hr)
	Safety factor for clogging	-	0.5

Figure 2 - GD01 Equation 13 for Water Quality Only Raingarden Sizing

A maximum infiltration rate of 1,000 mm/hr and a minimum size of 2% of the total catchment area are specified. The sizing was analysed with and without the minimum area requirement to assess the effect of including this parameter.

Table 1: Results for Auckland Raingardens as per GD01

Treatment System	Raingarden (WQ only as per GD01 guidance)					
Infiltration Rate, K (m/hr)	1.0	0.5	0.2	0.15	1.0	*1.0*
Infiltration Rate (mm/hr)	1,000	500	200	150	1,000	*1,000*[1]
Ponding Depth (mm)	150	150	150	150	200	*150*[1]
Footprint, A (m^2)	54	91	172	209	50	*200*[1]
Equivalent Rainfall Intensity (mm/hr)	4.2	3.5	2.6	2.4	3.9	*15.4*[1]
% of Total Runoff Treated	90%	90%	90%	90%	90%	*98%*[1]

1. *Applying the minimum area requirement of 2% of the total catchment when using an infiltration rate of 1,000 mm/hr and a ponding depth of 150 mm.*

To achieve the 90% annual runoff treated outcome, the equivalent rainfall intensity (underlined) is consistently well below the recommended 10 mm/hr, suggesting the systems would typically be oversized following this guidance (even when ignoring the minimum area requirement). *Note that this may be intentional to provide an in-built Factor of Safety (FoS) to any design.*

Regarding the 2% minimum requirement GD01 states "smaller devices will collect too much sediment relative to their size, requiring too much maintenance to operate efficiently". If the minimum area constraint is applied (as per the final column *italicised*) with an infiltration rate of 1000 mm/hr (and a ponding depth of 150 mm) 98% of the total runoff would be treated with an equivalent rainfall intensity of 15.4 mm/hr. It's not until the media infiltration rate is approximately 150 mm/hr that this equation provides a raingarden footprint > 2% of the total catchment (> 200 m^2). When this occurs the equivalent rainfall intensity (to achieve the intended outcome) is less than a quarter of the recommended 10 mm/hr (2.4 mm/hr). This however does provide a reasonable FoS for reduced permeability of the media from the 1000 mm/hr specified.

Furthermore, the results show that changing variables such as infiltration rate and ponding depth have a significant effect on the equivalent rainfall intensity used. The implication of this is that devices sized using this guidance will achieve different outcomes dependent on the inputs used.

4.1.2 PROPRIETARY SYSTEMS

Table 2: Results for Proprietary Systems in Auckland

Treatment System	Filterra	StormFilter
Footprint (m^2)	23.4	5.0
Equivalent Rainfall Intensity (mm/hr)	9.1	9.5
% of Total Runoff Treated	90%	90%

The equivalent rainfall intensities (underlined) required to achieve the intended outcome for the proprietary systems analysed were relatively consistent with the recommended 10 mm/hr. This is because the systems are sized based on a known flow rate per m^2 of media (Filterra) or cartridge (StormFilter). The Filterra was sized using an infiltration rate of 2,540 mm/hr and the StormFilter with a flow rate per cartridge of 1.42 L/s. As no safety factor is applied directly to the sizing of these systems and because there are no additional variables to alter (i.e., infiltration rate and ponding depth are consistent) the systems should therefore be treating a % of total runoff consistent with the 90% of total runoff assumed to be treated by a rainfall intensity of 10 mm/hr (determined from statistical analysis of rainfall data in the Auckland region).

The slight difference in equivalent intensities between the two systems is due to the systems' different treatment functions (e.g., the Filterra will immediately treat flows whereas the StormFilter doesn't treat flows until a certain water depth is exceeded within the chamber).

4.2 CHRISTCHURCH

4.2.1 RAINGARDEN

The Christchurch raingardens were sized as per Christchurch City Council's *Rain Garden Design, Construction and Maintenance Manual* (CCC, 2016) equations 1 & 2.

$$A_{rg} = 41.67 \cdot \frac{(V_{ff})(d_{rg})}{k(h+d_{rg})t_{rg}} \qquad \text{Equation (1)}$$

Where:

Symbol	Description	Unit	Recommended value
A_{rg}	= filtration area of rain garden	m^2	Calculated
V_{ff}	= first flush or first flush volume	m^3	Determined as per Equation 6-2 in WWDG and using 20mm as the first flush runoff depth
d_{rg}	= filter depth	m	0.6 (includes transition layer)
k	= coefficient of permeability	mm/hr	30
h	= average height of water	m	0.15 (half the recommended extended detention depth (EDD) of 300 mm)
t_{rg}	= time to pass V_{ff} through soil bed	day	One

$$A_{EDD} \geq \frac{0.4 \cdot V_{ff}}{(2 \cdot h)} \qquad \text{Equation (2)}$$

Where:

A_{EDD} = Extended detention (storage) area of rain garden (m^2)

Figure 3 - Rain Garden Design, Construction and Maintenance Manual Equations 1 & 2

Table 3: Results for Christchurch Raingardens as per Rain Garden Design, Construction and Maintenance Manual

Treatment System	Raingarden		
Infiltration Rate (mm/hr)	30	30	200
Ponding Depth (mm)	300	200	300
Base Area (m^2)	146	134	7.5
Top Area (m^2)	175	226	60
Equivalent Rainfall Depth (mm)	20.2	17.4	6.9
% of Total Runoff Treated	80%	80%	80%

When using the recommended values (as seen in the left-hand column) the equivalent rainfall depth (20.2 mm) is consistent with the recommended rainfall depth (20 mm). However, like the Auckland Raingardens, the equivalent design rainfall depths (underlined) change significantly when assumptions around ponding depth and infiltration rate are changed. This indicates some scope to further optimise raingardens based on depth and media permeability.

4.2.2 INFILTRATION BASIN

The Christchurch Infiltration Basins were sized based on Christchurch City Council's Waterways Wetland and Drainage Guide equations 6-7 to 6-9.

1) Determine First Flush Volume, V_{ff}

First flush volume (V_{ff}) is a function of contributing catchment area and rainfall depth. Refer to *Section 6.4: First Flush Interception,* for the recommended calculation procedure.

2) First Flush Basin Water Surface Area, A_{ff}

$$A_{ff} = V_{ff}/y_{ff} + 8\sqrt{(V_{ff}\, y_{ff})} \quad (m^2) \qquad \text{Eqn (6-7)}$$

where y_{ff} = soakage basin first flush depth (m)

$8\sqrt{(V_{ff}\, y_{ff})}$ = an approximation for 1:4 side batters

3) Storm Average Runoff Flow Rate, Q_{avg}

$$Q_{avg} = 2.78\ C\ i\ A/1000 \quad (m^3/s) \qquad \text{Eqn (6-8)}$$

where: C = rational method runoff coefficient

i = rainfall intensity (mm/hr)

A = full catchment area (ha)

C and i are both determined by the requirements and procedures of *Chapter 20: Inundation Design Performance Standards,* and *Chapter 21: Rainfall and Runoff.*

4) Basin Floor Infiltration Flow Rate, Q_{if}

$$Q_{if} = A_{if}\ f \quad (m^3/s) \qquad \text{Eqn (6-9)}$$

where: A_{if} = first flush basin infiltration area (m^2)

f = floor infiltration rate (m/s)

A_{if} will vary with basin water level but a good result can be obtained by adopting a mean value for A_{if} as the area at 2/3 y_{ff}.

Figure 4 - Waterways, Wetlands and Drainage Guide Equations 6-7 to 6-9

Table 4: Results for Christchurch Infiltration Basins as per Waterways, Wetlands and Drainage Guide

Treatment System	Infiltration Basin		
Infiltration Rate (mm/hr)	20	20	12.5
Ponding Depth (mm)	1,000	500	1,000
Base Area (m^2)	66	130	83
Top Area (m^2)	131	176	155
Equivalent Rainfall Depth (mm)	<u>10.2</u>	<u>10.0</u>	<u>12.7</u>
% of Total Runoff Treated	80%	80%	80%

Infiltration Basins are typically designed with a greater ponding depth than raingardens to reduce their footprint. Their sizing is usually an iterative process dependent on the storage required and the footprint available. The equivalent rainfall depth (<u>underlined</u>) is consistently lower than the 25 mm design depth normally applied in Christchurch. It is worth noting, however, though a 25 mm design depth is recommended (and required for greenfields developments) the value can be as low as 12.5 mm (*Waterways, Drainage and Wetlands Guideline*). A lower water quality rainfall depth in Christchurch is normally used in a retrofit application where use of 25 mm is not feasible due to footprint constraints.

The ponding depths tested appeared to have minimal impact on the equivalent rainfall depth, whilst the infiltration rate had a more pronounced effect.

4.2.3 PROPRIETARY SYSTEMS

Table 5: Results for Proprietary Systems in Christchurch

Treatment System	Filterra	StormFilter
Footprint (m2)	5.9	1.8
Equivalent Rainfall Intensity (mm/hr)	<u>2.3</u>	<u>2.4</u>
% of Total Runoff Treated	80%	80%

Christchurch guidance recommends the use of a rainfall intensity of 5 mm/hr understanding this is likely to result in the capture of more than 80% of total runoff. However, a prior study found that a rainfall intensity of just 2 mm/hr is required to achieve the 80% treated runoff outcome (Christensen & Parsons, 2014). The equivalent rainfall intensities determined for the proprietary systems are reasonably consistent with these prior results (considering the 2014 study used 30-minute time-steps as opposed to the 10-minute time-steps used in this analysis).

Although this suggests a design rainfall intensity of 5 mm/hr will result in a significantly oversized system the Christensen & Parsons study states "as this project has not attempted to assess the relationship between contaminant wash off and intensity, it was considered that a conservative intensity should be selected in order to achieve desired environmental outcomes" hence 5 mm/hr was ultimately adopted to provide an additional FoS.

5 RESULTS SUMMARY

The results consistently show that in most cases treatment systems are specified to be oversized relative to their intended outcomes (indicating that a lower rainfall depth or intensity than the recommended value is required to achieve the intended outcome). Furthermore, changes in the design variables can have a significant effect on the outcome and consequently there would currently exist considerable variance between the outcomes of different designs of the same system (despite being designed using the same guidance). *Some of this variation is likely to be due to Factors of Safety which are implicit within the design procedure rather than explicitly stated and hence our results should not be taken as a criticism of the various design procedures. See Section 6 below for further discussion.*

Additionally, location specific rainfall analysis is crucial. For example, the StormFilter requires an equivalent rainfall intensity of 3.7 mm/hr to achieve 90% annual runoff treated using Christchurch rainfall data (not shown in the results above) compared to 9.5 mm/hr to achieve the same outcome in Auckland. This shows that adopting water quality depths or intensities from other regions without performing local rainfall analysis can lead to modified outcomes.

6 SAFETY FACTORS & CATCHMENT LEVEL OUTCOMES

Most systems include an explicit FoS in their design, however some may also include additional implicit FoS. For example, conventional raingardens or Filterra may be sized using an infiltration rate well below the typical infiltration rate of the media (an implicit FoS). E.g., Christchurch rain gardens are designed to an infiltration rate of 30 mm/hr but the media typically achieves > 100 mm/hr post construction, Intelligro state their media has an infiltration rate of 100 – 280 mm/hr and recent field testing by WSP of three raingardens (< 1 year old) using this same media found the average infiltration rate was 440 mm/hr. Similarly, the Filterra is commonly designed to an infiltration rate of 2,540 mm/hr but can achieve > 4,000 mm/hr post construction. The StormFilter however uses an orifice to control the flow through each cartridge such that they do not exceed 1.42 L/s, this is to ensure there is sufficient contact time with the media to promote pollutant removal. As a result, although the media's flux has capacity to discharge greater than 1.42 L/s per cartridge, it is restricted from doing so, and as such does not have an inherent safety factor applied to the sizing design.

An example of an explicit FoS would be the specified 0.5 FoS for clogging in the calculation of the media area for the *GD01* water quality only raingarden.

This means that some BMPs, on average across a catchment, will deliver higher levels of treatment than the design procedure implies (due to explicit and implicit safety factors) whilst others will not.

Understanding this, using an outcome based sizing approach at the catchment level, 'typical operation' could be reflected versus minimum acceptable performance. This is of relevance when looking at outcomes across multiple systems where the 'typical' operation may be a more cost-effective outcome than assuming all systems always operate beyond the minimum allowable.

7 MAINTENANCE

The size of any stormwater system will affect the required maintenance frequency and operational cost. A smaller system will typically be less expensive to maintain (per maintenance) but will require maintenance more frequently. A system's maintenance frequency will be predominantly dependent on the system's function and site-specific sediment mass loads. As such, sediment mass load calculations are recommended in conjunction with this outcome based sizing approach to ensure a suitable maintenance frequency is achieved.

We are categorically not advocating for the downsizing of BMPs to their absolute minimum without consideration of the whole of life consequence on system operation and maintenance.

8 END USE

How might this approach be applied in the real world? The level of analysis required is significant for a one-off design or small development. However, the level of effort is justified where a Council is looking at regionwide catchment management, in terms of setting goals and outcomes, or developing regional or local design guidance.

This approach may also be justified on large scale projects, such as alliance projects, where optimising the size of stormwater treatment systems specific to the local rainfall, or looking at catchment wide treatment, could reduce construction cost, as well as reducing the associated embodied carbon, by reducing effort and materials.

Explicit definition of the FoS applied in contemporary design guidance would also allow for this approach to be applied with greater ease. Such a method should not be applied without first engaging with the local or regional Council first to understand the basis for their water quality rainfall depth and intensity selection if this were to be applied in a real-world application.

9 CONCLUSION

The findings of this paper demonstrate that stormwater systems can be sized to achieve consistent outcomes regardless of type and location. However, differences between certain systems require device specific design inputs rather than general water quality rainfall depth or intensity parameters to achieve this.

The findings also highlight that some current methods employed in Aotearoa New Zealand are not necessarily aligned to deliver a consistent outcome, with varying levels of conservatism implicit within the infiltration rates, rainfall depth and intensity parameters recommended. In some cases, this is being applied to proprietary systems despite having much better-defined media characteristics and in-built FoS. In some other cases, it would appear that the water quality rainfall depth or intensity include a FoS which is additional to the media FoS (e.g., the infiltration basin), essentially resulting in a compounding FoS.

The findings highlight that an outcome based approach to device sizing can provide opportunities for further optimisation of individual devices, or devices when employed across a catchment or region, or new products that come to market. This approach could be used to develop more consistent design guidance or to optimise the sizing of treatment devices to minimise materials and effort, reducing overall carbon emissions associated with construction, as well as costs (where unnecessary from a whole of life perspective).

The application of such an approach should always be discussed first with the approving / consenting authority and done with their agreement, as there may be further reasoning behind current guidance which is not specifically documented but that would need to be understood prior to undertaking the analysis.

Lastly this analysis is not intended to be used as substitute to contemporary design guidance, only as a test of the approach in general and to look at differences between BMPs when seeking a consistent outcome. Where local guidance is not provided, this approach could be used, but would ideally be optimised to balance treatment outcomes and initial outlay with whole of life cost and an appropriate FoS, where applicable, for each BMP type.

Outcome based sizing is desirable for achieving consistent and predictable environmental outcomes, regardless of device type. However, this is made more difficult currently by the existence of multiple, often implicit, safety factors in the design approach. Where safety factors are transparent and explicit, informed discussion can take place between designer and regulator to agree any appropriate adjustments, leading ultimately to an optimal environment outcome at an optimum cost.

REFERENCES

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KEYWORDS

Asset Management, Stormwater Treatment, Water Quality