OUR RAIN GARDEN SUCKS!? INVESTIGATING NATURE-BASED SOLUTIONS FOR VOLUME REDUCTION AND CLIMATE CHANGE RESILIENCE

M. Hannah, K. Jonathan & J. Watson (Stormwater 360), J. Lear & H. Jones (Pattle Delamore Partners Ltd)

ABSTRACT

Green spaces play a vital role in stormwater management, acting like giant sponges. They slow down the flow of rainwater and filter pollutants. Estimates suggest that urban vegetation can absorb up to a third of the water resulting from extreme rainfall events, showcasing the importance of green spaces in mitigating stormwater challenges, and embracing 'sponge cities,' a practice advocated by the Parliamentary Commissioner for the Environment, Simon Upton.

Central to achieving 'sponge cities' is runoff volume reduction, important for peak flow reduction, contaminant removal, habitat protection and maintaining environmental flows. By harnessing volume reduction methods like infiltration, water use, and evapotranspiration (ET), we can increase the capacity of our stormwater systems without enlarging infrastructure. Infiltration is known and quantifiable, as is water demand and supply. ET is not so well understood.

Regulations recognise the importance of volume reduction but reflect the ET knowledge gap. Stormwater management area flow (SMAF) requirements in Auckland aim to reduce stormwater runoff from impervious areas, and Waikato Regional Council defines the objectives for infiltration devices as: volume reduction, contaminant removal, and low stream flow augmentation. Attention isn't paid to volume reduction via ET potential in nature-based systems.

Pattle Delamore Partners Limited and Stormwater360 have undertaken a 12-month hydraulic investigation of a Filterra® high-flow biofiltration system (HFBF System). The fast infiltration system (›2500mm/hr) was developed in New Zealand using local materials to have greater ET potential and enhance plant available water. The system comprises a concrete vault and does not allow infiltration, therefore any volume reduction is associated with ET. Flows were monitored with six pressure transducers and two V-notch weirs, at the inlet and outlet. Despite the widespread assumption that HFBF systems aren't capable of such, the key areas of investigation were peak flow reduction, detention time, and runoff reduction to better understand the potential hydrological mitigation.

The study showed peak flow reduction between 2% and 80% and the lag time between the inlet and outlet peaks, a detention time proxy, suggested a runoff detention time between ~5 and 122 minutes. The results provide evidence to conclude that the HFBF is capable of peak flow reduction and detention; however, given the variability of the results the true extent is currently unclear.

Runoff volume reduction results were more consistent and demonstrated the HFBF system achieved a reduction in the final cumulative volume, averaging 35% across the observed events. Given that infiltration was intentionally prevented, ET was thought to be a significant driver of this phenomenon, which is in general accordance with various international literature asserting that ET provides 19-84% volume reduction for stormwater bioretention devices.

This study demonstrates ET as an important consideration in quantifying volume reduction for nature-based stormwater solutions, such as bioretention. Development of an industry wide design approach for volume reduction, which considers evapotranspiration and variables such as plant species, localised climate, and the available water capacity of the infiltration media, is warranted. Addressing 'unknowns' in volume reduction, such as ET, is paramount to adapting to climate change and designing resilient, nature-based stormwater solutions.

KEY WORDS

Volume reduction, nature-based solutions, evapotranspiration, bioretention, resilience, sponge cities

INTRODUCTION

In 2023, the New Zealand Parliamentary Commissioner for the Environment, Simon Upton, released a report, "Are we building harder, hotter cities? The vital importance of urban green spaces".

The report explores the rapid transformation of urban landscapes in response to population growth and its impact on green spaces. These spaces, including lawns, gardens, parks, and strips of vegetation, contribute significantly to environmental services such as temperature regulation, stormwater management, air filtration, and habitat provision. The report highlights that green spaces are a vital form of infrastructure, comparable to pipes and roads, benefiting not only individuals but the entire community.

Focusing on environmental services, there are various co-benefits including temperature regulation, carbon sequestration, flood mitigation, erosion control, food provision, air and water filtration and habitat provisioning.

In relation to stormwater management, stormwater regulation is crucial in managing rainwater runoff in urban environments where impervious surfaces, such as buildings, roads, footpaths, and driveways, prevent water from soaking into the ground. Traditional stormwater systems can be overwhelmed by large storm events, increased pressure from new developments, or insufficient maintenance, leading to blockages.

Ghosh et al. (2024) have been studying climate change impacts and solutions in the Charles River Watershed (catchment), Boston, Massachusetts, USA, which is home to over one million people. It has been recognised that although the Charles River catchment is experiencing a similar annual amount of rainfall, the rainfall events are becoming less frequent and more intense. Models predict that by 2070 a 25-yr storm will be the equivalent of the present day 100-yr storm. Only a small amount of increase in mm of rain during a heavy storm is enough to increase Charles River's volume by millions of litres, adversely affecting critical infrastructure such as hospitals, schools, and highways.

The importance of green infrastructure, increased tree canopy, wetlands, and open green space (e.g., recreation parks) is highlighted by the models. For example, the model found that if regulations are put in place to ensure 50% of impervious cover areas have storage for a 2-year storm (4.5″ or 114mm) going forward, the total runoff expected for a 10-year event can be reduced by 8% when compared to a ‘no action’ scenario. In addition, the models found that if no action is taken to protect currently undeveloped or unprotected green space, there would be a 7% increase in the total runoff from a 10-year storm by 2070 (EPA, 2024).

The initiative, led by the Charles River Watershed Association, highlights that small changes such as on-site storage and open space protection can have huge impacts on the future resilience of urban areas as we undergo climate change. Employing green infrastructure also helps to combat other threats from climate change such as water quality issues, and urban heat islands.

BACKGROUND

Water Sensitive Urban Design or WSUD uses natural plant and soil processes to manage stormwater and mimic the natural hydrological cycle. WSUD harnesses natural catchment processes such as attenuation (peak flow reduction), infiltration, conveyance, biological treatment, storage, and ET. As an alternative to conventional forms of urban development, such as buried pipe drainage systems, WSUD aims to reduce the impacts of urban development runoff and help maintain pre-development environmental flows. WSUD has also been called Low Impact Design (LID), Sustainable Drainage Systems (SuDS), Best Management Practices (BMPs), and Green Stormwater Infrastructure (GSI). Among others, these terms generally refer to infiltration basins and ponds, swales, rain gardens, and green roofs and are seen as a more sustainable approach to stormwater management (Stovin et al., 2013).

Green roofs and bioretention share similarities in that both use planting and media for runoff (volume) reduction, pollutant removal, and peak flow attenuation. Primarily, a green roof is designed to retain water within the soil (media) and to ET the retained water over time. This means they are generally not designed for infiltration and the media is engineered to have a high plant available water content. Hence, the most widely reported metric for green roofs is volume reduction and many publications document ET from green roofs. With reference to Figure 1 (Fassman & Simcock, 2012), field capacity can be regarded as detention and is the amount of water that the media can hold against gravity after it has been saturated and allowed to drain for one to two days. Plant available water (PAW), or the media's water retention capacity, can be defined as the portion of the water content of the media that is held between the field capacity and the permanent wilting point. The PAW is a function of the suction strength at which soil can hold water to supply plants (Kirkham, M.B., 2005; Singels et al., 2021).

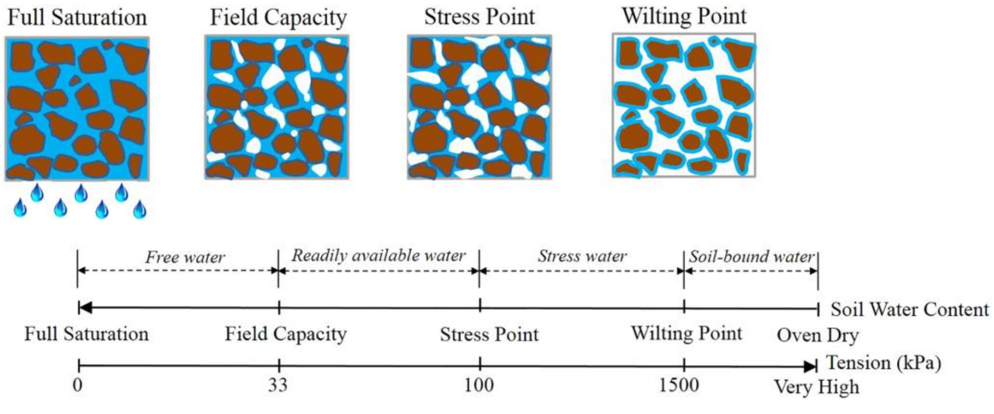

Figure 1 Illustration to demonstrate soil water storage metrics and the corresponding tensions (suction heads). From Fassman and Simcock (2012).

Green roof volume reduction, sometimes called percentage retention, can be calculated simply as the total percentage of rainfall captured by the green roof. Studies show volume reduction in green roofs ranges from 30-86% (Ebrahimian et al., 2019). The variability in results is attributed to factors such as antecedent dry time, antecedent rainfall, rainfall intensity and depth, wind speed, relative humidity, solar radiation, and time of year as well as properties of the green roof, such as water retention capacity of the media, age, slope and type of vegetation (Ebrahimian et al., 2019). Simcock et al. (2013) document that for green roofs the PAW typically increases with the media's organic content and smaller particle size distributions (PSD) but that the volume of ET is somewhat independent of media depth i.e., doubling the media depth does not necessarily mean double the rainfall will be captured. The smaller PSD findings are supported by Hess et al. (2017) who found 7% more ET in sandy loam media versus sand media.

The measurement of ET in raingardens is less well documented than for green roofs, which is most likely due to the perception that ET in raingardens is minimal and the difficulties in measuring such a phenomenon. There are, however, multiple international studies that show 19-84% of the water budget in raingardens can be attributed to ET (Ebrahimian et al., 2019). Of the literature reviewed, the Hargreaves Evapotranspiration model appears to provide the most reasonable results for ET in raingardens (Hess et al., 2017; Ebrahimian et al., 2019; Zhao et al., 2013). The Hargreaves method is one of the simplest temperature based methods for practical use and can be defined as:

$$ET_0 = 0.0135\ (T + 17.78)\ R_S \qquad (1)$$

Where ET = potential daily evapotranspiration, mm/day; T = mean temperature, °C; and R_S = incident solar radiation converted to depth of water, mm/day. For context, this method can be applied to calculate consumptive use for agricultural fields, which is the potential evapotranspiration (ET_0) for a field under no soil moisture stress (“field capacity”)(Wu, 1997).

Theories from green roof research, such as media retention capacity (PAW) and media depth, suggest there should not be any expectation of greater ET in a raingarden compared to a green roof based on a raingarden’s deeper layers of media. Research also suggests the reduced volume reduction in a raingarden versus a green roof can be partially explained by differences in the hydraulic loading ratio (Ebrahimian et al., 2019). The hydraulic loading ratio can be defined as the ratio of directly connected impervious area to the area of the stormwater control measure (SCM), which for raingardens tends to be large in comparison to a green roof. For example, using 10 dry days after a 50 mm rainfall and an ET rate of 5mm/day a typical rain garden with a loading ratio of 5:1 would only have 10% volume reduction by ET, whereas, for a typical green roof with a 1:1 loading ratio, ET would account for 50% of the volume removal. With this said, it can also be noted that although the higher hydraulic loading ratio of a raingarden decreases the percentage of ET by influent volume, the raingarden could have the potential to provide more PAW for increased and prolonged ET (Ebrahimian et al., 2019).

SITE DESCRIPTION

The Coatesville HFBF system is installed on the northwestern corner of the Coatesville Riverhead Highway roundabout (-36.71027, 174.667786 WGS84). The catchment area for the HFBF system is 3709m^2, of which 3309 m^2 is impervious. The surface area of the HFBF system is approximately 25m^2.

The design runoff flow rate for the catchment is 10.3 L/s and the system's design infiltration rate is 1526mm/hr, however, the media is manufactured and approved for infiltration up to 7640 mm/hr. A safety factor of 5 was applied at the design stage given the expected high sediment loading from highly trafficked roads. The average daily traffic flow at the roundabout is ~16,000 vehicles, and given the nature of the roading configuration more contaminants, such as brake dust, are expected to be higher than for a free-flowing highway. The outlet discharges into a sensitive estuary where excess copper or zinc would be a problem. Annotated site photographs are provided in Figure 2.

Figure 2 Annotated photographs to illustrate the site description and show the monitoring equipment of Figure 3. The stormwater manholes are labelled as SWMH in 2 and SWMH out 2 to provide context for Figure 4.

Applying the background research from the previous section, the hydraulic loading ratio for the HFBF system is approximately 130:1 and the available water capacity (PAW) of the media is between approximately 10% and 20%.

METHODS

Pattle Delamore Partners Limited (PDP) were engaged by Stormwater 360 (SW360) to measure the volume reduction ability of the HFBF System. The monitoring equipment (Figure 2, Figure 3, Figure 4) was installed to measure the influent, effluent, and infiltration rates. Monitoring was undertaken for 12 months between November 2021 and December 2022.

Monitoring Equipment Setup

The data capture methodology uses six separate vented pressure transducers (PTs). Two were positioned at 120° V-notch weirs, which are installed at the inlet and outlet of the device, two at the surface of the HFBF System, and another two at the interface between the media layer and the drainage layer at the base of the media. As shown in Figure 2, the HFBF System is divided into two ~$12.5m^2$ cells and each has a set of surface and base PTs. Refer to Figure 3 and Figure 4 for schematic illustrations of the monitoring equipment setup.

Flow Rate Calculation

The recordings from the pressure transducers are provided as water level (m). To better understand the performance of the device, the flow rate at the inlet and outlet was calculated using a V-notch weir chart from within the ISCO Open Channel Flow Measurement Handbook (2016) for 120° V-notch weirs. The equation from the chart is:

$$Q = 2391\ H^{2.5} \quad (2)$$

Where Q is the flow rate (m^3/s), and H is the height of water above the base of the V-notch (m).

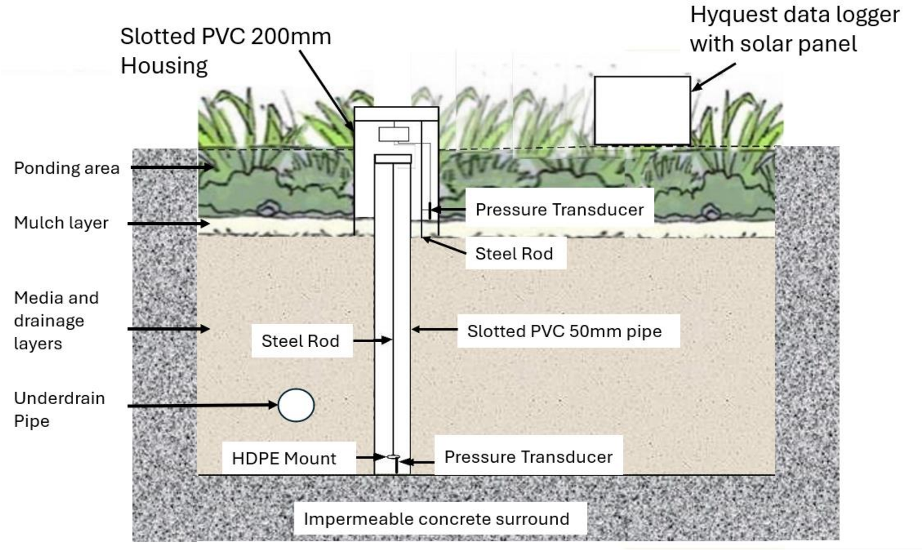

Figure 3 Monitoring setup schematic to illustrate the locations of the surface and base pressure transducers.

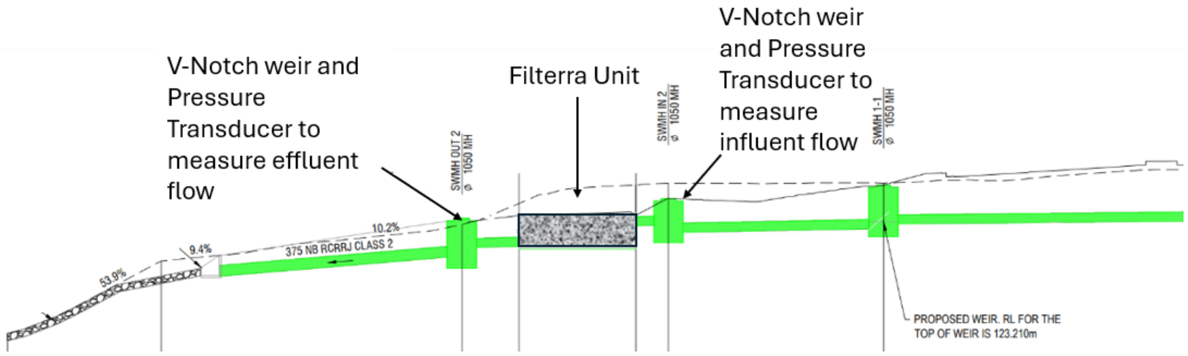

Figure 4 Longitudinal section illustrates the location of inlet and outlet V-notch weirs and pressure transducers.

Volume Calculations

The cumulative volume passing through the inlet and outlet of the device for each rainfall event was calculated as a cumulative sum of the flow rate at a given time multiplied by the interval between recordings (300 seconds).

Volume reduction is calculated as the percentage difference in the final cumulative volume between the inlet and the outlet.

Runoff Depth Calculations

The total depth of each rainfall event (runoff depth) was calculated as the cumulative volume at the inlet over the catchment area, 3709m^2.

The runoff depth reduction for each event was calculated by applying the volume reduction percentage to the total runoff depth.

Peak Flow and Peak Flow Reduction Calculation

The maximum flow rate at the inlet and outlet during the rainfall event was identified (peak flow), with the reduction being the difference between the inlet and outlet peak flow rates.

Peak Design Storm Calculations

The peak design storm was back-calculated using TP108 and the original design assumptions. The peak design storm for the site is 27mm over 24 hours.

Lag Time Calculation (Detention Proxy)

As a proxy for the detention time of the HFBF system, the ‘lag time’ between peaks at the inlet flow rate and the subsequent peak at the were determined.

To determine peaks consistently, a mathematical method was employed where a given point in the data is analysed based on its localised surroundings. If the flow rate data point is found to be higher than its neighbours, and ≥150% of the outlet flow rate average throughout the event, it is classified as a peak. The ‘lag time’ is then determined as the time interval between the peak at the inlet and the subsequent peak at the outlet, representing the detention time of the HFBF System.

Air Temperature Data

Air temperature data was obtained from the Auckland Council Research and Evaluation Unit (RIMU) for the Takapuna (-36.78031, 174.7489 WGS84) and Henderson (-36.86803, 174.62838 WGS84) Meteorology Stations.

Storm Event Segmentation

The total data were segmented into separate storm events based on readings from an Auckland Council Rain Gauge approximately 1.5 km away from the HFBF System at Albany Heights (-36.70992, 174.69101 WGS 84). For the purposes of segmentation, a single storm event was characterised as a period of rainfall that was preceded by a minimum of six hours without rainfall (i.e., if two separate periods of rainfall are within 6-hours of one another, they are classed as the same rainfall event). Each storm event was assigned an Event ID.

To account for the difference in the location of the Rain Gauge to the HFBF System, any events where the water level increase at the inlet of the HFBF system was less than 0.01m were excluded.

Storm Event Analysis

Storm events in 2022 that provided flow data and showed no obvious issues with the monitoring equipment were selected and summarised, which resulted in 32 events occurring between 01 February 2022 and 29 November 2022. The summary of results was analysed to determine if there were any correlations within the data. Of particular interest were investigating correlations between the percentage of runoff reduction versus the runoff depth, storm duration, average lag time, and average monthly temperature as well as the percentage of peak flow reduction versus the peak flow rate.

Further analysis was undertaken on a series of consecutive storm events. This comprised four consecutive February 2022 storm events, three consecutive April 2022 storm events, four consecutive June 2022 storm events, and three consecutive July 2022 storm events. The analysis sought to compare runoff volume reduction and peak flow reduction within each group of events to investigate the potential effects that antecedent conditions (dry and wet), rainfall intensity and duration, and air temperature may have on volume reduction. Peak flow attenuation was also considered.

Events that exceed the TP108 peak design storm were also analysed to investigate any patterns within larger storms. Potential compatibility with SMAF requirements during such events was also assessed.

RESULTS AND DISCUSSION

Summary Results

A results summary is provided in the Appendix. As outlined above, various correlations for the percentage runoff volume reduction versus other variables were explored. Percentage peak flow reduction versus peak flow was also explored. The analyses consistently identified Event 103 as an outlier, therefore, Event 103 was omitted from the analysis. The correlations found in the remaining 31 storm data are presented in Figure 5. For consistency, Pearson's correlation is being interpreted as shown in Table 1 herein.

Table 1 Context for correlation coefficients and the assigned terms zero, weak, moderate, strong, or perfect herein. Dancey and Reidy interpretation taken from Akoglu (2018)

Correlation coefficient (R^2)	Interpretation
0.0	Zero (no correlation)
0.1-0.3	Weak
0.4-0.6	Moderate
0.6-0.9	Strong
1.0	Perfect (perfect correlation)

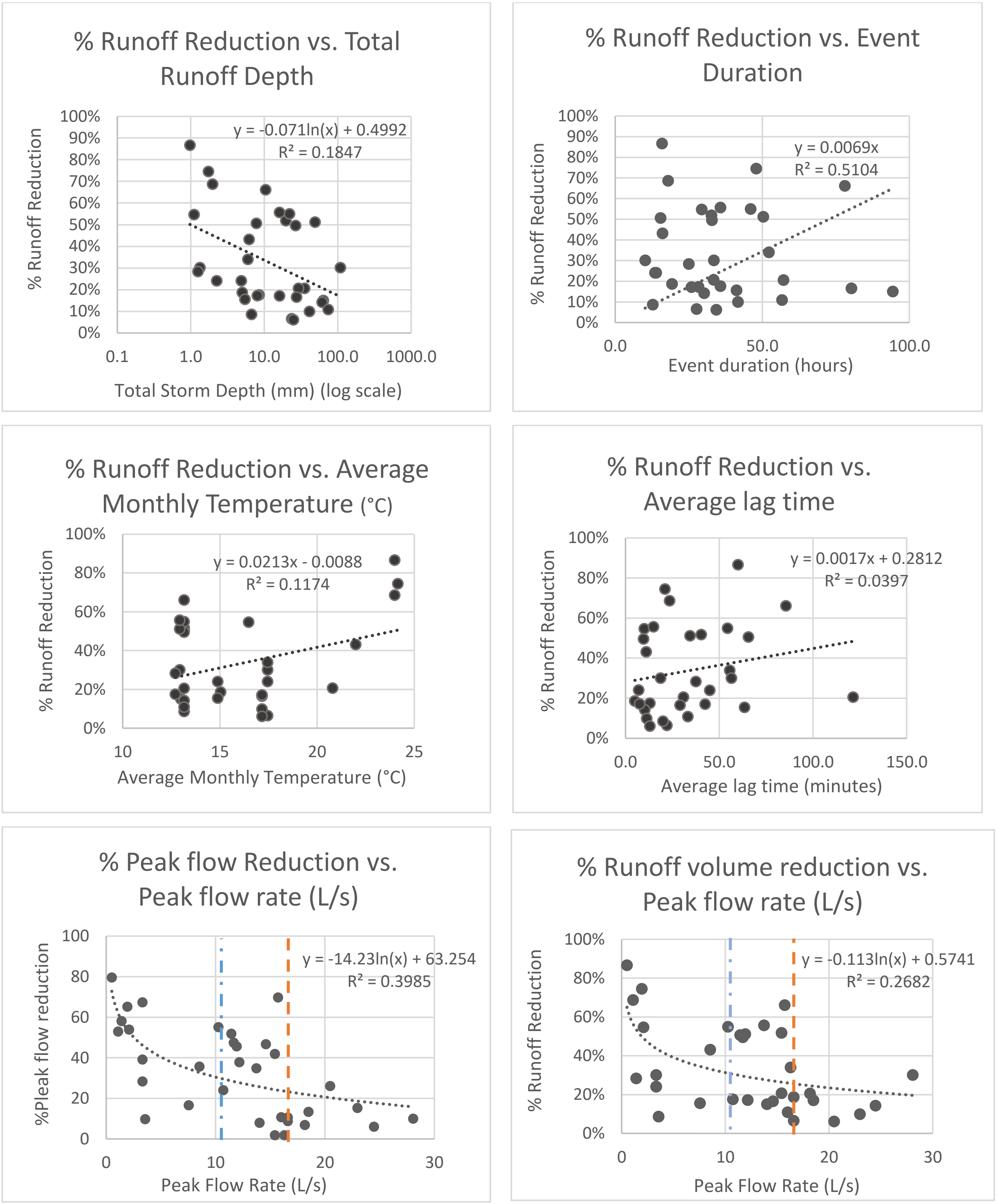

Figure 5 Correlations within the overall data with the Event 103 outlier omitted. For graphs with peak flows, the peak flow design rate (10.3 L/s) is illustrated by the blue dash-dot line and 17 L/s is indicated by the orange dashed line.

The overall data show a weak correlation between the percentage of runoff reduction and the total runoff depth (i.e., inlet cumulative volume over a catchment area of 3709m^2). Therefore, the data suggest that the runoff volume reduction is somewhat independent of the runoff depth. Smaller storms that are less than 25mm, however, do generally appear to have over 20% runoff volume reduction.

Runoff reduction versus event duration for the overall data shows a moderate correlation. It should be noted that the intercept of this interpretation was set to 0,0 (x,y) on the basis that if there is no event duration (i.e., zero hours (x)) then there can be no runoff volume reduction (y). The relationship suggests that longer-duration events may get more runoff volume reduction. This result could potentially be attributed to the water retention capacity, or PAW, of the media.

A weak correlation was found with percentage runoff reduction versus average monthly temperature. Notably, the correlation was worsened by considering average daily temperatures. This is interesting considering the temperature-based Hargreaves ET model, and the finding within the literature that the Hargreaves model seems to be the most appropriate and practical method for determining ET in raingardens. Perhaps this result is because the air temperature recordings are off-site and not representative of the HFBF system surface temperature.

The percentage runoff reduction versus lag time (detention proxy) showed no real correlation. The correlation can be considered zero in terms of Table 1. This suggests that the detention time is more likely dependent on other parameters.

A weak relationship was seen where the percentage peak flow reduction was dependent on peak flow rates. With reference to Figure 5, this relationship suggests that lower flows, up to and around approximately 15 L/s, are generally well attenuated and reduced by at least 20%. Where peak flow rates are above 15 L/s, and much higher than the 10.3 L/s design rate, the reduction in peak flow rate generally drops to beneath 20%. It's interesting that both the runoff reduction and peak flow rate reduction percentages ‘drop off’ when peak flows reach 17 L/s. It's possible that the HFBF system is going into bypass and therefore not attenuating flows or reducing the runoff volume at flow rates above 17 L/s.

February 2022

Table 2 provides a summary of the data from consecutive rainfall events in February 2022. High-level observations of Table 2 suggest that the average lag time (detention time proxy) and runoff volume reduction increase with wet antecedent conditions i.e., with each consecutive storm event. Events 16 and 17 were small in comparison to Events 14 and 15 (Figure 6), however, which likely accounts for these patterns but it’s difficult not to consider the water retention properties of the media.

Figure 7 shows a strong correlation between the percentage of runoff reduction versus the total runoff depth and the percentage of peak flow rate reduction versus peak flow rate. These data are inconsistent with the relationship found in the overall data set. This is interesting given that the storms occurred when there was an average daily temperature of 21°C±2°C and could suggest the Hargreaves temperature model may be applicable in this case.

Table 2 Summary of results for consecutive February Rainfall events. Total runoff depth refers to the total volume over the catchment area.

Event ID	Start Time	End Time	Peak flow rate (L/s)	Peak Flow Rate Reduction (%)	Average Lag Time (mins)	Event Duration (hours)	Total runoff Depth (mm)	runoff depth reduction (mm)	% Volume Reduction
14	6/2/2022 1:00	6/2/2022 17:05	8.54	36%	11.0	16.1	6.3	2.7	43%
15	6/2/2022 17:10	8/2/2022 2:40	15.42	2%	30.9	33.5	35.6	7.4	21%
16	8/2/2022 2:45	8/2/2022 20:45	1.09	53%	23.6	18.0	2.0	1.4	69%
17	8/2/2022 20:50	9/2/2022 12:45	0.51	80%	60.0	15.9	1.0	0.8	87%

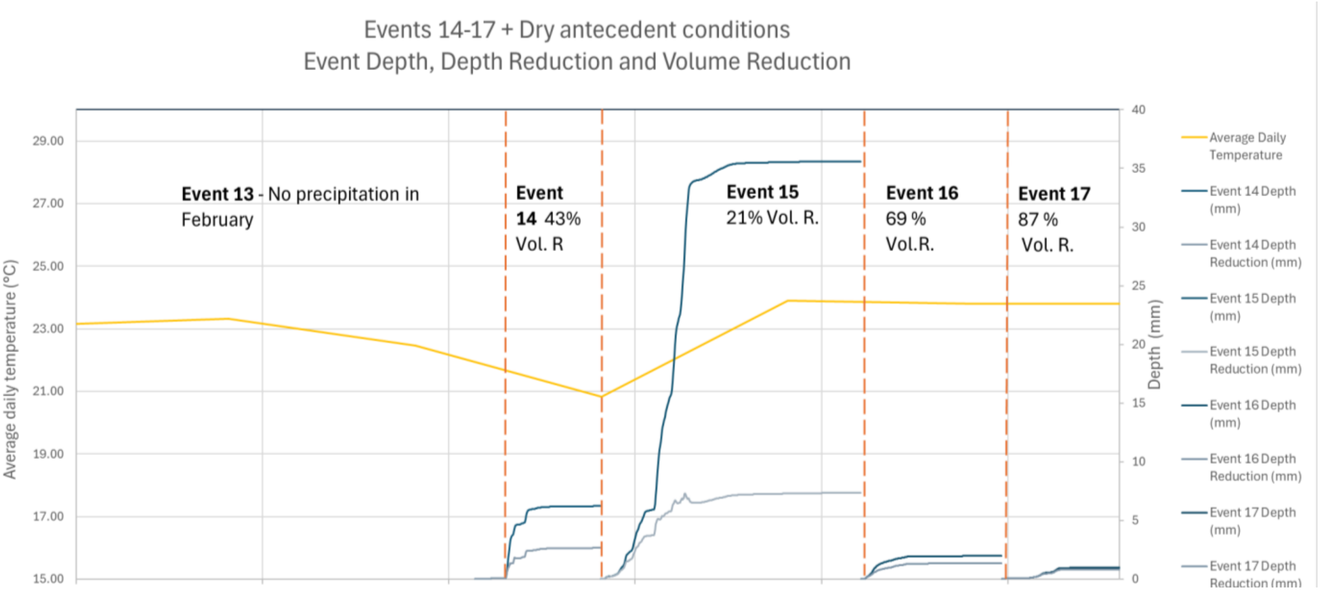

Figure 6 Graphical representation of data provided in Table 2 . Each vertical gridline represents 24 hours.

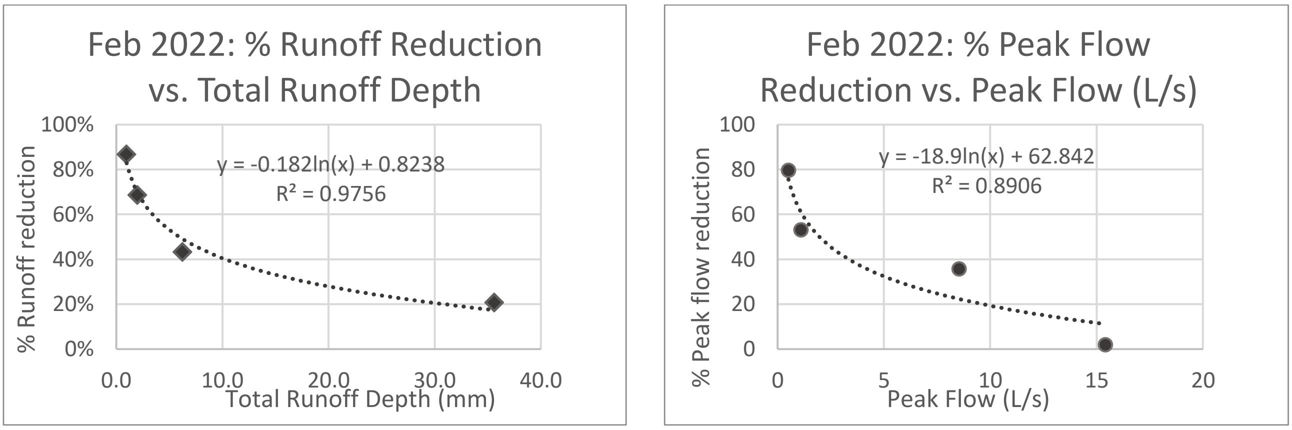

Figure 7 Correlations for consecutive storms (Feb 2022) & most curious parameters explored for the overall data.

April 2022

Table 3 provides a summary of the data from consecutive rainfall events in April 2022. Again, high-level observations suggest that the average lag time (detention time proxy) and percentage of runoff reduction increase with wet antecedent conditions, although these patterns do not apply to Event 40. Events 39 and 41 were small in comparison, which could account for the lower runoff volume reduction seen in Event 40, however, the average lag time is greater than both and still of interest. This data may demonstrate the water retention properties within the media. The data of Table 3 are illustrated in Figure 8.

In terms of Table 1, the data show a strong correlation between the percentage runoff reduction and runoff depth, and a moderate correlation between percentage peak flow reduction and peak flow (Figure 9). These results are consistent with the relationships found in the February 2022 data but inconsistent with the overall data set.

Table 3 Summary of results for consecutive April Rainfall events. Total runoff depth refers to the total volume over the catchment area.

Event ID	Start Time	End Time	Peak flow rate (L/s)	Peak Flow Rate Reduction (%)	Average Lag Time (mins)	Event Duration (hours)	Total runoff Depth (mm)	Runoff depth reduction (mm)	% Volume Reduction
39	18/4/2022 10:45	19/4/2022 0:15	3.33	28	7.0	13.5	4.9	1.2	24%
40	19/4/2022 0:20	20/4/2022 4:00	16.6	9	22.1	27.7	23.7	1.6	7%
41	20/4/2022 4:05	20/4/2022 14:15	3.33	67	18.8	10.2	1.3	0.4	30%

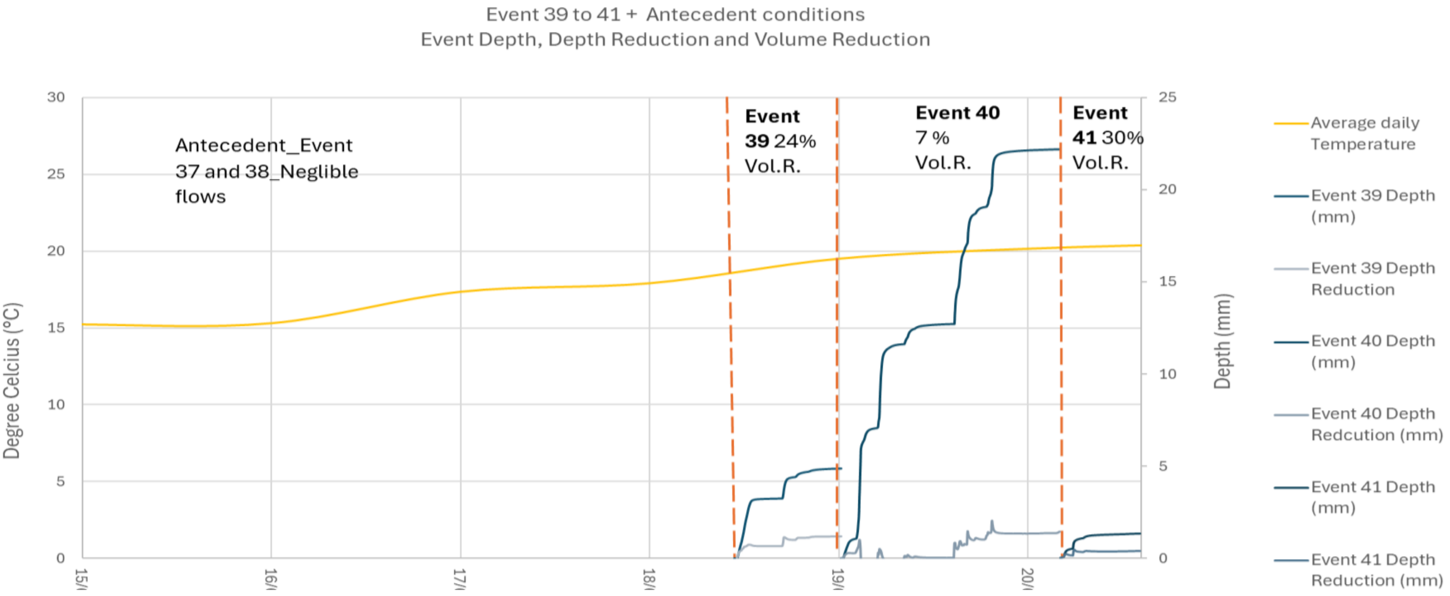

Figure 8 Graphical representation of data provided in Table 3. Each vertical gridline represents 24 hours.

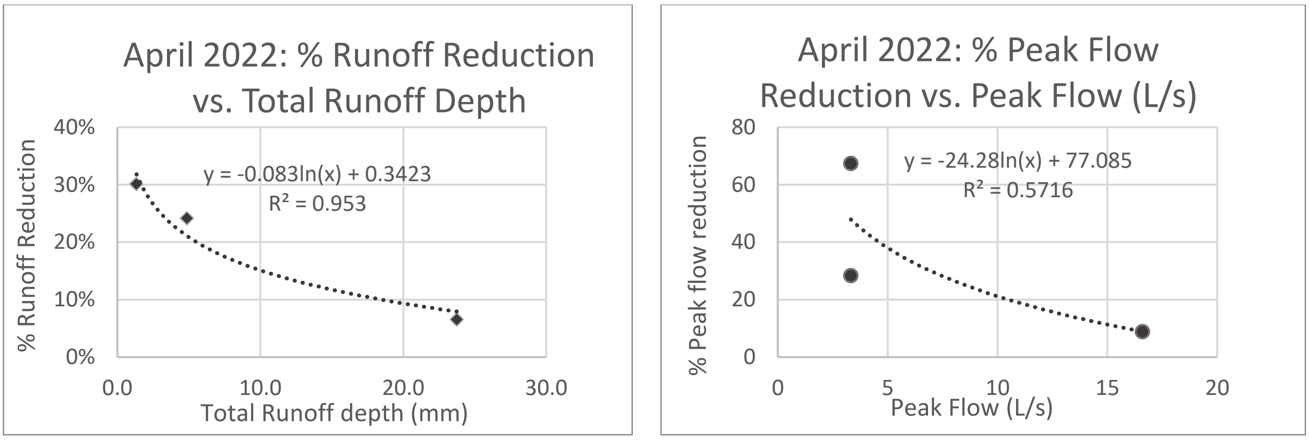

Figure 9 Correlations for consecutive storms (April 2022) & most curious parameters explored for the overall data.

<u>June 2022</u>

Table 4 provides a summary of the data from consecutive rainfall events in June 2022. Similar to other consecutive storm analyses, high-level observations suggest increased average lag time and runoff reduction with consecutive storms. Again, it's difficult not to consider PAW and water retention due to the suction strength of the media. In terms of Table 1, the data shows zero correlation for percentage runoff reduction versus total runoff depth or percentage flow rate reduction versus peak flow (Figure 10). This could potentially be explained by the system bypassing, as discussed under summary results. Figure 11 provides a graphical representation of the data provided in Table 4.

Table 4 Summary of results for consecutive June Rainfall events. Total runoff depth refers to the total volume over the catchment area.

Event ID	**Start Time**	**End Time**	**Peak Flow Rate (L/s)**	**Peak Flow Rate Reduction (%)**	**Average Lag Time (Mins)**	**Event Duration (Hours)**	**Total runoff Depth (mm)**	**Runoff Depth Reduction (mm)**	**% Volume Reduction**
76	10/6/2022 21:30	11/6/2022 12:55	11.44	52	65.6	15.4	7.8	4.0	51%
77	11/6/2022 13:00	12/6/2022 21:45	15.42	42	40.4	32.8	19.7	10.2	52%
78	12/6/2022 21:50	14/6/2022 19:55	10.26	55	54.4	46.1	22.1	12.2	55%
79	14/6/2022 20:00	18/6/2022 2:05	15.72	70	85.6	78.1	10.5	6.9	66%

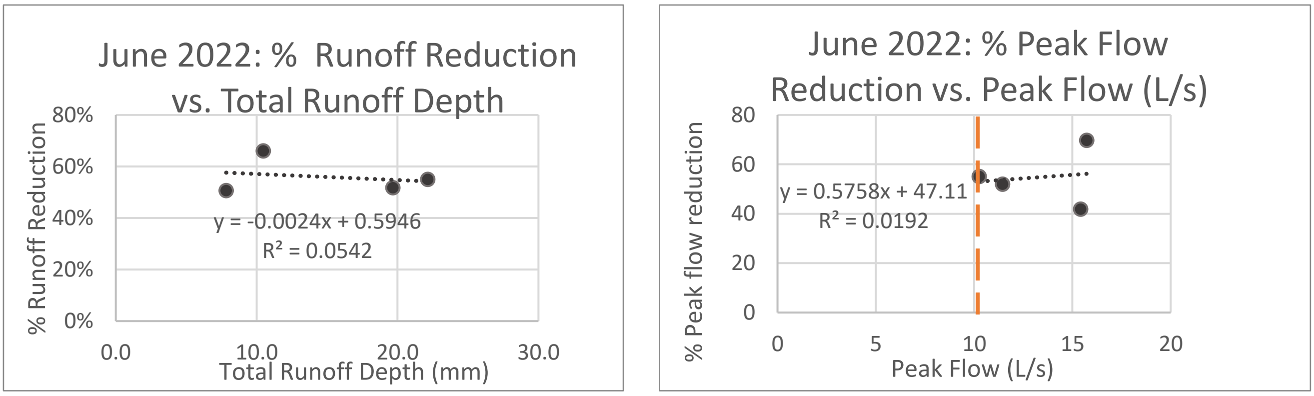

Figure 10 Correlations for consecutive storms (June 2022) & most curious parameters explored for the overall data. The design flow rate (10.3 L/s)is indicated by the orange dashed line.

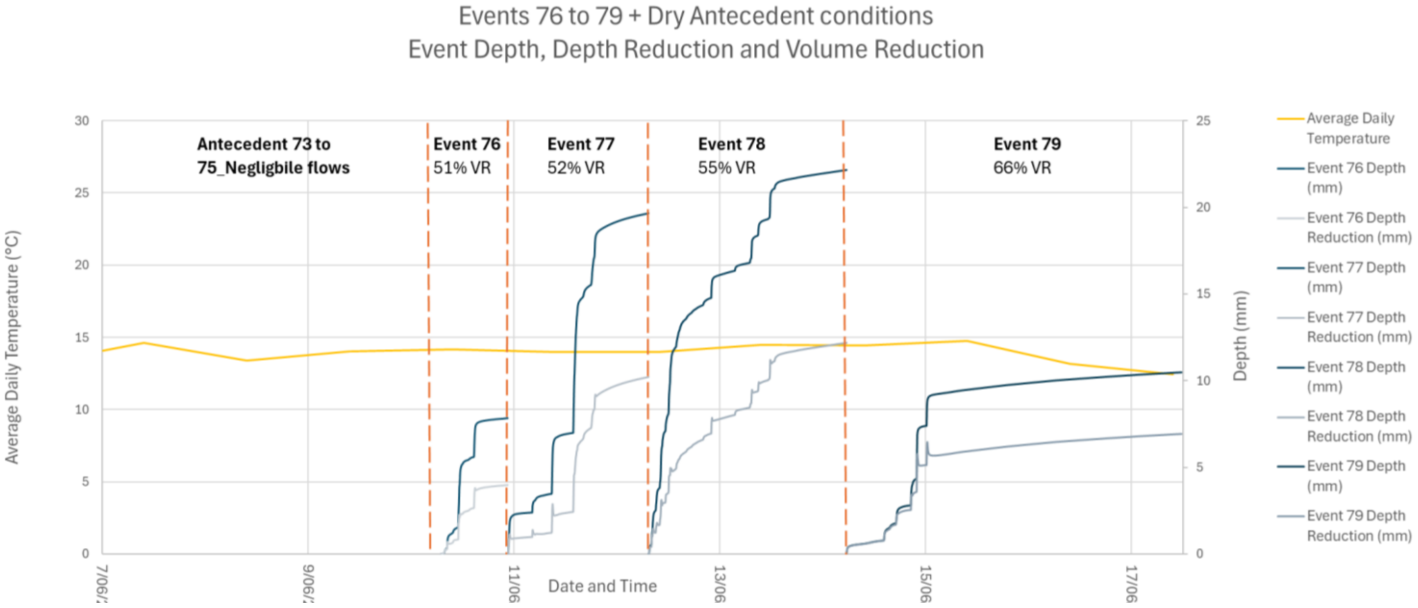

Figure 11 Graphical representation of the data provided in Table 4. Each vertical gridline represents 48 hours.

July 2022

Table 5 provides a summary of the data from consecutive rainfall events in July 2022. Similar to other consecutive storm analyses, the average lag time seems to increase with wet antecedent conditions, however, the runoff volume reduction throughout the events shows a general decrease. Event 91 is the only event so far to exceed the peak design storm of 27mm over 24 hours. It is worth noting that 30% runoff volume reduction is achieved during this event. Figure 12 provides a graphical representation of the data provided in Table 5.

The data show strong correlations between runoff depth reduction versus peak flow rate and between runoff depth reduction versus runoff depth (Figure 13).

Table 5 Summary of results for consecutive July Rainfall events. Total runoff depth refers to the total volume over the catchment area.

Event ID	**Start Time**	**End Time**	**Peak flow rate (L/s)**	**Peak Flow Rate Reduction (%)**	**Average Lag Time (mins)**	**Event Duration (hours)**	**Total runoff Depth (mm)**	**Runoff depth reduction (mm)**	**% Volume Reduction**
89	5/7/2022 12:40	7/7/2022 15:00	11.93	46%	34.4	50.3	49.5	25.3	51%
90	7/7/2022 15:05	11/7/2022 13:25	14.05	8%	-	94.4	63.8	9.9	15%
91	11/7/2022 13:30	12/7/2022 23:05	28.07	10%	56.6	33.6	109.0	32.9	30%

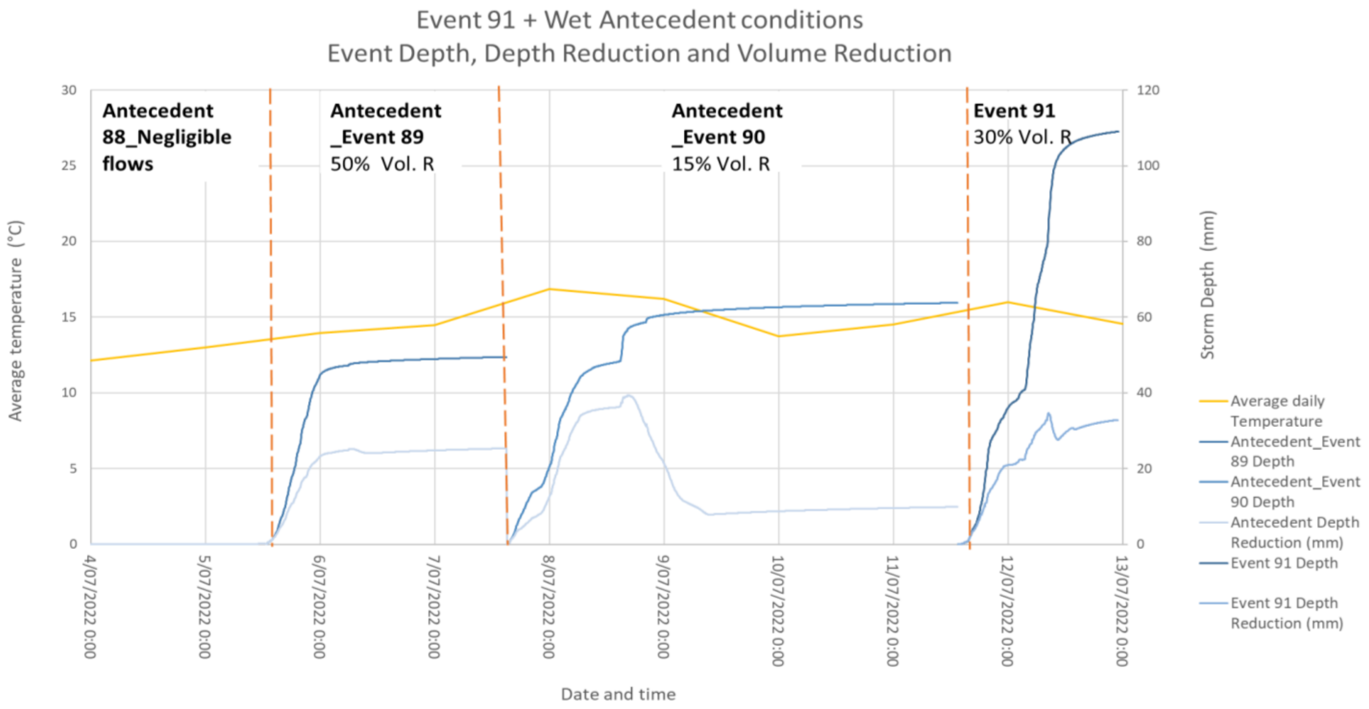

Figure 12 Graphical representation of data provided in Table 5.

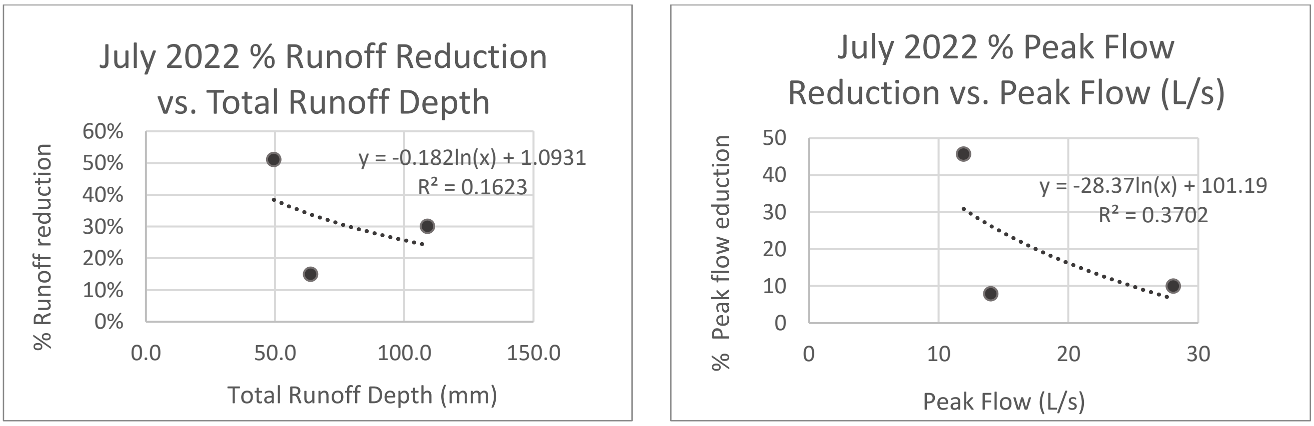

Figure 13 Correlations for consecutive storms (July 2022) & most curious parameters explored for the overall data.

TP108 Peak Design Storms

Three storms within the data set for the period Jan 2022 to November 2022 met TP108 peak design storm depth. Table 6 provides the data and Figure 14 illustrates relationships within the data. The data suggests that larger storms get more runoff reduction, but cannot be considered conclusive given that there are only three data points. The data also suggest peak flow reduction is somewhat independent of peak flows, which can likely be explained by the peak flow rates generally being much greater than the design flow rate.

SMAF requires the HFBF system to provide retention (volume reduction) of at least 5mm runoff depth for the impervious area for which hydrology mitigation is required. The system must also provide detention. The detention requirement for the site under SMAF is a drain-down rate of no more than 0.52 L/s. The data show the HFBF system meets SMAF retention requirements, but is unlikely to meet the detention requirements without some form of outlet flow control.

Table 6 Data for all events that meet or exceed the TP108 Peak Design Storm

	EVENT ID		
	91	**130**	**146**
Start Time	11/7/2022 13:30	5/9/2022 5:50	30/9/2022 1:15
End Time	12/7/2022 23:05	6/9/2022 12:05	2/10/2022 10:00
Design Flow Rate HFBF System (L/s)	10.3	10.3	10.3
Peak Flow Rate (L/s)	28.07	24.48	16.01
Peak Flow Rate Reduction (L/S)	2.8	1.5	1.7
Peak Flow Rate Reduction (%)	10	6	11
Average Lag Time (Mins)	56.6	10.3	33.3
Event Duration (Hours)	33.6	30.3	56.8
% Volume reduction	30%	14%	11%
Average Monthly Temp. (°C)	13	13	13
Total Runoff Depth (mm)	109.0	61.8	74.2
Total Runoff Depth Reduction (mm)	32.9	8.8	8.1
Runoff Depth Over 24 Hours (mm)	77.9	49.0	31.4

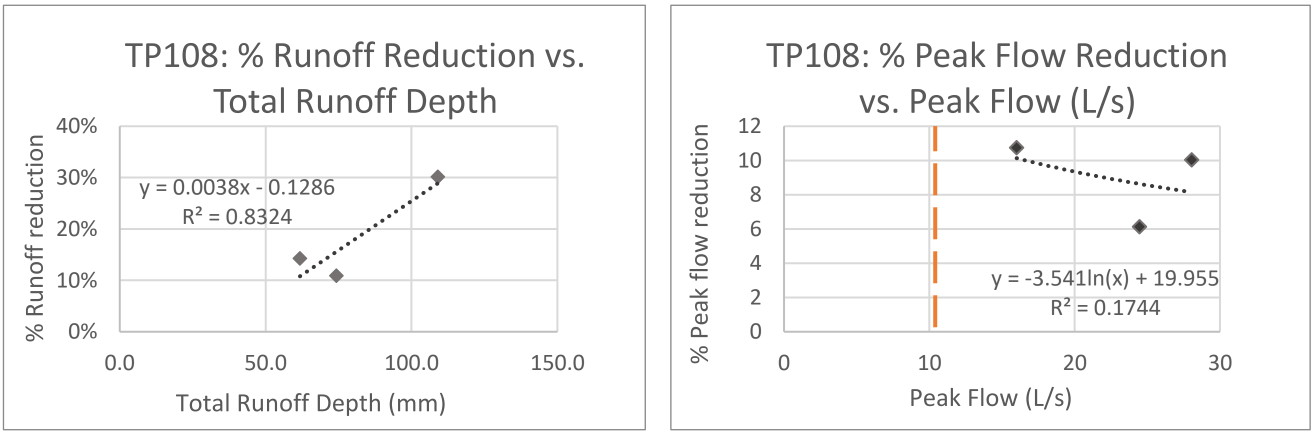

Figure 14 Correlations for TP108 peak design storms & most curious parameters explored for the overall data. The 10.3 L/s design flow rate is indicated by the orange dashed line.

SUMMARY, CONCLUSIONS AND FUTURE WORK

It's difficult to draw any conclusions and reliably quantify ET from the HFBF system based on the data investigated throughout this study, however, there are some promising results. As background research suggested for the variability of green roof results, the variability in these results can most likely be attributed to a combination of factors such as antecedent dry time, antecedent rainfall, rainfall intensity and depth but could also be attributed to wind speed, relative humidity and incident solar radiation at the site. One pattern that was fairly consistent throughout the results, however, was that the average lag time (detention proxy) did tend to increase with consecutive rainfall events. It could be considered that with dry antecedent conditions and completely drained media, less moisture is absorbed by the media and it behaves somewhat hydrophobic allowing most of the water to drain out under gravity (i.e., remains at field capacity). As wet conditions persist, the media appears to become more hydrophilic and hold more water which could be attributed to negative pore pressures (suction head) and the retention properties of the media. Perhaps there is superficial crusting of some media during dry periods, which is eventually overcome with time and moisture. This theory could also explain why infiltration rates observed in the laboratory when testing the media are faster at the start of testing and in unsaturated conditions.

The investigation found that the majority of peak flow rates were higher than the design flow rate. It's quite possible that peak flow rates over 17 L/s put the system into bypass given that there is a notable drop in peak flow attenuation and runoff volume reduction at this point (Figure 5). Other factors that could affect peak flow attenuation and runoff volume reduction at higher flow rates could include blockages (e.g., litter or sediment) forcing the system to bypass, or preferential flow paths developing within the media that increase the hydraulic conductivity and prevent the applicability of Darcy's law.

It's worth looking at the available water capacity of the HFBF system as a whole, and comparing the runoff reduction volumes observed with the science used to determine volume reduction via ET in green roofs. The HFBF system at Coatesville has between 10-20% PAW by volume, and the depth of the media is 550mm. This means the volume of media within the HFBF system is 13.4m^3, which would be equal to 1.3m^3 – 2.6m^3, or 1300 litres – 2600 litres, of PAW in theory. Therefore, a maximum of 2600 litres volume reduction should be possible via ET. The difference in final cumulative volumes between the inlet and outlet for the HFBF system ranges from 1300 litres to 121000 litres. This is a curious outcome considering there is no avenue for infiltration.

Limitations of the study include the time step of monitoring. Perhaps the assumptions made in converting the flow rates to volume by way of multiplying the litres by 300 seconds could be partly to blame for the seemingly outrageous runoff reduction volumes. Further limitations include that the data required for ET models, such as the Hargreaves ET Model, has not been collected at the site to date. The results for volume reduction are much more promising than expected, hence the site set-up was initially geared towards high-level observations as opposed to any detailed analyses. In addition, the data and inherent design of the HFBF media suggest that all flow is unsaturated. A point of 'equilibrium' does not seem to occur, which may be affecting results. Future work requires a reduced monitoring interval, such as one minute, in addition to soil moisture measurements and on-site meteorological monitoring to develop a more detailed and robust dataset. That said, to generate useful and practical results for design applications it may be necessary to employ a simplified ET model, such as the Hargreaves method, to estimate ET in the HFBF system at Coatesville and for raingardens in general.

Despite the limitations of the study, it appears that retention can be achieved in an HFBF system and the system may meet SMAF requirements. If the system was allowed to infiltrate, the retention and detention properties would likely be enhanced. Further future work should include monitoring runoff reduction in an HFBF system where the base is permeable for comparison. Renaming of HFBF to High Flow Bioretention (HFBR) could be proposed considering that the system in this study had no means of infiltration but still displays retention properties.

If runoff reduction via ET is possible with HFBF, imagine what we would find for a typical raingarden. In line with the findings of Ebrahimian et al. (2019), it would appear that the ET potential could only be improved. The results also suggest that ET becoming a design consideration and part of regulations in New Zealand is plausible. More research is certainly required, as is a connection with regulatory bodies, to work towards adapting to climate change and designing more resilient, nature-based stormwater solutions in New Zealand.

ACKNOWLEDGEMENTS

Jim Lenhart for his reviews from a different time zone and the wider Stormwater360 group for site work monitoring and maintenance.

REFERENCES

Fassman-Beck, E.A. and Simcock, R. (2013) Living roof review and design recommendations for stormwater management. Auckland Council technical report TR2013/045 ed. Auckland: Prepared by Auckland UniServices for Auckland Council.

Fassman, E. and Simcock, R. (2012) 'Moisture measurements as performance criteria for extensive living roof substrates.' Journal of Environmental Engineering, 138(8), pp. 841-851.

Ghosh, I., Wood, J., Moonan, J. (2024) Forecasting the future: The Charles River Watershed flood model mitigates regional flood challenges. Available: https://www.stormwater.com/home/article/55002291/forecasting-the-future-the-charles-river-watershed-flood-model-mitigates-regional-flood-challenges?oly_enc_id=4153J4575989C0A

Hess, A., Wadzuk, B., Welker, A. (2017) 'Evapotranspiration in Rain Gardens Using Weighing Lysimeters.' Journal of Irrigation and Drainage Engineering, 1(1), pp. 1 - 7.

ISCO (2016) Open Channel Flow Measurement Handbook, 8th Edition: Teledyne ISCO.

Kirkham, M., 2005. Principles of Soil and Plant Water Relations. Kansas: Elsevier Inc.

NCDEQ (2020) NCDEQ Stormwater Design Manual: C-8. Green Roof, Raleigh: North Carolina Department of Environmental Quality.

Parliamentary Commissioner for the Environment (2023) 'Are we building harder, hotter cities? The vital importance of urban green spaces. Wellington: Ministry for the Environment.

Simcock, R., Fassman-Beck, E., Ansen, J. (2013) Application of living (Green) Roof Design Recommendations for Stormwater Management. Auckland, Water New Zealand.

Singels, A., Jackson. P., Inman-Bamber. G. (2021) Chapter 21: Sugarcane. In: V. a. C. D. Sadras, ed. Crop Physiology Case Histories for Major Crops. Adelaide: Elsevier, pp. 674-713.

Stovin, V., Poë, S., Baretta, C. (2013) A modelling study of long term green roof retention performance. Journal of Environmental Management, Volume 131, pp. 206-215.

Wu, I.-P. (1997) The Hargreaves Evapotranspiration Model. University of Hawaii at Manoa: College of Tropical Agriculture and Human Resources, Department of Biosystems Engineering.

Zhao, L., Xia. J., Xu, C-Y., Wang, Z., Sobkowiak, L. (2013) 'Evapotranspiration estimation methods in hydrological models.' Journal of Geographical Sciences, 23(2), pp. 359-369.

APPENDIX

Event ID	**Start Time**	**End Time**	**Peak flow rate (L/s)**	**Peak Flow Rate Reduction (L/s)**	**Peak Flow Rate Reduction (%)**	**Average Lag Time (mins)**	**Event Duration (mins)**	**Event Duration (hours)**	**Inlet Event Cumulative Volume (L)**	**Oultet Cumulative volume (L)**	**% Difference in Final Cumulative Volume**	**Average Event temperature (deg C)**	**Total Runoff Depth (mm)**	**Total runoff depth reduction (mm)**
14	6/2/2022 1:00	6/2/2022 17:05	8.54	3.0	36	11.0	965.0	16.1	23195.6	13179.0	43%	22.0	6.3	2.7
15	6/2/2022 17:10	8/2/2022 2:40	15.42	0.3	2	30.9	2010.0	33.5	132062.6	104763.5	21%	20.8	35.6	7.4
16	8/2/2022 2:45	8/2/2022 20:45	1.09	0.6	53	23.6	1080.0	18.0	7342.3	2299.2	69%	24.0	2.0	1.4
17	8/2/2022 20:50	9/2/2022 12:45	0.51	0.4	80	60.0	955.0	15.9	3609.5	479.1	87%	24.0	1.0	0.8
19	11/2/2022 7:50	13/2/2022 7:45	1.94	1.3	65	21.0	2875.0	47.9	6466.9	1645.8	75%	24.2	1.7	1.3
24	18/3/2022 17:55	19/3/2022 23:20	2.11	1.1	54	10.0	1765.0	29.4	4110.5	1862.1	55%	16.5	1.1	0.6
39	18/4/2022 10:45	19/4/2022 0:15	3.33	0.9	28	7.0	810.0	13.5	18065.7	13704.6	24%	17.5	4.9	1.2
40	19/4/2022 0:20	20/4/2022 4:00	16.6	1.5	9	22.1	1660.0	27.7	88068.0	82297.8	7%	17.5	23.7	1.6
41	20/4/2022 4:05	20/4/2022 14:15	3.33	2.2	67	18.8	610.0	10.2	4964.1	3469.0	30%	17.5	1.3	0.4
47	24/4/2022 16:55	26/4/2022 21:10	16.3	0.3	2	55.6	3135.0	52.3	22203.7	14647.1	34%	17.5	6.0	2.0
63	29/5/2022 0:10	29/5/2022 19:30	16.6	1.8	11	5.0	1160.0	19.3	18723.8	15228.3	19%	15.0	5.0	0.9
71	5/6/2022 4:00	7/6/2022 13:15	18.17	1.3	7	121.5	3435.0	57.3	109091.4	86624.8	21%	13.2	29.4	6.1
76	10/6/2022 21:30	11/6/2022 12:55	11.44	5.9	52	65.6	925.0	15.4	29052.8	14332.7	51%	13.2	7.8	4.0
77	11/6/2022 13:00	12/6/2022 21:45	15.42	6.5	42	40.4	1965.0	32.8	72978.1	35133.6	52%	13.2	19.7	10.2

78	12/6/2022 21:50	14/6/2022 19:55	10.26	5.7	55	54.4	2765.0	46.1	82118.9	36968.1	55%	13.2	22.1	12.2
79	14/6/2022 20:00	18/6/2022 2:05	15.72	11.0	70	85.6	4685.0	78.1	38853.5	13163.8	66%	13.2	10.5	6.9
83	24/6/2022 15:35	26/6/2022 0:30	11.68	5.5	47	9.6	1975.0	32.9	99468.0	50129.4	50%	13.2	26.8	13.3
89	5/7/2022 12:40	7/7/2022 15:00	11.93	5.4	46	34.4	3020.0	50.3	183553.9	89564.9	51%	12.9	49.5	25.3
90	7/7/2022 15:05	11/7/2022 13:25	14.02	1.1	8	-	-	94	-	-	15%	13.0	63.8	9.9
91	11/7/2022 13:30	12/7/2022 23:05	28.07	2.8	10	56.6	2015.0	33.6	404393.1	282509.9	30%	12.9	109.0	32.9
92	12/7/2022 23:10	14/7/2022 10:55	13.74	4.8	35	15.0	2145.0	35.8	60210.1	26667.1	56%	12.9	16.2	9.0
123	22/8/2022 21:10	24/8/2022 8:55	10.72	2.6	24	13.0	2145.0	35.8	31606.9	26051.7	18%	12.7	8.5	1.5
124	24/8/2022 9:00	25/8/2022 10:00	1.4	0.8	58	37.5	1500.0	25.0	4656.9	3336.3	28%	12.7	1.3	0.4
130	5/9/2022 5:50	6/9/2022 12:05	24.48	1.5	6	10.3	1815.0	30.3	229090.9	196441.7	14%	13.2	61.8	8.8
139	22/9/2022 13:35	23/9/2022 2:20	3.56	0.4	10	20.0	765.0	12.8	24991.6	22835.5	9%	13.2	6.7	0.6
146	30/9/2022 1:15	2/10/2022 10:00	16.01	1.7	11	33.3	3405.0	56.8	275353.8	245376.2	11%	13.2	74.2	8.1
154	14/10/2022 1:20	14/10/2022 15:15	3.33	1.3	39	45.0	835.0	13.9	8411.7	6386.8	24%	14.9	2.3	0.5
156	17/10/2022 13:45	19/10/2022 7:00	7.56	1.3	17	63.5	2475.0	41.3	20252.2	17102.9	16%	14.9	5.5	0.8
166	17/11/2022 11:55	19/11/2022 5:40	22.98	3.5	15	11.4	2505.0	41.8	153669.1	138395.4	10%	17.2	41.4	4.1
169	20/11/2022 11:20	21/11/2022 13:15	18.49	2.5	13	42.5	1555.0	25.9	59886.9	49639.4	17%	17.2	16.1	2.8
172	22/11/2022 14:40	24/11/2022 1:00	20.49	5.4	26	13.0	2060.0	34.3	92773.1	87078.4	6%	17.2	25.0	1.5

173	24/11/2022 1:05	27/11/2022 9:25	14.6	6.8	47	29.0	4820.0	80.3	102162.5	85249.4	17%	17.2	27.5	4.6
175	29/11/2022 19:40	1/12/2022 0:00	12.17	4.6	38	7.5	1700.0	28.3	29880.9	24733.6	17%	17.2	8.1	1.4