

Performance evaluation of retrofit planters as nature-based solutions for urban stormwater attenuation

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Article

Keywords:

Posted Date: August 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10436306/v1>

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Additional Declarations: No competing interests reported.

Abstract

Retrofit planters are among the simplest nature-based solutions (NBS) for urban stormwater management. However, their performance, flood mitigation benefits and implementation challenges are yet to be fully evaluated. We evaluate the hydrological performance of retrofit planters at two scales: measuring inflow and outflow from individual planters at the University of Hull, UK and pre- and post-installation sewer monitoring at the network scale for a group of planters in Grimsby, UK. Event-based analysis of high temporal resolution data (5 minute intervals) for individual planters shows a median peak delay of 35 minutes and a median peak flow reduction of 49.8%, with no significant performance differences between installations. Network scale monitoring indicated longer event durations and reduced peak flows following installation. Inflow comparisons revealed unequal effective roof contributions between nominally similar downpipes, highlighting uncertainty in assumed roof catchments for retrofit design. These findings provide empirical evidence to support and guide the integration of monitored NBS into urban drainage strategies.

Introduction

Managing rainfall to mitigate the impacts of flood and drought within the urban environment is an increasing challenge with the effects of climate change on the hydrological cycle¹ and the limitations of drainage network capacity². Urbanisation increases surface runoff by reducing vegetative cover and expanding impervious surfaces, diminishing interception, infiltration and percolation^{3–7}. Historically, urban drainage systems were designed to convey rainfall into underground networks as rapidly as possible^{8,9}. Globally, around 67% of the population are expected to live in the urban environment by 2050¹⁰, with urban populations in England, UK and the USA expected to be as high as 83%¹¹ and 80%¹², respectively. Accelerating urbanisation increases the challenge to deliver the UN sustainable development goal (SDG11) of making cities safe, resilient and sustainable imperative¹³. Nature-based solutions (NBS) respond to this challenge by restoring elements of the natural water cycle within the urban landscape^{14,15}. A shift has occurred towards making water more visible in the environment as blue spaces or through blue-green infrastructure and water sensitive design at city wide scale^{16–18}.

A range of urban water management frameworks have emerged internationally, including Sponge Cities (China)¹⁹, Low Impact Development (USA)²⁰, Water Sensitive Urban Design (Australia)²¹ and Sustainable Drainage Systems (SuDS) (UK)²². These approaches are increasingly recognised as NBS that restore hydrological function by intercepting, storing, and slowing runoff within the urban landscape²³. While these systems are now routinely incorporated into new developments, retrofitting them into existing urban fabric presents distinct challenges and opportunities^{24–27}.

Retrofitting water management solutions has become an important strategy, particularly the use of small scale, multifunctional systems that can store, slow, and filter runoff in constrained urban settings²⁸. Retrofit systems span a range of scales, levels of expertise required for installation and cost^{29,30}. We

distinguish between household scale systems, represented here by individually monitored planters at the University of Hull, and authority scale schemes, represented by the grouped installation at a primary school (Wybers Wood Academy). Planters are among the simplest retrofits to implement, intercepting roof runoff and temporarily storing it before releasing it to the drainage network at a restricted rate. Their small footprint and modular design make them suitable for constrained urban sites, while the inclusion of vegetation and growing medium provides additional ecosystem services including amenity value and biodiversity gain^{31,32}. They can be installed at a household/ building level, acting as a single point of interception, or in a large grouping (e.g. around an office building or complex). However, passive retrofit planters are limited by their storage capacity, and once exceeded, outflow rates approach inflow rates, limiting their effectiveness during prolonged or intense rainfall. Whether planters deliver consistent hydrological performance across varying antecedent moisture and rainfall conditions remains poorly understood³³.

Effective design of retrofit schemes requires empirical evidence of how individual assets influence water storage and time to peak discharge, yet field performance data for these interventions remain scarce^{34,35}. Indeed, a national survey of over 500 UK practitioners found that the majority did not quantify the costs or benefits of deployed schemes, with respondents identifying long-term monitoring and performance evidence as critical gaps constraining future uptake³⁶. High-temporal resolution data are therefore needed to effectively characterise flow within an urban environment, with sub hourly intervals (e.g. 5 minutes) required to resolve urban hydrograph peaks without temporal smoothing^{37,38}. However, NBS are not commonly supplied with an in-built mechanism to monitor performance or identify whether they are producing any quantifiable hydrological benefits to the drainage network. Urban drainage models are often employed to understand the impact of NBS at a network scale, but these may omit the spatial influence of interventions and real-world conditions^{39,40}. Limited site scale data exist for assessing the impact of multiple retrofit systems to overall drainage network level behaviour. This knowledge gap constrains both model calibration and the evidence base needed for informed NBS deployment⁴¹. These hard barriers of data availability are seen as a hurdle to NBS implementation, with stakeholders requiring long-term performance data to support future works³³.

This study is among the first to combine individually monitored retrofit planter performance with pre- and post- installation network scale sewer monitoring, evaluating NBS effectiveness across both individual asset and collective scheme scales. We address the lack of high resolution, long-term performance data for retrofit SuDS by evaluating the hydrological performance of retrofit planters at both scales. First, we examine individual planter behaviour using a novel suite of sensors installed on four SuDSPlanters® at the University of Hull, UK (Fig. 1a), where each planter intercepts roof runoff from a building downpipe and is independently monitored for inflow, storage and outflow at 5-minute intervals (Fig. 2). Second, we assess the collective impact of ten retrofit planters installed at Wybers Wood Academy, a primary school in Grimsby, UK (Fig. 1b), where pre- and post- installation sewer monitoring enables evaluation of network scale drainage response. The planters have an approximate water storage capacity of 0.5 m³ and are infilled with a sandy loam growing media above a water storage reservoir, with vegetation

selected for local conditions. Using event based hydrological analysis of data collected across 2023, we quantify the flood attenuation characteristics of individual planters and a group of planters, including their capacity to delay and reduce peak flows and to store water. In doing so, we provide the empirical evidence base needed to support the integration of NBS into urban drainage strategy and contribute to the growing body of work on performance assessment for circular water management in cities.

Results

We first examine individual planter performance before assessing collective network scale impact.

Individual Planters

Peak flow delay and peak flow reduction were estimated for the 50 largest events selected for analysis. An example of the differences between inflow and outflow is shown in Fig. 3a. The input from the roof produces a short, sharp peak while the planter output is suppressed and elongated. This event produced a peak discharge reduction of approximately 70% and a peak delay of approximately 40 minutes. The cumulative inflow and outflow volumes for this event converge at approximately 1.1 m³ (Fig. 3b), indicating full passage of the event water through the system. The cumulative curves reveal a sustained delay of approximately 90 minutes between inflow and outflow throughout the event.

Across all planters, the peak delay is consistently positive, with a pooled median of 35 minutes and an interquartile range of 20 to 50 minutes. The individual planter panels (Fig. 4a) and pooled distribution (Fig. 4b) show that delays cluster around the median with a long positive tail. A one sample Wilcoxon signed rank test confirms a positive delay ($V = 7021$, $p < 0.0001$). Differences between individual planters are evident but remain small when tested formally. The Kruskal-Wallis result indicates no detectable variation in delay across different planters ($p = 0.9988$), indicating near identical performance across installations.

Peak flow reduction shows a different pattern, but the overall impact is similar (Fig. 4c and 4d). Most events show a marked reduction in peak flow, and the pooled distribution centres around a median reduction of 49.8% with an interquartile range from 36.0% to 61.3%. This consistent reduction is confirmed by the corresponding Wilcoxon signed rank test ($V = 7381$, $p < 0.0001$). Some planters display slightly broader or narrower spreads in Fig. 4c and 4d, though these contrasts are modest. The Kruskal-Wallis test does not identify statistically meaningful differences between planters ($p = 0.7018$).

The cumulative event volumes indicate that each planter consistently released less water than it received (Fig. 5). For Planter-001 the total inflow was about 5.6 m³ and the corresponding outflow was about 5.0 m³. Planter-002 received the greatest cumulative inflow at roughly 18.4 m³ and released about 16.8 m³. Planter-003 showed a cumulative inflow of approximately 11.8 m³ and an outflow near 7.4 m³. Planter-004 had the smallest totals with an inflow close to 5.6 m³ and an outflow of about 4.0 m³. The pattern is consistent across installations because inflow always exceeds outflow, which suggests effective retention during events rather than simple throughflow.

Network Level

The complete time series for the pre- and post- SuDS periods shows the broad behaviour of the local network over each monitoring window (Fig. 6a). The two periods contain different rainfall characteristics owing to natural variability in rainfall between the two monitoring periods, so direct comparison is descriptive rather than diagnostic. Notwithstanding, both records exhibit the same general pattern of short-lived peaks superimposed on long periods of low flow, and neither period indicates persistent change in baseline discharge.

A one week extract centered on 15 May 2023 highlights a recurring diurnal signal in the time series (Fig. 6b). Flow increases are confined almost entirely to school hours, which confirms that the outfall drains exclusively from the school site. This provides useful context for the subsequent event scale analysis because it shows that the network response measured here is dominated by a single land use rather than a wider catchment. The consistency of this diurnal signal across both periods provides the basis for separating baseline foul flow from rainfall driven response.

Event duration and event volume follow clear power law relationships in both datasets (Fig. 6c). Longer events produce larger total volumes, but with distinct differences in scaling. The pre-SuDS period is described by

$$V = 21.288 D^{0.68} (R^2 = 0.58)$$

and the post-SuDS period by

$$V = 17.744 D^{0.66} (R^2 = 0.66)$$

where V is event volume in m^3 and D is duration in hours. As an illustration, a $150 m^3$ event is estimated to last approximately 26 hours in the pre-SuDS record and around 32 hours in the post-SuDS record. This represents a modest lengthening of the drainage response, although the magnitude of any apparent change must be considered alongside the fact that the two monitoring periods experienced different rainfall.

The tail of the flow duration curve (Fig. 6d) shows the highest flows expressed as non-exceedance probability. Both periods share a similar shape, with the steep upper section indicating that peak flows are infrequent. The post-SuDS values are consistently lower in this upper tail, suggesting that the most intense short-lived discharges were slightly reduced during the later period. Again, rainfall differences limit the strength of this inference, but the pattern is internally consistent with the event-based analysis.

Taken together, these results show that the monitored network behaves in a broadly similar way before and after SuDS installation, with some indications of longer event durations and slightly reduced extreme flows in the post SuDS period. Given the variability in rainfall across the two monitoring windows, these observations should be interpreted cautiously, yet they provide initial evidence that pathway level attenuation effects may be detectable at the outfall.

Discussion

Monitoring of NBS enables a better understanding of how water moves through the environment, addressing the challenge of limited empirical evidence for urban drainage strategy.

Performance and Evidence Gaps

System performance for the planters in this study can be assessed by their ability to 'slow the flow' through peak delay and/or the reduction in peak magnitude. The results show that the peak flow is delayed by approximately 35 minutes. However, delay varied both between different planters during the same events, or by the same planters during similar events. The heterogeneity of performance of a planter is partly based upon antecedent conditions, such as the time of year, dictating if plants are in active growth, if the soil is frozen, or the existing soil moisture, and the spacing between rainfall events. Despite this variability, statistical testing confirms that both peak delay and peak flow reduction are consistently greater than zero across all planters, with no statistically detectable differences in performance between installations.

Peak delay reduces downstream flood risk only if it desynchronises outflows from multiple contributing sources, an effect that depends on the spatial configuration and timing of flows across the drainage network. Peak flow reduction from the outflow of planters is a more significant performance metric since it will reduce the maximum flow at any point downstream in the network. The median peak flow reduction of 49.8% is consistent with the broader empirical evidence base for bioretention systems, where field monitored peak reductions range from approximately 50% in lined flow through cells to over 95% in systems with significant exfiltration capacity^{42–44}. Storm Water Management Models (SWMMs), such as MicroDrainage, typically represent planters using manufacturer specified flow attenuation parameters^{24,45}. Without real-world monitoring data there is ambiguity in these calculations. For example, the average calculated maximum outflow from the planters is 0.07 l/s, 30% below the manufacturer specified maximum of 0.1 l/s. Under the conditions observed, no planter reached the discharge rate that would trigger the overflow mechanism, suggesting that the units were not operating at full capacity. The consistent surplus of inflow over outflow across all planters indicates that temporary retention occurs during events, though the relative contributions of drainage between events, evapotranspiration, and measurement uncertainty cannot be fully partitioned with the current dataset.

A critical finding from the individual planter monitoring is the substantial variability in effective roof catchment area. Pre-installation design estimates assumed Planter-001 and Planter-002 had similar roof catchment areas, with each system receiving similar inflow. However, event-based comparison of inflow peak shows that Planter-002 receives approximately three times more water than Planter-001. Differences in actual inflows suggest that design calculations based on annual exceedance probability become unreliable if the actual roof catchment area and downpipe flow are not measured accurately. This may present a risk to installations being vulnerable to rainfall exceeding their design capacity or that the impact of a planter may be less than its capacity would suggest. The threefold difference in

rainfall reaching each downpipe means that if Planter-001 is optimised for a 1 in 30-year event, Planter-002 needs to be optimised for a 1 in 100-year event for the same input rainfall. The imbalance of roof catchment drainage is not usually considered in the design of retrofit systems since actual downpipe flow rates are unknown and they can be significantly affected by rainfall direction and associated shadowing, wind direction, morphological barriers on the roof, and the local gradient of roof sections and gutters.

Monitoring is essential to build the evidence base that stakeholders require before committing to future retrofit investment⁴⁶. Monitoring at the micro-watershed, individual planter scale enables an understanding of the hydrology at a fine resolution⁴⁷. To understand the benefits of retrofit NBS, it is important to look at the wider scale, such as a per scheme basis, since that encompasses the assets that need to be protected. However, to plan and optimise for the future, individual performance is still desirable as wider scale schemes may include different interventions or with different inputs. At the authority level, benefit assessment is typically framed in terms of avoided flood damage costs and the number of properties protected. The benefit analysis at the stakeholder level is dependent on predetermined factors: cost, number of people affected, level of protection achieved within an impact assessment, and improvement dependent on options available⁴⁸. The retrofit planter schemes at Wybers Wood Academy are seen as a protective mechanism for properties further down the drainage train (~ 10 residences), as well as for the school. Therefore, when comparing the cost of ten planters to the expected property damage costs, the authority deemed the investment in planters a risk worth taking. In this context, space to benefit or cost to benefit ratios may be limited, and securing land for multifunctional uses can be challenging and not always cost effective^{49–51}. The results from the sewer data show that there appears to be a benefit to the retrofit, with an elongation of the event duration within the sewer (Fig. 6). Event scale analysis further indicates a change in the relationship between event duration and runoff volume following installation, with longer drainage response times for equivalent volumes and improved fit of the post retrofit scaling relationship. Longer event durations have meant that there is less pressure in the system overall and reduces the likelihood of surcharges. Similar reductions in peak discharge following scheme level retrofit have been reported elsewhere⁵². No sewer surcharge events have been recorded since planter installation, whereas surcharges occurred during the pre-installation period, though differences in rainfall between the two periods preclude a definitive causal attribution.

Beyond hydrological performance, retrofit planters deliver co-benefits that align with the broader objectives of NBS^{53,54}. However, introducing a retrofit system to an existing structure or feature presents issues that would usually be considered during drainage strategy stages in the planning process for new buildings or infrastructure^{55–57}. The educational aspect of the planters around the school enables the opportunity to open discussions around water in the environment, making it more physical and engaging (Fig. 7). The introduction of green and blue space within the school grounds contributes to amenity value and educational engagement, and aligns with evidence linking blue green infrastructure to improved wellbeing⁵⁸. Introducing a system that aims to help improve water quantity issues gives the possibility of

opening other avenues for discussion within a setting, whether it is at an educational or community level. Climate adaptation measures can, when embedded in broader participatory planning processes⁵⁹, support wider community engagement with climate adaptation and related urban environmental goals⁶⁰.

Practice and Policy

Retrofit schemes are becoming increasingly important within global urban water management strategies⁶¹. However, persistent challenges to their implementation and performance can affect future schemes. There is a cost to benefit that needs to be met for funding, and if past retrofit schemes have not delivered, then they are unlikely to be built in future. Only through the monitoring of assets using a compare and contrast methodology can key aspects of performance be identified to inform optimisation for the future. The differences between the outflows from individual planters at the University of Hull on account of different drainage catchment areas could be considered as a failure of the system if one planter is found to overflow or cause local flooding whereas the other does not since it is assumed that they drain equally.

Monitoring of retrofit NBS faces practical barriers, including cost and the need to establish clear monitoring objectives from the outset of scheme design. To know whether retrofit schemes have improved resilience within the drainage network there needs to be pre- and post-project monitoring in place. These challenges have been noted previously, with retrofit schemes often constrained by short funding cycles focused on delivering immediate objectives rather than long term performance evaluation⁶². A focus on delivering short term objectives can limit data collection, reducing the availability of high-quality hydrological data across a range of conditions. In the UK, sewers beyond property boundaries are primarily the responsibility of water companies, and their cooperation is essential to enable monitoring of the receiving network. This institutional requirement must be addressed at the scheme design stage. Drain evaluations are commonly short in duration, limiting the data to a small number of events which may not represent the full range of behaviour. In this study, we prioritised extended pre-installation monitoring to establish a robust baseline of network response. We therefore recommend that any drain monitoring begins from the moment a scheme is being designed or considered, to maximise the potential for pre-retrofit data collection. However, there may still be challenges associated with the representativeness of different monitoring periods, for example in this case the pre-retrofit period since 2022 was drier compared to 2023.

The modular design of retrofit planters lends itself to deployment at scales beyond those examined here. This study demonstrates consistent performance at the individual planter scale and provides initial evidence of aggregate network level effects from a grouped installation of ten units. Scaling to whole catchment deployment would require consideration of spatial configuration, cumulative storage capacity, and the interaction between planter outflows and other drainage inputs. The unequal roof catchment contributions identified at the Hull site underscore the importance of site specific characterisation when designing at scale, since design assumptions that hold for one installation may not transfer to another.

Nevertheless, the low cost, small footprint, and minimal maintenance requirements of retrofit planters make them strong candidates for distributed deployment as part of a scalable NBS strategy for surface water management.

This study provides empirical evidence that retrofit planters, as a class of NBS, deliver measurable hydrological benefits at both individual and network scales. Peak flow reductions of approximately 50% and median delays of 35 minutes demonstrate that even simple, low cost NBS can meaningfully attenuate urban runoff. At the same time, the substantial variability in effective roof catchment area reveals that design assumptions for retrofit systems require field validation if performance targets are to be met reliably. These findings reinforce the case for embedding monitoring within NBS deployment as standard practice, providing the evidence base needed to move retrofit SuDS from localised pilot schemes to mainstream urban drainage strategy. In the context of circular water economies, where the objective is to intercept, retain, and manage rainfall within the urban landscape rather than discharging it as rapidly as possible, monitored retrofit NBS offer a scalable and evidence based pathway towards the resilient and sustainable cities envisaged by SDG 11.

Methodology

We evaluated the long term performance of retrofit planters at two sites in northeast England. The first, at the University of Hull's Blue Green Lab, examines individual planter performance as part of the SuDS*lab* programme. The second, at Wybers Wood Academy in Grimsby, assesses collective network performance as part of the Doncaster, Immingham and Grimsby (DIG) Surface Water Resilience Project.

Experimental Setup – Individual planter performance

Four SuDSPlanters® retrofit planters were installed at the University of Hull campus in mid-2022, diverting flow from roof downpipes (Fig. 1a) and fitted with an independent monitoring system. Downpipes were selected on the basis of public visibility (for demonstration purposes) and compatibility between estimated roof catchment area and planter storage capacity. The roof area and potential roof runoff rates were calculated using a synthetic 60-minute storm and estimated roof drainage areas from aerial photographs (Table 1). The planters have a stated approximate water storage capacity of 0.5 m³ within a 2.0 × 0.6 × 0.95 m (length × width × height) design. They are infilled with a special pre-mixed sandy loam growing medium located above a water storage reservoir. Vegetation was selected by the supplier for tolerance to the intermittent wetting and drying regime and the specific aspect of each installation. Therefore, planting regimes were different in Planters 001 and 002, which were west facing with an open aspect, and Planters 003 and 004, which were north-facing and shaded by large trees and buildings. Planter outflows discharged into separate parts of the university drainage system, precluding collective network performance assessment at this site.

Data were collected using the Davis Instruments EnviroMonitor Gateway and Node system. Planters were individually monitored as shown in Fig. 2. As part of the SuDS*lab* monitoring network, data were

collected at 5 minute intervals from each sensor⁶³. Precipitation was monitored using a tipping bucket rain gauge (0.1 mm per tip) on a Davis Vantage Pro 2 weather station (located 400 m away from the roof). Water inflow and outflow were measured using a Pulsameter 2 tipping bucket gauge, in which $1 \times 10^{-4} \text{ m}^3$ (100 ml) is recorded per tip. Table 2 shows their respective monitoring accuracy.

Table 1

Design discharge rates for retrofitted planters under varying rainfall return periods of 1, 30 and 100 years (Q_1 , Q_{30} , and Q_{100} , respectively) and the 100 year return period plus a 30% climate change allowance ($Q_{100 + 30\% \text{ CC}}$). Estimated contributing roof area is also listed.

Planter	Roof Area (m^2)	Discharge Rate ($10^{-3} \text{ m}^3 \text{ s}^{-1}$)			
		Q_1	Q_{30}	Q_{100}	$Q_{100 + 30\% \text{ CC}}$
001/ 002	136	1.01	2.38	3.33	4.33
003/ 004	170	1.26	3.56	4.17	5.42

Table 2

Sensors used on the retrofitted SuDS for both individual and grouped planters.

Sensor	Range	Accuracy
Pulsameter 2	$0 - 8.3 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$	$\pm 1.7 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$
Triton + (Depth)	0.015 -3.5 m	$\pm 1\%$
Triton + (Velocity)	0.03–9 m/s	$\pm 4\%$

Experimental Setup – Collective planter performance

Ten SuDSPlanters® were installed in February 2024 at Wybers Wood Academy, a primary school in Grimsby, UK (Fig. 1b). Planters were installed on as many downpipes as was feasible. This was determined by space availability and proximity to doorways and access routes to ensure that planters did not create unnecessary obstructions. It was not feasible to monitor individual planters owing to cost considerations and their location on buildings that could not support monitors. Precipitation was monitored using a tipping bucket rain gauge (0.1 mm per tip) on a Davis Vantage Pro 2 weather station (located 50 m from the school) reporting at 5-minute intervals. In addition, all surface water drainage from the school site is discharged through a single 0.375 m diameter combined sewer that conveys both surface water and foul water. Pre- and post-installation sewer monitoring campaigns were undertaken to determine the collective impact of retrofitted SuDS on outflows from the school. Sewer monitoring was

undertaken by IETG on behalf of Yorkshire Water, within infrastructure managed by Anglian Water, from July 2022 to October 2024 using a Triton+ flow monitor with Peak Combo area velocity sensors (Table 2). Both the depth and velocity were monitored in real-time at 5-minute intervals. The system is routinely maintained and configured, with built-in redundancy through three different methods of identifying depth. Discharge was calculated from concurrent depth and velocity measurements using the area velocity method, assuming a circular pipe cross section of 0.375 m diameter.

Data Processing and Analysis

Data were processed as shown in Fig. 8. Data were collected in real-time by the network from January 2023 to December 2023. In that time, each sensor collected nearly 100,000 measurements, with a combined dataset of 3.4 million measurements from the planters on campus. Quality assurance and quality control checks are therefore important to ensure that data are both reliable and robust. Data were processed in MATLAB 2024b. First, independent peaks were identified by applying the *findpeaks* function to both the inflow and outflow hydrographs, noting that the start and end of events was being clearly distinguishable from the baseflow of zero. Second, for the individual planters, events where total volume of outflow exceeded inflow were removed from the analysis. This occurs when the inflow pipe entering the tipping bucket gauge is blocked and the flow bypass operates to prevent water damage. This processing step removed 32 events but retained more than 350 peaks, yielding an acceptance rate of approximately 84%. For sewer records, peaks were only retained if concurrent and coincident rainfall records indicated a rainfall event. Third, the remaining peaks were filtered by magnitude to retain only the 50 largest events. This number of events was selected following trials that suggested that 50 events was the optimal number to retain all large peaks, remove bias introduced by small peaks and could be applied consistently across all sensors. Thresholding removed unintended tips of the bucket through passive water entering the system. However, in sewer measurements the flow does not return to zero (due to other inputs) and the baseflow fluctuates depending on sewage flows. Baseflow was therefore calculated using an average sewer flow rate after removing the estimated surface water input. The total volume of water (using *trapz*), peak flow, time-to-peak and duration were then calculated for each retained event (as shown schematically in Fig. 9).

Statistical analysis was performed on the filtered dataset. Descriptive statistics (median, IQR) were visualised using boxplots overlaid with jittered raw data points to display the underlying distribution density. A one-tailed (right-sided) Wilcoxon signed-rank test was used to confirm if delays and reductions were significantly greater than zero. Comparisons between the four planter systems were conducted using the Kruskal-Wallis test. The significance level was set at $\alpha = 0.05$.

Blockages in the gauge system or flows exceeding the $8.3 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$ for the tipping bucket's upper recordable limit were identified as the two main causes of erroneous measurement. Blockages tended to make water circumvent the Pulsameter 2 tipping bucket gauge via the overflow system connected to the downpipe inflow (see Fig. 2), while extremely high flows exceeded the capability of the gauge and led to low inflow measurements.

Declarations

Acknowledgements

This work has been supported by the University of Hull through the Estates Department's sustainability strategy. Special acknowledgement is given to Hiatt Jackson, Giles Davidson and Brendan Murphy for their dedication in building the SuDS^{lab} network and providing ongoing support. Funded from the University of Hull and NERC Discipline Hopping for Environmental Solutions(<https://hull-repository.worktribe.com/project/3888550/nerc-discipline-hopping-for-environmental-solutions>). This work was partially funded through the UK government's Flood and Coastal Resilience Innovation Programme (FCRIP), which is part of the government's National Flood and Coastal Erosion Risk Management Strategy for England. FCRIP is funded by Defra and managed by the Environment Agency. Additional support has been provided by City of Doncaster Council, North East Lincolnshire Council, Anglian Water and Yorkshire Water.

Conflict of Interest

The authors declare there are no conflicts of interest for this manuscript.

Data Availability Statement

The data that support the findings of this study will be available from DOI: 10.17632/hkpp7c85mg.1

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Figures



Figure 1

(a) Locations of retrofitted SuDSPlanters around the University of Hull, Hull, UK. Photographs of the retrofitted planters. (b) Locations of retrofitted SuDSPlanters[®] around the Wybers Wood Academy, Grimsby, UK. Photograph of a retrofitted planter with interactive display.

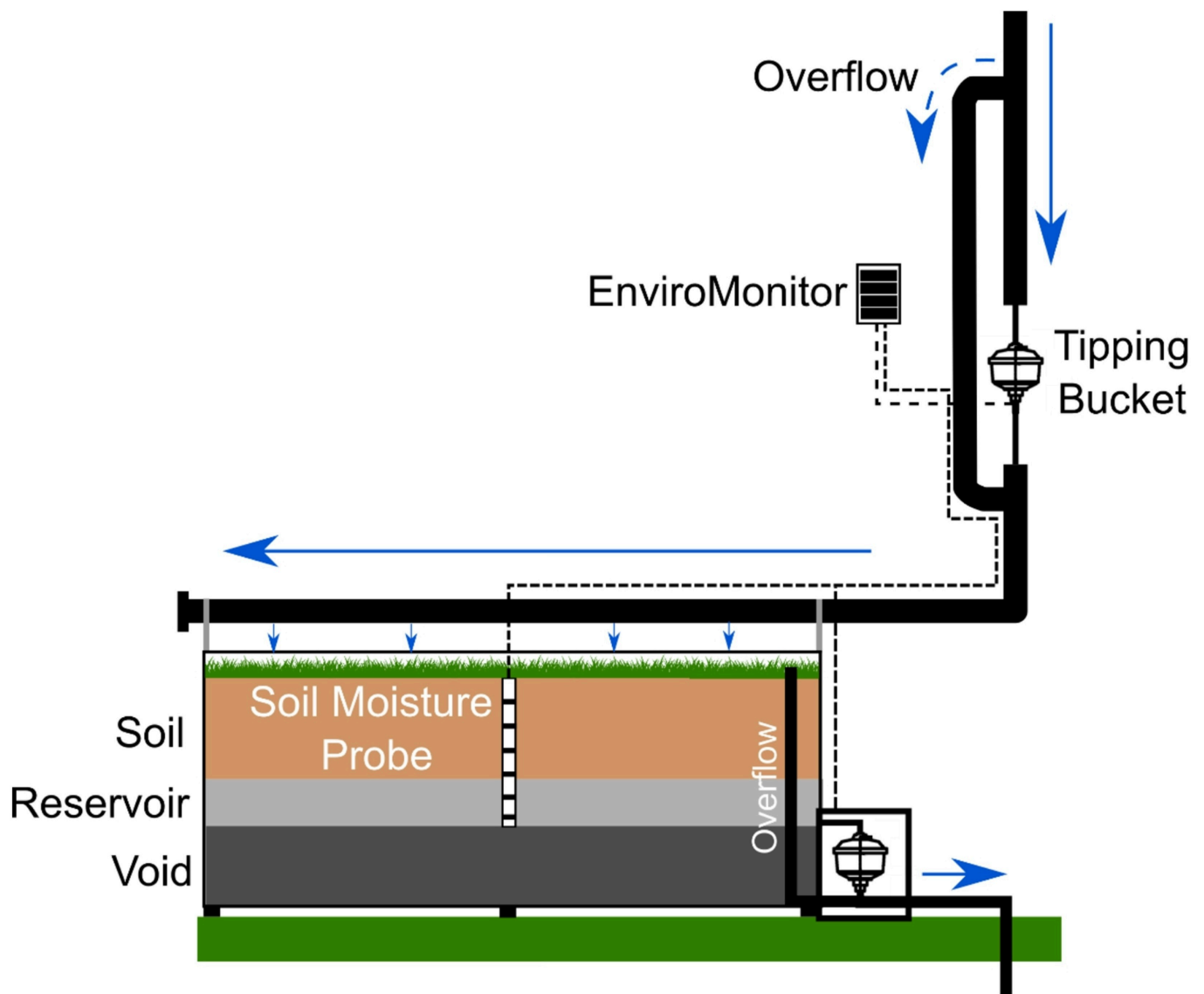


Figure 2

Illustrative diagram of the monitoring of a retrofitted planter.

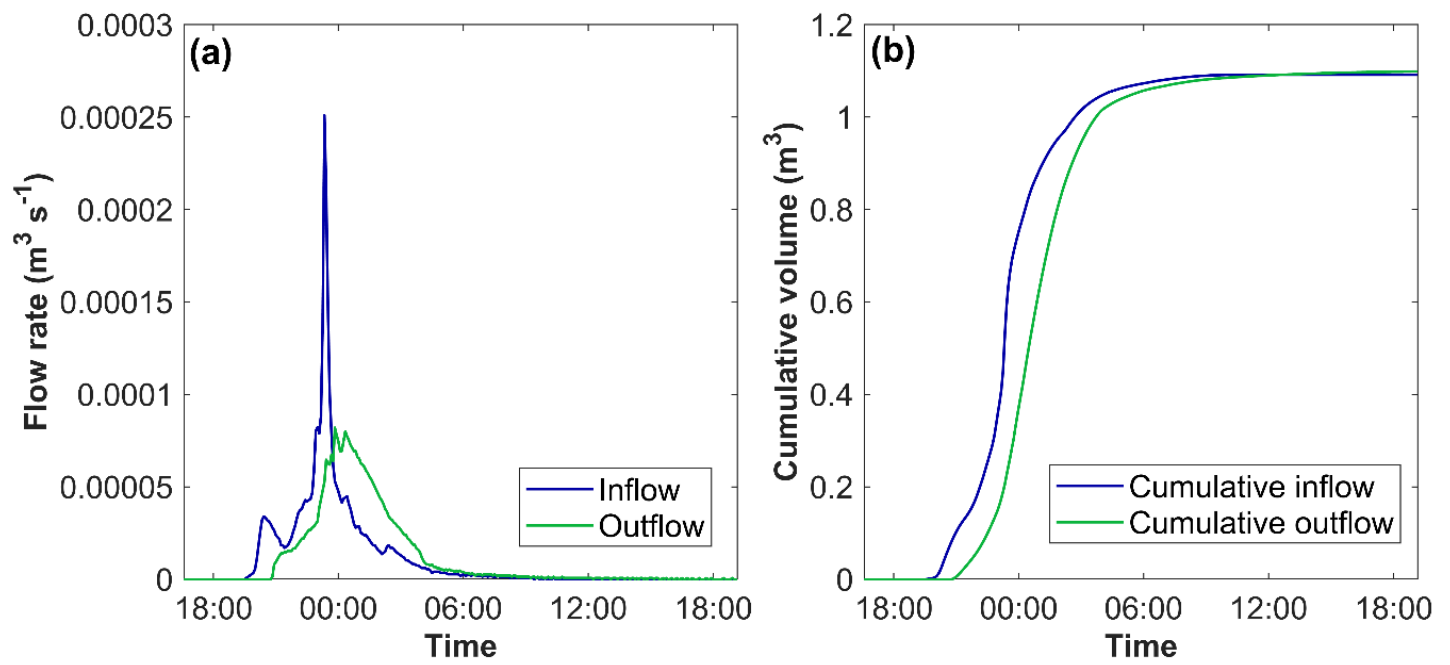


Figure 3

(a) Zoomed in hydrograph from Planter-001 during a storm event on 15 September 2023 comparing inflow from the roof (blue) and outflow from the planter (red). (b) Cumulative inflow and outflow from the same storm event.

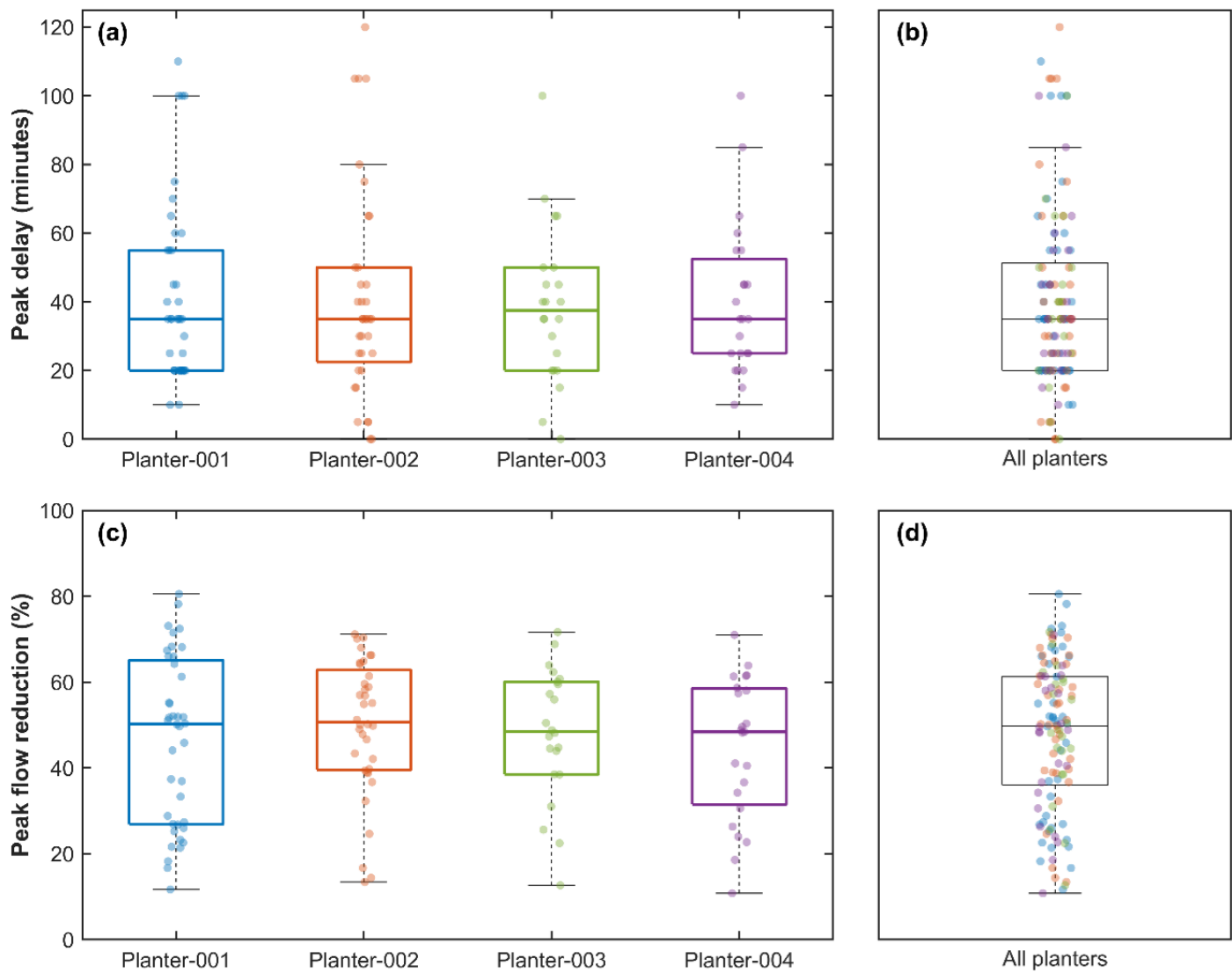


Figure 4

Peak delay and peak flow reduction for four individual planters (Planter 001 to Planter 004). (a) Boxplots of peak delay for each planter with jittered raw data points. (b) Pooled peak delay across all planters. (c) Boxplots of peak flow reduction (%) for each planter. (d) Pooled peak flow reduction across all planters. Boxes show interquartile range with median line; whiskers extend to the most extreme data points within 1.5 times the interquartile range.

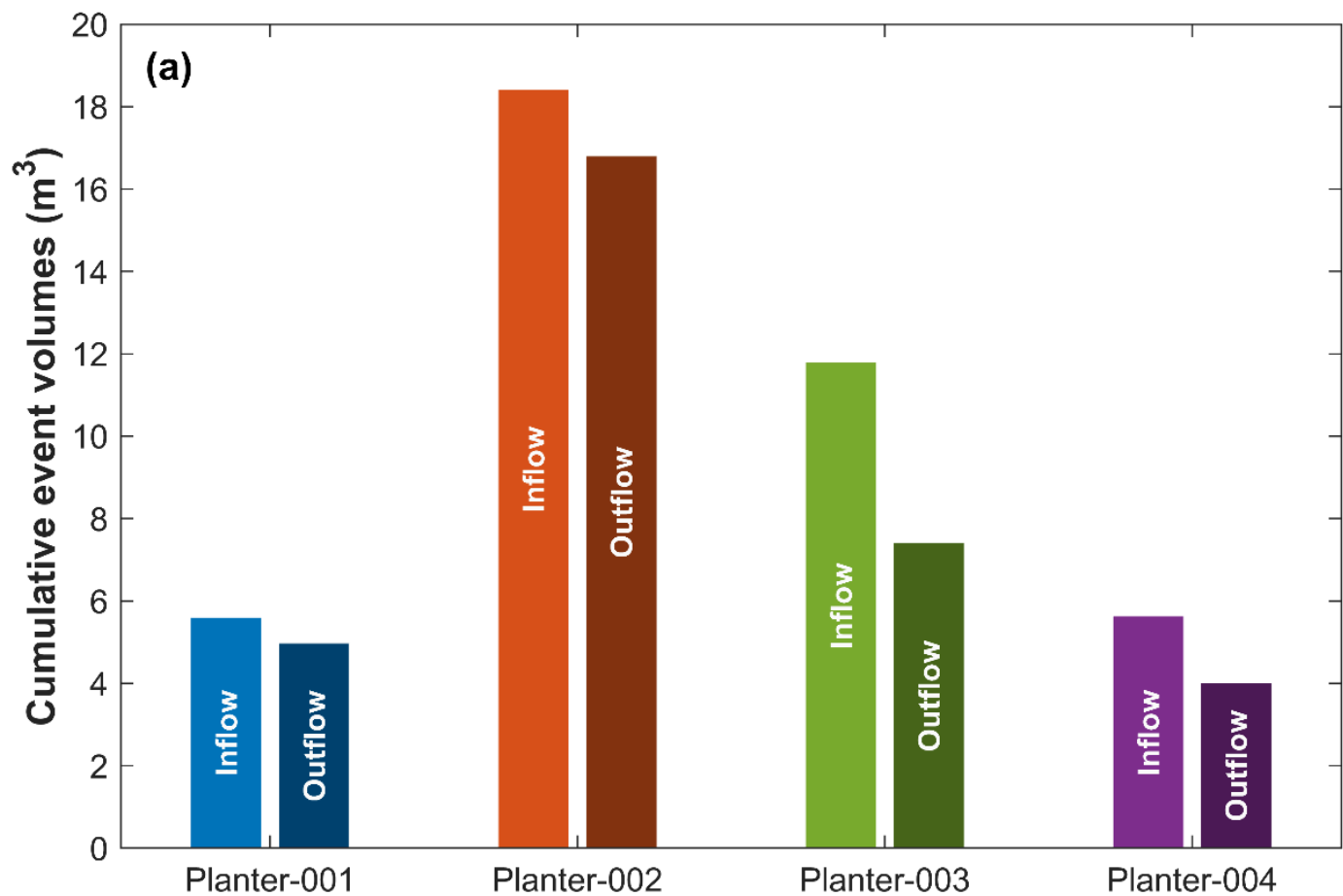


Figure 5

Cumulative inflow and outflow volumes summed across all identified events for each planter. Bars show the total event driven water entering and leaving each system, illustrating the relative magnitude of treated volumes across the four installations.

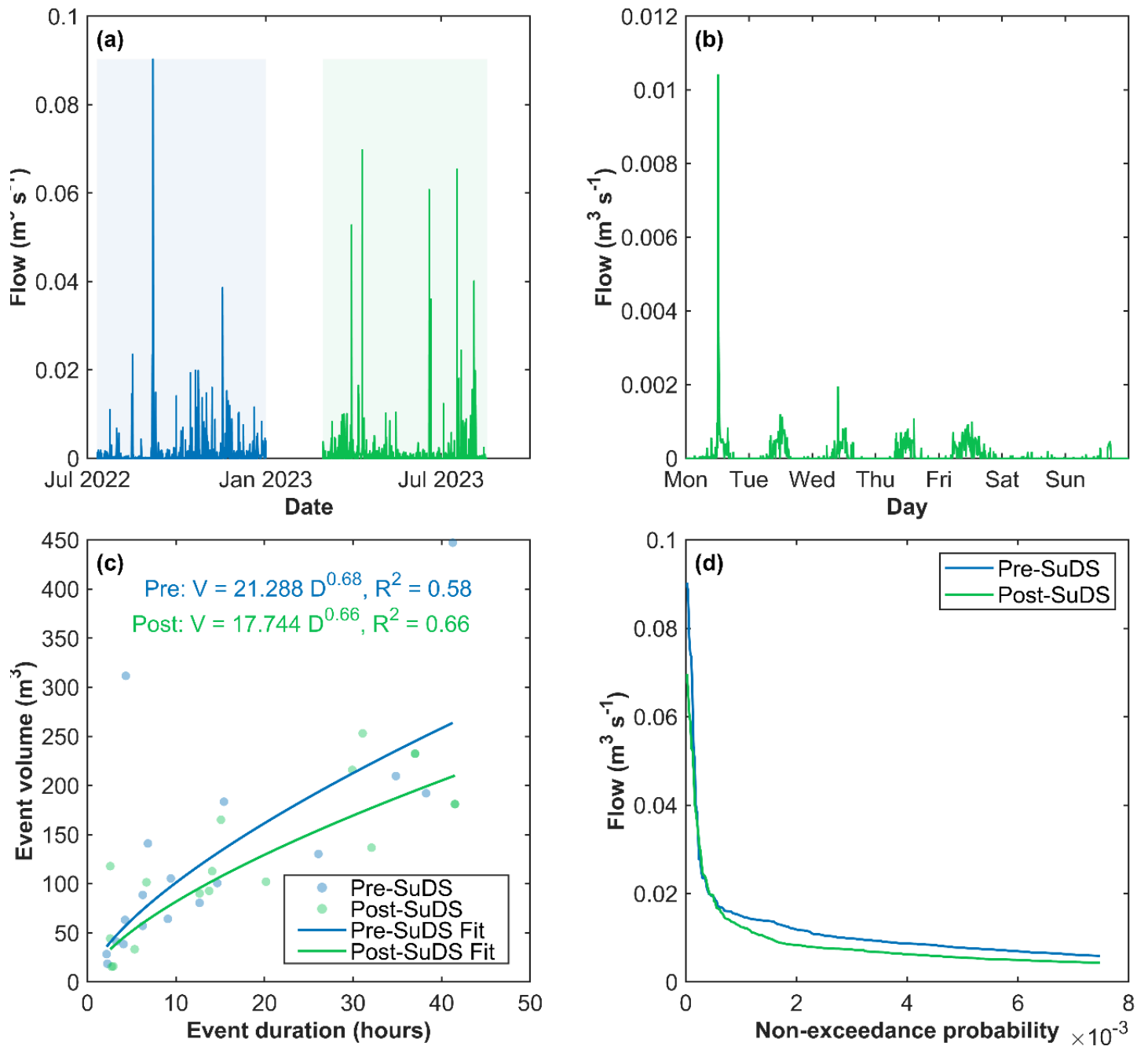


Figure 6

Sewer flow characteristics for the Wybers catchment before and after SuDS installation. (a) Complete time series of pre-SuDS and post-SuDS sewer flows. (b) One week of sewer flow data centred on 15 May 2023 showing short duration weekday peaks associated with school activity. (c) Event duration versus event volume for pre-SuDS and post-SuDS conditions with fitted power law relationships. (d) Flow duration curves highlighting differences in high flow exceedance probabilities between the two periods.



Figure 7

Photographs of the planters installed as part of the DIG project showing (a) the interactive elements, (b) the instrumentation setup of a planter and (c) an educational display of the SuDS in Schools programme.

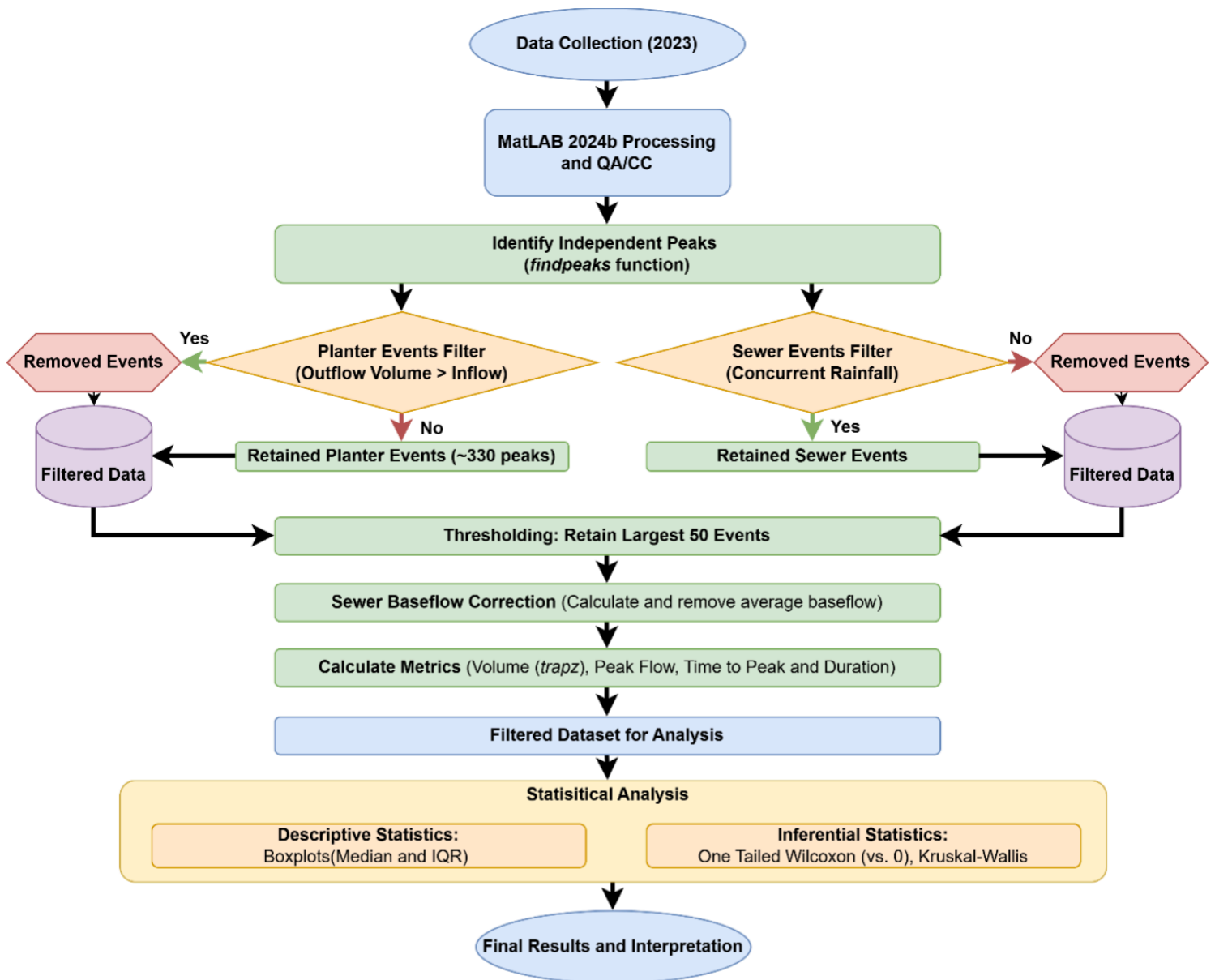


Figure 8

Typical workflow for processing flow event data. It outlines preparation of raw data, detection of peaks, selection of major events, delineation of event boundaries, and final quantification of duration and volume.

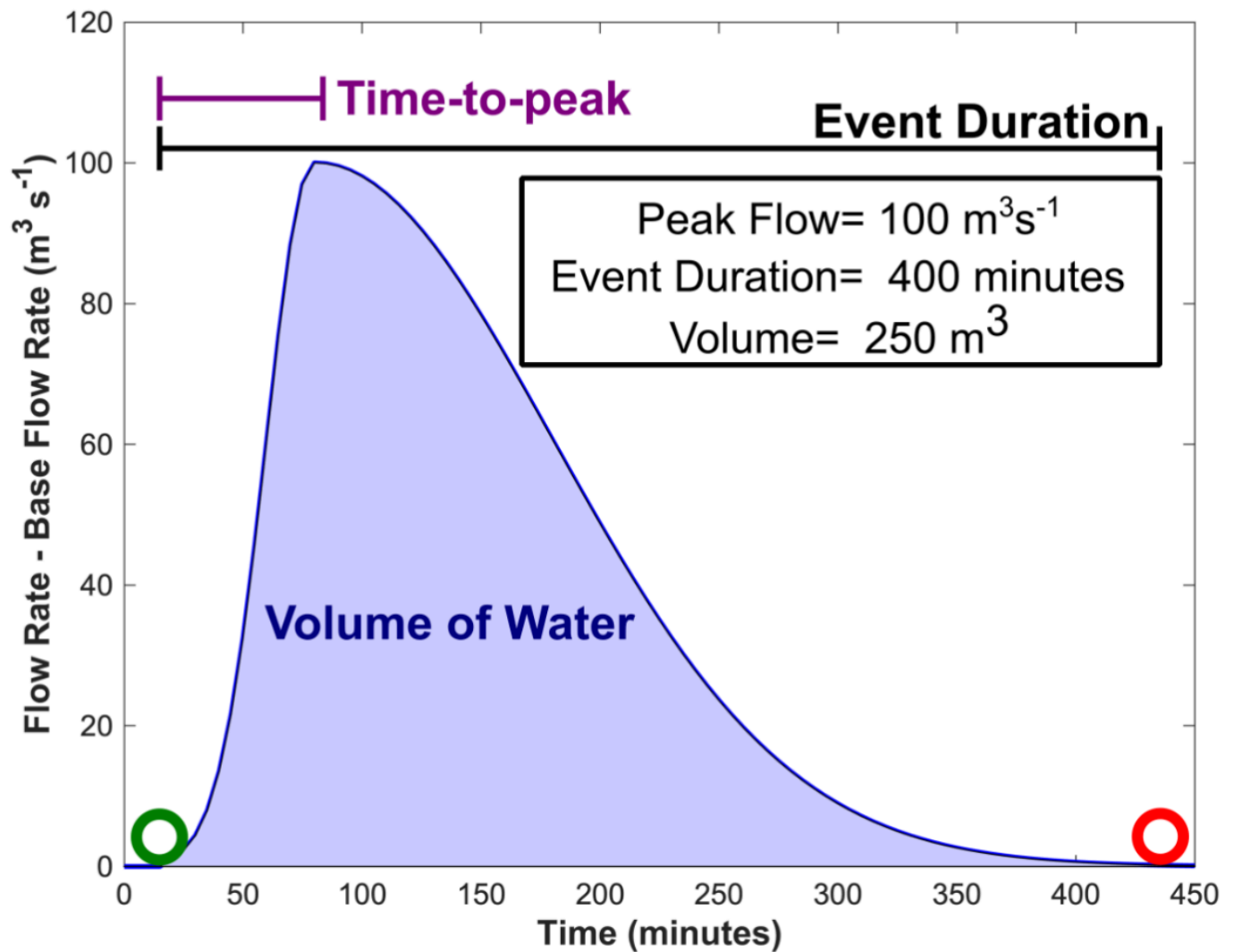


Figure 9

Example of event based calculations. If there is a non-zero baseflow, this baseflow may be subtracted from the total flow rate to help identify peaks. Green circle identifies the start of an event, blue circle represents the event peak and the red circle identifies the end of an event

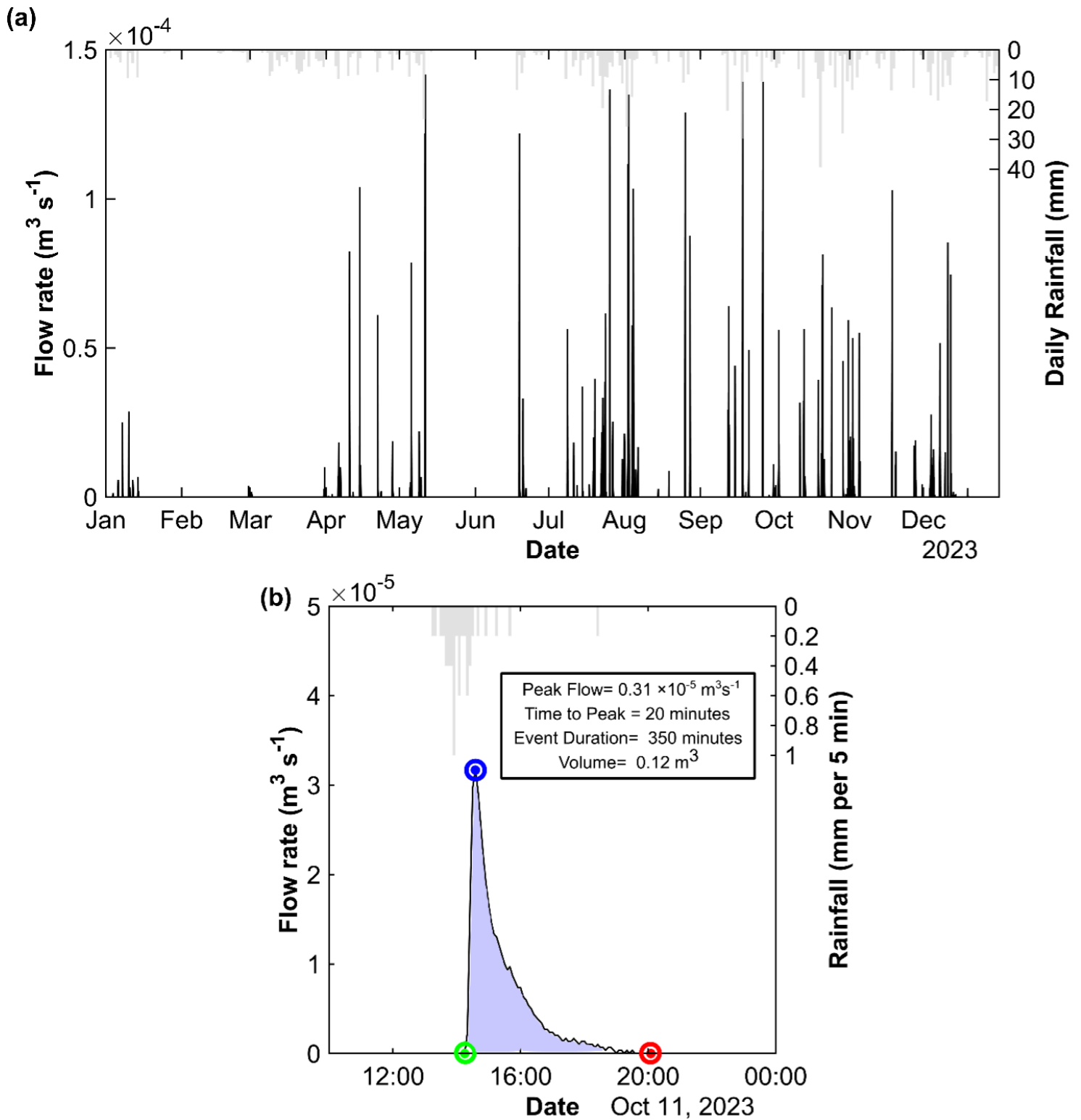


Figure 10

(a) Planter-001 inflow rate from the tipping bucket gauge system from January 2023 to December 2023 with daily rainfall collected from the onsite weather station. (b) Zoomed in on 11 October event with green circles identify the start of an event and red circles identify the end of an event. Blue circles represent event peaks.