This is the author's pre-print copy of the manuscript.

Accepted for publication in Ecological Engineering on 24 July 2018.

Field evaluation of precipitation interception potential of green façades

A. Tiwary[1], K. Godsmark[2], J. Smethurst[3]

[1] *Faculty of Engineering and the Environment, Northumbria University, Newcastle upon Tyne, U.K.*

[2] *WSP Consultants, Mountbatten House, Basing View, Basingstoke RG21 4HJ, U.K.*

[3] *Faculty of Engineering and Physical Sciences, University of Southampton, SO17 1BJ, U.K.*

Abstract

This paper evaluates the potential of living green façades in intercepting precipitation and delaying 'canopy through-flow' (i.e. total precipitation minus canopy interception). Precipitation interception and delayed through-flow or discharge from two visually distinct mixed-species green façade configurations – one, fully-foliated and the other twiggy (respectively as proxies for well-managed and degenerated stands) – were monitored using rain gauges located at their base. The precipitation interception levels for the fully-foliated and the twiggy stands respectively ranged between 54-94% and 10-55% of the total precipitation. Regression of the experimental data showed interception volumes were proportional to the ambient precipitation up to a maximum tested event size of 35 mm. The fully-foliated façade gave a delay of at least 30 minutes from the start of precipitation events to the first measured through-flow, compared to about 15 minutes for the twiggy façade. This highlights the potential for well- foliated and maintained façades to contribute to reducing peak flows within urban drainage infrastructure, and the importance of façade maintenance in ensuring good interception and delay properties.

Keywords: *green façade; stormwater interception; sustainable drainage; vertical greening*

1. Introduction

Conventional urban drainage systems are often overwhelmed during adverse hydrological events, as they mainly rely on collection in a singular or a networks of sewer systems (Kew et al., 2014; Nickel et al., 2014). In recent years, the combined use of vertical greening structures and green roofs has been increasingly adopted as “bioclimatic” design to complement (or partially replace) urban grey drainage infrastructure systems (Nickel et al., 2014; Pérez-Urrestarazu et al., 2015). As almost 80% of the existing housing stock across Europe will still be in use in 2050 (Sandberg et al., 2016), vertical surfaces could be effectively utilised for green infrastructure (GI) stormwater management solutions (Francis and Lorimer, 2011; Kew et al., 2014). Urban environments provide a plethora of vertical surfaces; an early UK estimate from 1980s suggested that approximately one-tenth of urban land surface is made up of vertical walls (Darlington, 1981). This has grown further through regeneration and construction of high-rise buildings in most cities over the last two decades.

Considerable focus has been placed on the role of green roofs in stormwater management (Köhler, 2008; Li and Babcock, 2014; Stovin et al., 2015; Vergroesen et al., 2010), alongside additional low impact options, including trees, porous pavements, swales, rain gardens and rainwater harvesting (Nickel et al., 2014). So far green façade performance has been evaluated as a combined category along with greenroofs (Sinnett et al., 2016). Unlike flat green roofs, which occupy a large horizontal plan area and where flow from precipitation is predominately horizontal (and thus quite slow), green façades occupy a much smaller plan area and flow is mainly vertical (and likely more rapid) which limits their role in direct runoff reduction and delay. Nevertheless, green façades can be effectively combined with greenroofs as part of augmented designs for stormwater management, mainly enhancing rain interception, evapotranspiration, retention within the soil and peak delay etc.

To date there is little empirical evidence on the potential role of vertical greening systems of different density in building-scale stormwater management under real-world conditions. Previous studies have focused on specific issues: for example, assessing the ability of vertical greening solutions to moderate urban hydrological regimes (Loh, 2008) or simulated retention of roof runoff using a cistern to irrigate the greenwalls (Kew et al., 2014). There is also ambiguity in the extent to which implemented schemes can be deemed sustainable, mainly in terms of the installation of the 'living materials' and the regular maintenance, nutrient and water requirements that are necessary for optimal performance over its lifetime (Perini et al., 2011). The majority of these studies have a planning focus, supported largely through modelling, and there is still a lack of adequate experimental evidence (Mell, 2016). This work represents the first step trying to quantify the stormwater management mechanisms of green façades of varying composition. The paper specifically evaluates the potential of green façades in intercepting precipitation and delaying the vertical discharge from the base of the plant canopy. The monitored and modelled precipitation interception patterns of two visually distinct 'real green façade' configurations are reported – one densely foliated and the other degenerated and twiggy. The implications of the precipitation interception and delay are then discussed in terms of role of green façade systems in building-scale stormwater management.

2. Methodology

2.1. Site description

Two co-located vertical green façades, comprising mixed-species climbing evergreen Common Honeysuckle (*Lonicera Periclymenum*) and Winter Jasmine (*Jasminum Nudiflorum*) of visually distinct vegetation densities, were selected for this study – one, fully-foliated (G1) and the other, predominantly twiggy (G2). Both were about 3 m high, 0.5 m deep and 1.2 m wide, supported by wooden trellis and wire systems, but G1 was denser whereas G2 had several interruptions to its vegetation cover, mainly attributed to the difference in the levels of maintenance. Therefore, the two stands were selected for comparison as proxies for well-managed and degenerated stands. No obstacles in the form of guttering and window ledges were present, and thus the site was considered suitable for sampling the reduction in precipitation as a result of only interception by the canopy. The green façades were located on the south facing brick wall of a detached residential property in southern part of UK; the choice of this site ensured a secure location whereby equipment could be left unattended during long unperturbed sampling. Surrounding infrastructure was limited to a garage, positioned approximately 50-60m south-east of the façades.

2.2. Precipitation interception monitoring

Tipping bucket rain gauges (two Oregon Scientific gauges of the WMR series and one Campbell Scientific ARG100 gauge respectively having collecting funnel areas of approximately 78.5 cm^2 and 500 cm^2) were selected for use in this study due to their following advantages: high accuracy in low to intermediate precipitation events, reliability, and their ability to provide data in a digital format (Stovin et al., 2015; Vasvári, 2005; Vergroesen et al., 2010). The tip size was 0.202 mm of rainfall or 10 ml for the Campbell Scientific gauge, and 1 mm of rainfall or 7.85 ml for the Oregon Scientific gauge.

Canopy through-flow measurements were made for a period of 12 weeks between 18th March and 16th June 2016. The period was free of any storm events with high winds, or freezing and/or snow events that might alter the canopy through-flow behaviour. The Oregon Scientific rain gauges were located beneath the canopy of each of the green façades (**Figure 1**), levelled via placement upon a gravel bed. Guttering (in 50 cm segments with a width of 12 cm) was placed in a constructed wooden frame under each canopy at 15 degrees to measure the canopy through-flow, (i.e. precipitation minus canopy interception) from a segment of the façade and direct it into the gauge, following (Blocken et al., 2013). A control rain gauge was placed as close as possible to the green façade such that it would not be directly influenced by the vegetation (i.e. outside of the extent of the plant canopy) to record the total precipitation received in individual events. 'Interception' was defined as the difference in collected precipitation below the plant canopy and the total precipitation recorded by the control gauge. A potential limitation of the monitoring system was that it was not able to ascertain the proportion of the total precipitation that was retained within the canopy of the green façade, from that which may have bounced off, missing the collection infrastructure. For both the control and façade gauges, data loggers were set to record at one-minute intervals to provide high-resolution data. Owing to the storage limit of the loggers, the data were downloaded and the data loggers reset every 10 days. Additionally, the equipment was checked and cleaned of any plant debris.

2.3. Data analysis

In total, 27 precipitation events were recorded across the 12-week measurement period. Gauge calibration curves and their associated equations were applied to correct the raw data. Conversions to absolute volumes (ml) were applied and subsequently to mm since this is the standard unit used for reporting precipitation. Following initial data processing, total precipitation (in mm) was analysed on an event-by-event basis taking each of the 27 individual events in turn. Based on this, the largest 8 events (in terms of precipitation amount) were chosen, and the precipitation data for these events were processed from 1-minute to 10-minute intervals (the choice of this interval allowed for management of data without significant loss of precision). This was then used to produce cumulative plots, comparing volumes from the control gauge and two contrasting façade sites. Peak intensities (mm/hr) were calculated per event and used to determine functionality thresholds for both façade sites. For all 27 events, statistical analysis was performed to determine if there was a significant difference between measured volumes for G1 and G2. Mann Whitney U-tests were employed following normality tests, which indicated that the data was not normally distributed.

2.4. Regression analysis

An empirical model was developed for estimating canopy precipitation interception capacity as a function of the total precipitation (in mm) for both the fully foliated and twiggy green façades. For this purpose, only the recorded data for those events when the wind direction had least influence of the building structure on the performance of the green façade were regressed against the corresponding total precipitation. Wind speed and direction were acquired from the British Atmospheric Data Centre (BADC) for the entire duration of the experiments (BADC, 2016).

3. Results and Discussion

3.1. Façade precipitation interception

A clear relationship was obtained between vegetation cover and canopy precipitation interception for the two green façades in the experiment. **Figure 2** shows the plots for the eight largest precipitation events during the sampling period in descending order of maximum ambient total precipitation. There is a clear demarcation of the temporal profiles of the precipitation monitored by the three rain gauges from the onset of the rain. Shown alongside is the prevalent wind condition during each event. Mann Whitney U-tests indicated that there were statistically significant differences in the precipitation recorded by the fully foliated and the twiggy façades respectively ($U = 3.00$, $Z = -3.07$, $P < 0.01$ and $U = 70.00$, $Z = -2.91$, $P < 0.01$). As expected, the average delay (i.e. the difference in time between the onset of the precipitation event, and the first measurement by the monitoring gauges below the green façades) was consistently higher for the fully foliated façade (G1), with average delay lengths that were double or even triple that of the twiggy façade (G2). Of the 8 precipitation events (**Figure 2**), the first four were considered as moderate (average rainfall between 2 - 4 mm/hr) and the other four as light (under 2 mm/hr). The difference between the delay for the two façades was particularly prolonged for light precipitation events, and thus is directly associated with event intensity. On these occasions the delay even extended to low residual flows beyond the end of the precipitation event.

Nearly 44% of all 27 events prompted breakdown of (i.e. some through-flow from) the twiggy façade compared to only 15% for the fully foliated façade. Precipitation was intercepted within the G1 and G2 plant canopies below peak intensities of 9.0 mm/hr and 2.6 mm/hr respectively (**Figure 3**). Generally, events that exceeded these intensity thresholds led to breakdown of the canopy interception and occurrence of through-flow. The results indicate that the threshold for breakdown may also rely on the event duration and the prevailing wind environment, the latter mainly influenced by the wind direction and intensity. The wind direction recorded at the site was SW for many of the 27 events, which ensured the green façade remained windward, and thus the role of the house sheltering the green façade was ignored. The experimental observations demonstrated that the canopy density of the vertical greening systems significantly affected the level of precipitation interception. It is noteworthy that this study only evaluated the vertical precipitation interception by the plant canopy; some of the canopy 'through-flow' will form recharge into the soil at the base of the façade meaning that estimates of 'true stormwater runoff reduction' could be much greater.

For the fully-foliated façade, 87% of all the precipitation events showed a delay of greater than 0.5 hr (30 minutes) before the first through-flow was recorded by the monitoring gauge (**Figure 2**). This observed delay in precipitation reaching the ground surface is broadly speaking, in line with a previous observation for a green roof, which concluded that nearly two thirds of all the precipitation events resulted in runoff delays of a minimum of 30-minutes (Czemiel Berndtsson, 2010). However, given the faster flow under gravity in a vertical green façade, its delay should be lower than in a green roof (Kew et al., 2014). Retention of a proportion of precipitation in this manner, and its eventual evaporation and transpiration, and the delay associated with flow through the system, can potentially reduce the peak flows and the consequential overwhelming of urban drainage infrastructure (Czemiel Berndtsson, 2010; Loh, 2008). This may minimise the frequency and risk of surface water flooding and the occurrence of combined sewer overflows (Carter and Fowler, 2008; Nickel et al., 2014; Stovin et al., 2015). On the other hand, the typical delay in the first precipitation recorded by the gauge underneath the twiggy façade was found to be around 0.25 hr (15 mins) for over 90% of all the precipitation events. This difference between the delays for the two façades signifies the importance of regular maintenance on their ability to reduce peak flows and aid stormwater management.

The canopy interception by the fully-foliated façade, in terms of both total volumes and delay, is found to be relatively higher than interception values for a tree. This can be attributed to the tall, thin, vertical nature of the façade which creates a dense canopy, capable of holding quite a lot of water. In general, the findings corroborate previous studies suggesting the proportion of precipitation interception is directly proportional to the vegetation cover (Czemiel Berndtsson, 2010; Kew et al., 2014; Natarajan et al., 2015). The vegetation cover is linked to the extent to which the building façade is enveloped, and dictates its ability to retain and prevent precipitation from entering drainage infrastructure. Green façades exhibiting significant interruptions to their vegetation cover have reduced retention capabilities, a conclusion that is supported by the findings of this study. Under more managed practice, regular maintenance interventions may be required to ensure the health, and thereby the 'theoretical interception efficiency' of the green façades. The number of such interventions cannot be easily predicted, as they may rely on future patterns of aggressive weather events.

3.2. Interception modelling

The precipitation interception estimates for the denser façade are found to be clustered in the upper half of **Figure 4 (see left panel**), representing a high interception of over 60% of total precipitation in the majority of cases (ranging between 54-94%). On the other hand, the rainwater interception by the twiggy façade varied significantly (ranging between 10-55%) and remained below 50% of total precipitation in most cases (**Figure 4, right panel**). In both cases, there were occasions of 100% interception at very low precipitation volumes. As first stage models, the fitted curves allow approximation of the relationship between total ambient precipitation and the varying degree of interception by the two green façades. As can be seen from the plots, the modelled rain water capture of the denser façade remains pretty high for lower magnitudes of precipitation and then decreases, levelling off at about 70% of total precipitation. For the twiggy façade, where there is a greater scatter in the plotted points, trying to fit a similar relationship gives a low R^2 value. The fitted curve levels off at about 30% interception beyond 10 mm total ambient precipitation. Similar data driven approaches have been conducted in other GI studies (Carson et al., 2013; Krebs et al., 2016). However, the absence of green façades in current stormwater management models suggests that their modelling is in its infancy and would benefit from additional research. It is notable that the regression models were developed for the maximum total precipitation event of approximately 35 mm. Extrapolation of the precipitation interception/retention capacity trends for the green façades beyond this limit is not advisable since higher magnitude precipitation levels could reduce interception levels as a proportion of total rainfall. Overall, for the 8 largest rainfall events considered (total 1325 data points each), the precipitation interception potential for the fully-foliated green façade showed a stronger linear dependence on the incident ambient precipitation levels (R^2=0.96) (**Figure 4, bottom panel**).

4. Conclusions and further research needs

This study quantified the potential precipitation interception for two real green façades with distinct morphological features as follows: fully-foliated façade - over 60% interception (typical range 54-94%); twiggy - below 50% (typical range 10-55%). The fully-foliated façade gave a delay of at least 30 minutes from the start of precipitation events to the first measured flow-through, compared to about 15 minutes for the twiggy façade. This highlights the potential for well- foliated and maintained façades to contribute to reducing peak flows within urban drainage infrastructure, and the importance of façade maintenance in ensuring good interception and delay properties.

The regression model presented here used the experimental data from this study. Further refinement of the model, using more representative parameters, including façade base material, evapotranspiration rates and leaf area index of the plant species, is expected to provide more realistic estimation of stormwater interception potential. In order to extend this study to evaluate the potential of green façades for water retention, both canopy and potting soil hydrology need to be examined. Further, the study is based on evergreen plant species and no consideration has been given to seasonal foliage profiles for deciduous species. It utilised data from a 12-week measurement campaign; a more extended experimental dataset is required in future to estimate the stormwater reduction potential of vertical greening systems under different weather and seasonal conditions. The authors acknowledge that the installation of green façades will not exclusively solve urban stormwater management issues. Instead, a coupled approach, integrating several runoff reduction methods needs to be considered, which would require modelling of available/innovative techniques at differing time scales in order to attain accuracy in predictions. Plausible green façade design may be inspired by a tree-pit where water is stored in the ground below the green façade and used to ensure a supply of water to plants in summer. Such a green façade could then receive runoff water from other areas of impervious pavement, extending its overall benefit.

5. Acknowledgements

Kate Godsmark acknowledges the technical assistance provided by Harvey Skinner in modifying the rain gauges and with their calibration, and the academic support from Dr Patrick Osborne in Faculty of Environmental and Life Sciences at University of Southampton.

6. References

BADC, 2016. British Atmospheric Data Centre [WWW Document]. URL http://badc.nerc.ac.uk/data/ (accessed 7.10.17).

Blocken, B., Derome, D., Carmeliet, J., 2013. Rainwater runoff from building facades: A review. Build. Environ. 60, 339–361. https://doi.org/10.1016/J.BUILDENV.2012.10.008

Carson, T.B., Marasco, D.E., Culligan, P.J., McGillis, W.R., 2013. Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems. Environ. Res. Lett. 8, 24036. https://doi.org/10.1088/1748-9326/8/2/024036

Carter, T., Fowler, L., 2008. Establishing Green Roof Infrastructure Through Environmental Policy Instruments. Environ. Manage. 42, 151–164. https://doi.org/10.1007/s00267-008-9095-5

Czemiel Berndtsson, J., 2010. Green roof performance towards management of runoff water quantity and quality: A review. Ecol. Eng. 36, 351–360. https://doi.org/10.1016/J.ECOLENG.2009.12.014

Darlington, A., 1981. Ecology of Facades. Heinemann Educational Books, London.

Francis, R.A., Lorimer, J., 2011. Urban reconciliation ecology: The potential of living roofs and walls. J. Environ. Manage. 92, 1429–1437. https://doi.org/10.1016/J.JENVMAN.2011.01.012

Kew, B., Pennypacker, E., Echols, S., 2014. CAN GREENWALLS CONTRIBUTE TO STORMWATER MANAGEMENT? A STUDY OF CISTERN STORAGE GREENWALL FIRST FLUSH CAPTURE. J. Green Build. 9, 85–99. https://doi.org/10.3992/1943-4618-9.3.85

Köhler, M., 2008. Green facades—a view back and some visions. Urban Ecosyst. 11, 423–436. https://doi.org/10.1007/s11252-008-0063-x

Krebs, G., Kuoppamäki, K., Kokkonen, T., Koivusalo, H., 2016. Simulation of green roof test bed runoff. Hydrol. Process. 30, 250–262. https://doi.org/10.1002/hyp.10605

Li, Y., Babcock, R.W., 2014. Green roof hydrologic performance and modeling: a review. Water Sci. Technol. 69, 727. https://doi.org/10.2166/wst.2013.770

Loh, S., 2008. LIVING WALLS – A WAY TO GREEN THE BUILT ENVIRONMENT. BEDP Environ. Des. Guid. 1, 1–7.

Mell, I., 2016. Global green infrastructure : lessons for successful policy-making, investment and management.

Natarajan, M., Rahimi, M., Sen, S., Mackenzie, N., Imanbayev, Y., 2015. Living wall systems: evaluating life-cycle energy, water and carbon impacts. Urban Ecosyst. 18, 1–11. https://doi.org/10.1007/s11252-014-0378-8

Nickel, D., Schoenfelder, W., Medearis, D., Dolowitz, D.P., Keeley, M., Shuster, W., 2014. German experience in managing stormwater with green infrastructure. J. Environ. Plan. Manag. 57, 403–423. https://doi.org/10.1080/09640568.2012.748652

Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco-Salas, A., Egea, G., 2015. Vertical Greening

Systems and Sustainable Cities. J. Urban Technol. 22, 65–85. https://doi.org/10.1080/10630732.2015.1073900

Perini, K., Ottelé, M., Haas, E.M., Raiteri, R., 2011. Greening the building envelope, facade greening and living wall systems. Open J. Ecol. 1, 1–8. https://doi.org/10.4236/oje.2011.11001

Sandberg, N.H., Heidrich, O., Dawson, R., Dimitriou, S., Vimm-r, T., Filippidou, F., Stegnar, G., Šijanec Zavrl, M., Brattebø, H., 2016. Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy Build. 132, 26–38. https://doi.org/10.1016/J.ENBUILD.2016.05.100

Sinnett, D., Calvert, T., Martyn, N., Williams, K., Burgess, S., Smith, N., 2016. Green Infrastructure Research into Practice.

Stovin, V., Poë, S., De-Ville, S., Berretta, C., 2015. The influence of substrate and vegetation configuration on green roof hydrological performance. Ecol. Eng. 85, 159–172. https://doi.org/10.1016/J.ECOLENG.2015.09.076

Tiwary, A., Williams, I.D., Heidrich, O., Namdeo, A., Bandaru, V., Calfapietra, C., 2016. Development of multi-functional streetscape green infrastructure using a performance index approach. Environ. Pollut. 208, 209–220. https://doi.org/10.1016/J.ENVPOL.2015.09.003

Vasvári, V., 2005. Calibration of tipping bucket rain gauges in the Graz urban research area. Atmos. Res. 77, 18–28. https://doi.org/10.1016/J.ATMOSRES.2004.12.012

Vergroesen, T., Man Joshi, U., van de Giesen, N.C., van de Ven, F.H.M., 2010. High resolution rainfall – runoff measurement setup for green roof experiments in a tropical environment. Hydrol. Earth Syst. Sci. Discuss. 7, 9367–9410. https://doi.org/10.5194/hessd-7-9367-2010

List of Figures

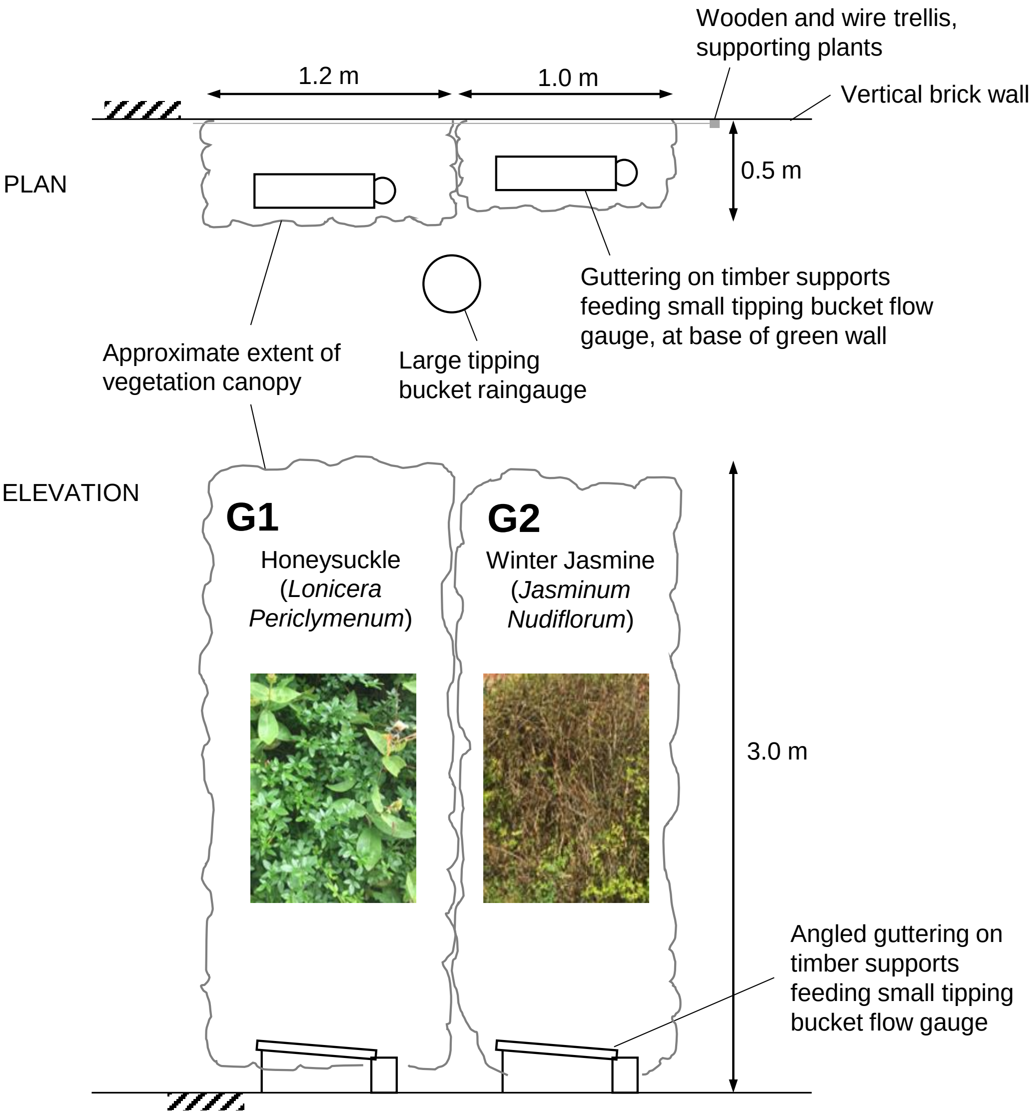

Figure 1. Planar view of the two green façades - densely foliated (G1, top left) degenerated and twiggy (G2, top right), tipping bucket rain gauge arrangement (bottom)

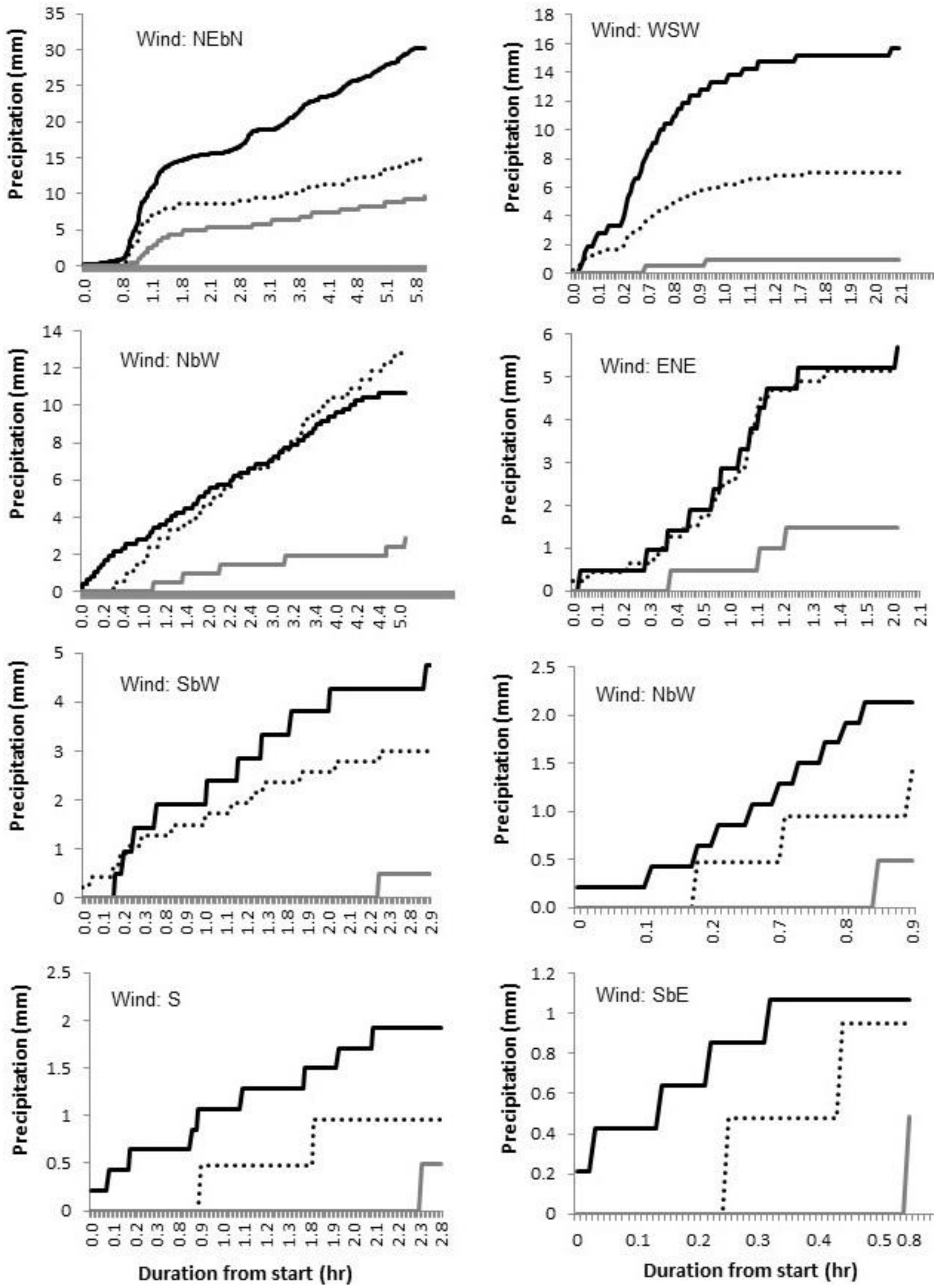

Figure 2. Cumulative curves for precipitation recorded by the control gauge (solid black line) (mm) and the corresponding precipitation totals (mm) reaching the monitoring gauge underneath the fully-foliated (G1, dark grey) and the twiggy (G2, dotted) façades for the top 8 events, presented in descending order of maximum total ambient precipitation.

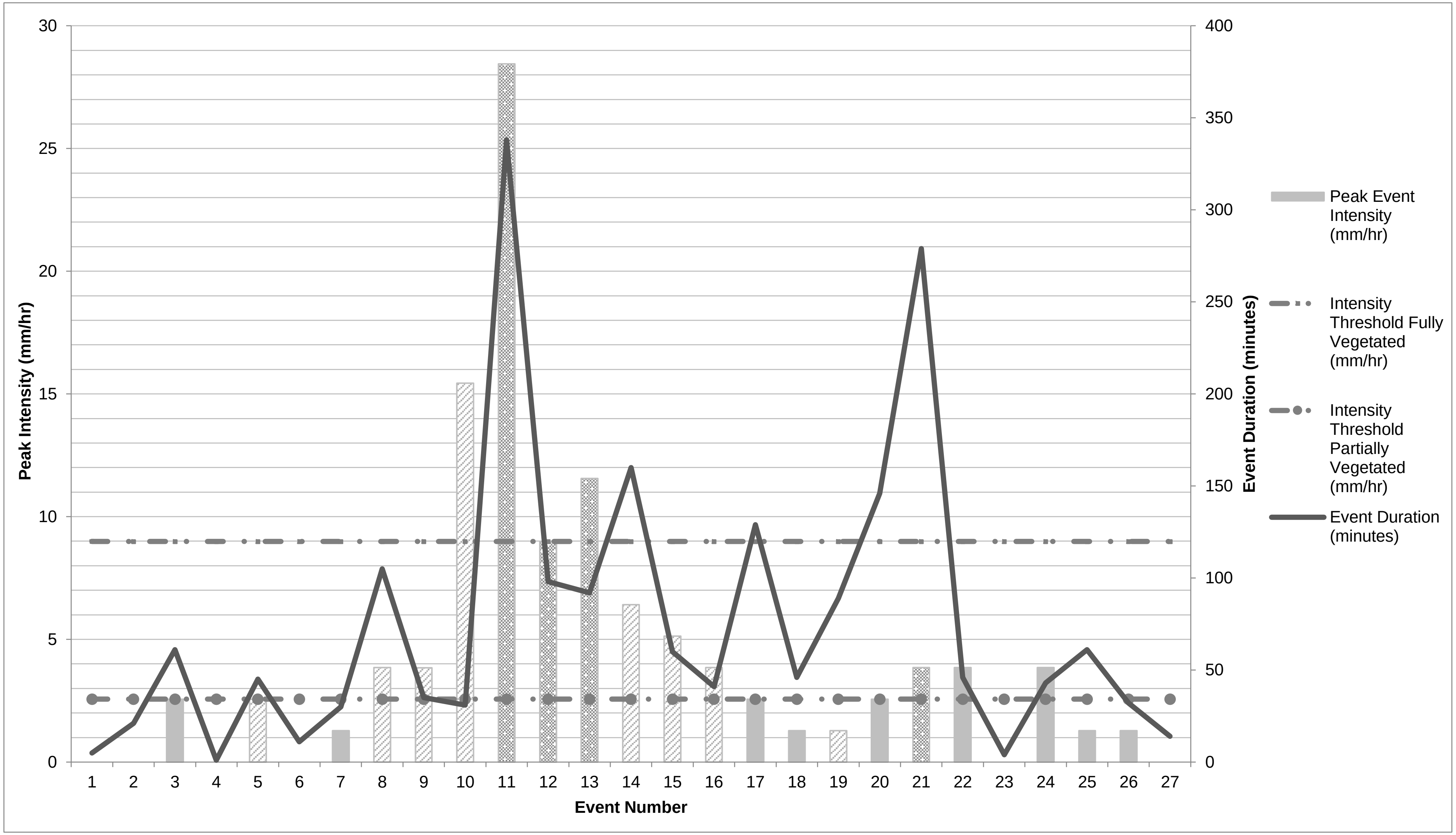

Figure 3. Precipitation events against peak event intensity (mm/hr) and total duration (minutes). Dotted bars indicate breakdown (cessation of interception) of the fully-foliated façade, and hatched of the twiggy (degenerated) façade only. Intensity thresholds (mm/hr) for functionality for the fully-foliated (dashed line) and the twiggy (dashed-dotted line) façade are also included.

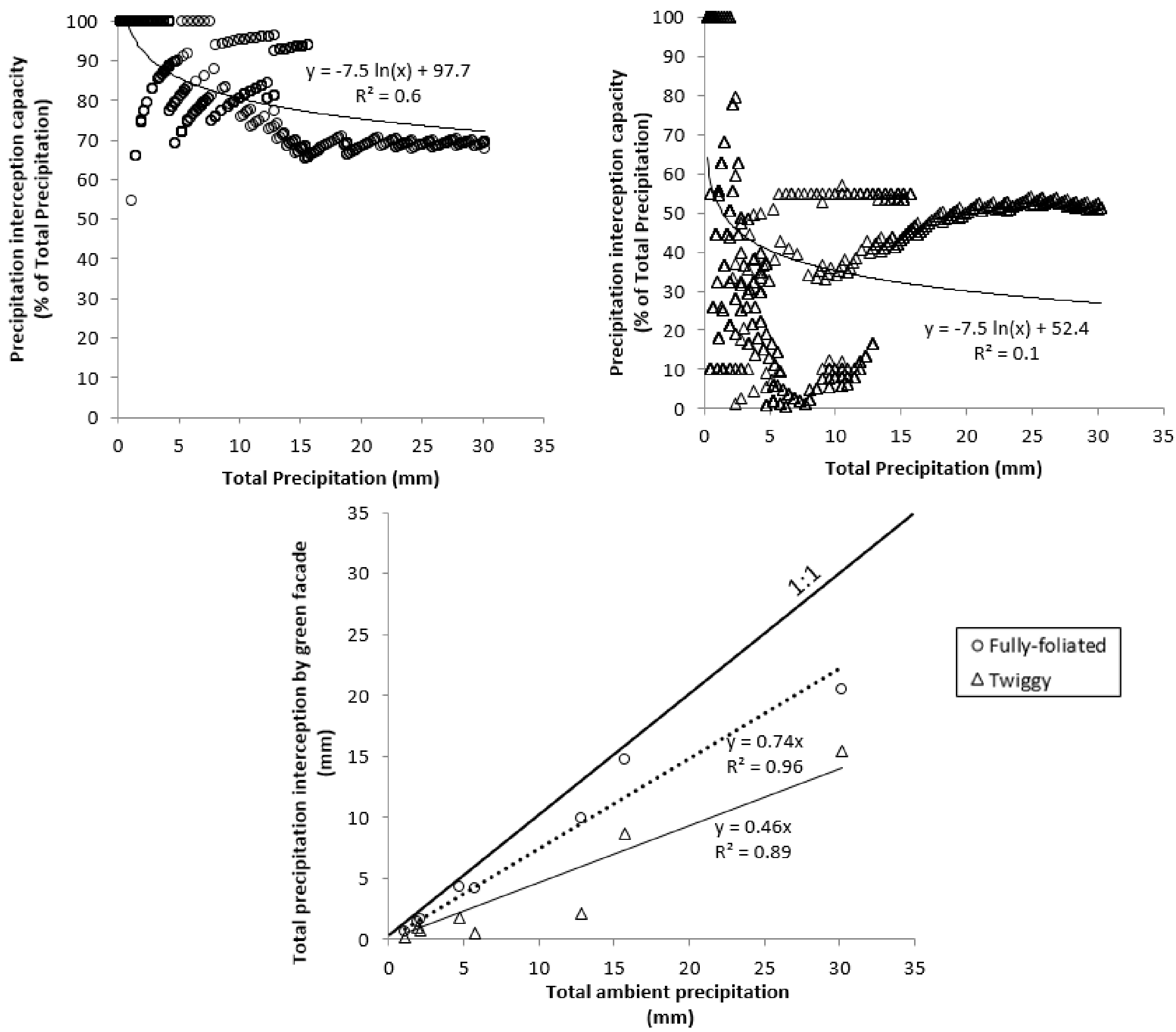

Figure 4. Precipitation interception as a function of total precipitation (%) for the dense (top left panel) and the twiggy (top right panel) green façades. Regression model showing the dependence of the rainwater interception of the two green façades on the total ambient precipitation (bottom).