

Green Roofs – getting sustainable drainage off the ground

Toits Verts – un assainissement pluvial durable hors sol

Virginia Stovin*, Nigel Dunnett† and Adrian Hallam#

*The University of Sheffield, Department of Civil and Structural Engineering, Mappin Street, Sheffield, S1 3JD UK, v.stovin@sheffield.ac.uk

†The University of Sheffield, Department of Landscape, Western Bank, Sheffield, S10 2TN, n.dunnett@sheffield.ac.uk

#Ark Design Management Ltd., 15 Napier Street, Sheffield, S11 8HA, arkdm@thearkhive.com

RESUME

Les toits verts ont le potentiel considérable pour la commande de précipitation exceptionnelle, pour le nouveau développement et comme option de modification. Au Royaume Uni le manque de données quantitatives locales d'exécution et des modèles des outils pourraient expliquer leur prise limitée jusqu'ici. Cet article présente des résultats préliminaires d'une parcelle de terrain d'essai à échelle réduite située à Sheffield, au Royaume Uni. En printemps 2006 la conservation moyenne en volume était de 34% et la réduction maximale moyenne était de 57%. Les causes déterminantes hydrologiques principales étaient la période sèche antécédante, l'intensité moyenne de précipitation et la profondeur de précipitation. L'évaluation structurale d'une gamme de types plats de toits suggère qu'un toit vert soit une option faisable dans nombreux cas, en particulier pour les toits dale en béton.

ABSTRACT

Green roofs have considerable potential for stormwater source control, both for new developments and as a retrofit option. In the UK the lack of local quantitative performance data and modelling tools may explain their limited uptake to date. This paper presents preliminary findings from a small-scale instrumented green roof test plot located in Sheffield, UK. During Spring 2006 the average volume retention was 34% and the average peak reduction 57%. The key hydrological determinants were the antecedent dry weather period, mean rainfall intensity and rainfall depth. Structural appraisal of a range of flat roof types suggests that retrofitting a green roof will be a feasible option in many cases, particularly for concrete slab roofs.

KEYWORDS

Attenuation, Green Roof, Runoff, Retention, Stormwater

1 INTRODUCTION

Stormwater runoff from urban roofs makes a significant contribution to sewerage derived flooding and urban water quality problems. In most developed cities, roofs account for approximately 40-50% of the impermeable urban surface area. Any technique that reduces the rate and volume of roof runoff has the potential to contribute to improved stormwater management.

Green roofs provide an opportunity to reduce and attenuate storm runoff at source (Figure 1). *Extensive* green roofs typically take the form of a 'carpet' of plants, supported by lightweight growing media and overlying a drainage layer (Figure 2), whereas *intensive* green roofs incorporate more deeply planted vegetation. During a storm event the key hydrological mechanisms operating within the green roof are the interception of rainfall by the plant layer, infiltration and storage in the substrate and reservoir storage in the drainage layer. Moisture will be lost to the atmosphere as a result of evapotranspiration during dry periods.

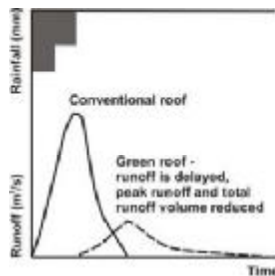


Figure 1 – Rainfall runoff response

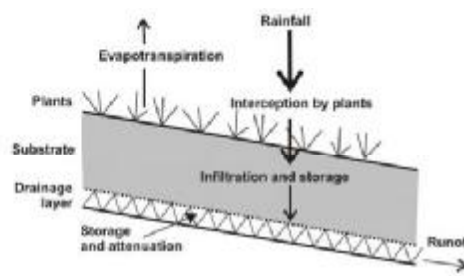


Figure 2 – Green roof hydrological processes

It is sometimes argued that the land-use requirements associated with Sustainable Drainage Systems (SUDS) make them incompatible with high density urban environments; green roofs differ from many other SUDS approaches in that they have no additional land-take requirement beyond the footprint of the building. In addition to stormwater source control, green roofs may also reduce building energy requirements, increase the design life of a roof, improve urban air quality, add aesthetic value to urban architecture and enhance biodiversity.

Over the last 20 years green roofs have become relatively commonplace in Germany, Austria and Switzerland; 14% of the flat roofs in Germany (13.5 km²) support green roofs (Herman, 2003). In the UK the latest CIRIA guidance (CIRIA, 2004) strongly endorses green roofs as a SUDS technology. However, uptake to date has been rather limited. Possible reasons for this include the perceived risks associated with a technology that has not been widely used in the UK and – perhaps more significantly – the lack of UK validated data and modelling tools to enable green roofs to be evaluated against alternative stormwater management approaches.

The aim of this paper is to provide a broad overview of the current state of knowledge relating to the stormwater management opportunities associated with green roofs. The review will include preliminary analysis of monitored data relating to a green roof test bed and an outline of a full-scale green roof retrofit project in Sheffield.

2 EXISTING DATA ON HYDROLOGICAL PERFORMANCE

To date, hydrological green roof research has been undertaken using test facilities at Michigan State University (VanWoert *et al.*, 2005), the Penn State Center for Green

Roof Research, and European facilities at KULeuven (Mentens *et al.*, 2003) and Neubrandenburg (Köhler *et al.*, 2002). These test facilities complement a number of full-scale instrumented green roof demonstration projects (e.g. Hutchinson *et al.*, 2003). Typically vegetation type, planting substrate and slope have been investigated (e.g. VanWoert *et al.*, 2005), with continuous runoff monitoring being provided either by tipping bucket gauges or rainwater collection tanks incorporating depth sensors. These studies consistently show that high levels of stormwater attenuation can be achieved with the use of green roofs. For example, Kolb (2004) reported that green roofs reduced *annual* runoff by 45-70%, Moran *et al.* (2004) report 60% total rainfall retention and an 85% reduction in peak flowrate. However, seasonal effects can be significant. Johnston *et al.* (2004) noted that runoff could rise to 100% with prolonged heavy rainfall. In Portland, where “ecoroofs” must be irrigated for 3 months in the summer, Liptan (2003) suggests that a 10-35% volume reduction during the wet season and 65-100% volume reduction in the dry season can be achieved.

Although clearly demonstrating the potential stormwater management benefits associated with green roofs, these lumped performance figures give no indication of the temporal runoff profile that will arise in response to an individual storm event. Furthermore, these findings cannot reliably be assumed to apply in different climatic regions, where rainfall regime and plant growth characteristics may not be comparable. The lack of representative data for UK conditions is a particular problem, as the maritime climate – characterised by frontal rainfall – results in higher rainfall depths/intensities and reduced evaporation compared with the continental locations associated with published performance characteristics.

3 SHEFFIELD CENTRE FOR GREEN ROOF RESEARCH

The University of Sheffield, Sheffield City Council and Groundwork Sheffield have secured European funding (Objective 1, Measures 33 (sustainable building)) to establish local demonstration green roofs and the first UK-based green roof research centre. The project aims to enhance existing knowledge with respect to the full range of green roof performance characteristics, including energy conservation and contributions to biodiversity. This paper focuses on the development of facilities to measure and model the hydrological performance of green roofs.

3.1 Test plot for monitoring hydrological performance

3.1.1 Configuration of test bed and instrumentation

A green roof test rig has been established at the University of Sheffield. The test bed (3 x 1 m) uses a standard commercial (Alumasc/Zinco) extensive green roof system, comprising a sedum vegetation layer growing in an 80 mm depth of substrate. The base of the rig is laid at a slope of 1.5°. The substrate is composed of a mixture of crushed brick and fines. A fine particle filter membrane separates the substrate from the underlying FloraDrain FD25 ‘egg box’ drainage layer. The drainage layer alone has a retention capacity of 3 l/m² (i.e. 3 mm rainfall).

Runoff from the roof is collected in a tank via a gutter at its downstream end. The collection tank is tapered to provide greatest sensitivity for low levels of runoff. Depth in the collection tank is monitored using a pressure transducer. The transducer resolution is 0.1 mV, and a change of 1 mV in the pressure transducer reading equates to only 2 x 10⁻³ mm runoff. The runoff data is therefore measured at a significantly higher resolution than the 0.2 mm increments that rainfall is measured in. Rainfall is monitored using a standard rain gauge sited adjacent to the test bed. Data from the pressure transducer and the rain gauge is logged using a Campbell Scientific data logger (CR1000) at 5-second intervals.

3.1.2 Preliminary Results

Figure 3 presents sample monitored data from a storm that occurred on 14-15 Feb 2006. In this event 9.2 mm rain fell, resulting in only 3.55 mm runoff, i.e. 61% stormwater volume retention. The peak reduction was 61%. Over the whole of the (wet English) Spring, 11 events were monitored, and the average volume retention was found to be 34%, with an average peak reduction of 57%. These figures are comparable with other European data reviewed by Mentens *et al.* (2003). Based on average volume retention of 34%, it may be inferred that the roof could reduce annual runoff in many parts of the UK by 300 mm when compared with a conventional roof.

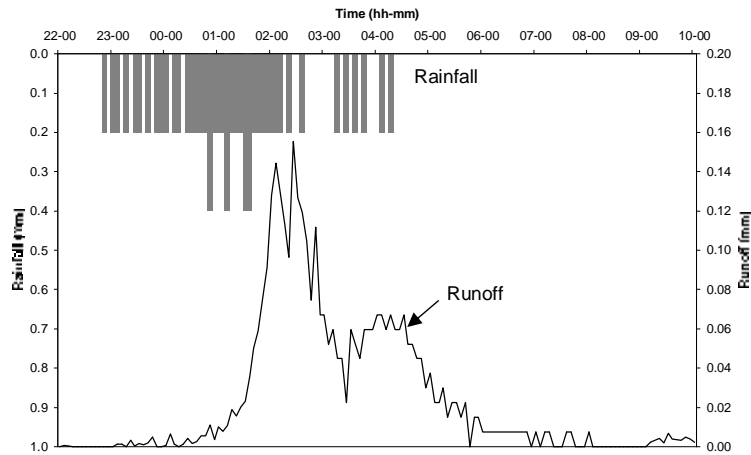


Figure 3. Rainfall-runoff response of the green roof test plot 14-15 February 2006

Regression analysis was undertaken to identify key parameters for the prediction of % volume retention (%VR) and % peak reduction (%PkR). The variables considered were: total rainfall depth (R) (mm); mean rainfall intensity (i) (mm/hr); peak rainfall intensity (i_{max}) (mm/5 mins); and the Antecedent Dry Weather Period (ADWP) (days). ADWP was defined as the length of time since the last recorded rainfall in a rainfall event with a mean intensity in excess of 0.6 mm/hr. Preliminary analysis suggested that – due to the resolution of the rain gauge – i_{max} was either 0.2 or 0.4 mm/5 mins for all monitored events, and this parameter was not considered further.

Figure 4a shows that total runoff was positively correlated with total rainfall, but that the amount of runoff was affected by the ADWP. It may be inferred – as indicated by the dashed extrapolation of the trend line – that, for ADWPs less than two days, the test bed retained a minimum of 1.6 mm rainfall. Following an ADWP greater than 2 days, however, this value increased to 3.9 mm. The total amount retained increased in proportion to total rainfall, with as much as 7.4 mm retention being recorded during the largest storm (20 mm rainfall, ADWP = 4.04 days).

Figure 4b shows that the % volume retained (%VR) decreased in proportion to total depth of rainfall, and was also dependent upon the ADWP. No significant correlation between %VR and rainfall intensity (i) was apparent. The following regression equation has been fitted to the preliminary data set:

$$\%VR = 59.64 + 8.35(ADWP) - 19.80(\ln(R)) \quad (R^2 = 96\%) \quad (1)$$

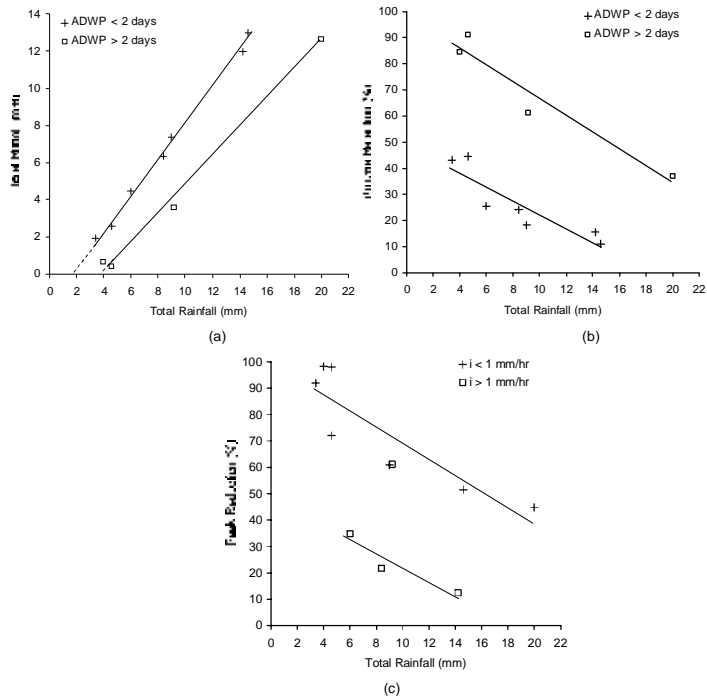


Figure 4. Relationships between total rainfall and a) total runoff, b) volume retention (%) and c) peak reduction

Figure 4c shows that the % peak reduction also decreased in proportion to total rainfall. In this case the absolute values were also strongly influenced by the mean storm intensity, i , with a cut-off value of 1 mm/hr. This finding is supported by Johnston *et al.* (2004). The one point that does not appear to fit this relationship was affected by experimental problems (suspected leakage from the collection tank drain valve). Inclusion of ADWP in the regression equation for %PkR provided a small improvement over an equation based on R and i alone:

$$\%PkR = 78.9 - 18.8(\ln(R)) - 24.5(\ln(i)) + 4.5(ADWP) \quad (R^2 = 89\%) \quad (2)$$

The regression analysis confirms that the parameters ADWP, R and i are important determinants of the roof's response to a rainfall event. Although the ADWP values for the four storms having an ADWP in excess of 2 days ranged from 3.00 to 7.44 days, the fact that these data points appear to form a coherent data set suggests that the system is essentially dry within 2-3 days. ADWP values in excess of this duration are not expected to result in higher levels of retention. Equations (1) and (2) will therefore need to be modified to reflect this once more data is available.

3.2 Full scale green roof retrofitting and monitoring project

Although green roofs represent a useful stormwater management option for new builds, most cities in Europe experience significant stormwater management problems relating to existing infrastructure. There may, therefore, also be widespread

opportunities to retrofit green roofs to address CSO discharge and flooding problems in developed urban areas. Swan and Stovin (2002) have promoted the concept of retrofit SUDS to address issues associated with poor stormwater management in existing urban catchments. In Lambeth, London, residents of the Ethelred Housing Estate were instrumental in securing possibly Europe's largest (6,000 m²) retrofit green roof (Bauder, 2005). However, this does not reflect widespread practice.

One of the most important constraints when considering retrofitting a green roof is the strength of the existing structure. Older buildings will often have more capacity than those designed in the last thirty years due to initial over-design and changes in building regulations. Many UK medium-rise office buildings support flat concrete roofs which could accept a green roof without any requirement for structural modification.

The Ryokka Project has been set up on the roof of a refurbished office building (15 Napier Street, Sheffield) which houses the offices of Ark Design Management Ltd. The long-term aim of the project is to retrofit as much of the roof-space as is practically possible with a range of green roof experimental plots and demonstration systems, including intensive green roofs and areas of wetland or aquatic planting.

There are three structural roof types on the Ryokka Project building: reinforced concrete; steel frame and timber frame (Figures 5 and 6). Preliminary structural analysis has been undertaken to explore the viability of retrofitting a range of green roof types onto these three different structural roof areas. The concrete slab roof has an estimated capacity of 8-10 kN/m². This is sufficient to support an intensive green roof with significant substrate depth (up to 800 mm) or an area of aquatic planting with water depth up to 700 mm. This portion of the roof currently hosts a range of experimental green roof trial beds, primarily aimed at investigating the performance of different combinations of green roof flora and substrate (Figure 7a).



Figure 5 – Aerial view of the Ryokka project building (local.live.com)

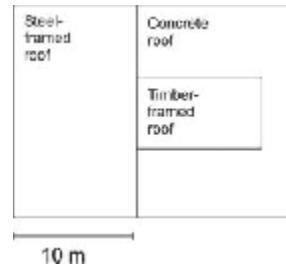


Figure 6 – Roof areas on the Ryokka project building

The highest roof level comprises universal steel beams overlain by profiled steel decking surfaced with plywood. Preliminary calculations suggest that the capacity of the primary beams in this structure is approximately 2.98 kN/m²; assuming the existing secondary beams and decking are retained, the loading associated with a retrofitted extensive green roof (allowing for snow load and access) approaches 2.67 kN/m². Although this is clearly marginal, careful placing of trial beds on the roof has now gone ahead (Figure 7b).

The intermediate roof level is supported by a timber frame. This also appears to be structurally marginal in terms of spare capacity, and further survey work is required to establish the strength of the timber. If the timber corresponds to 'special structural grade', then an extensive green roof system could be retrofitted without structural

modification. These preliminary calculations show that retrofitting can be considered even for non-concrete-slab types of roof, although it is clear that detailed structural survey and assessment will be required for many traditional types of flat roof.

In terms of hydrological performance, runoff from the upper steel-framed roof section is directed onto the timber-supported roof section. This provides an excellent opportunity to intercept and monitor the runoff from this full-scale green roof installation. The installation of runoff monitoring equipment is planned for early 2007.

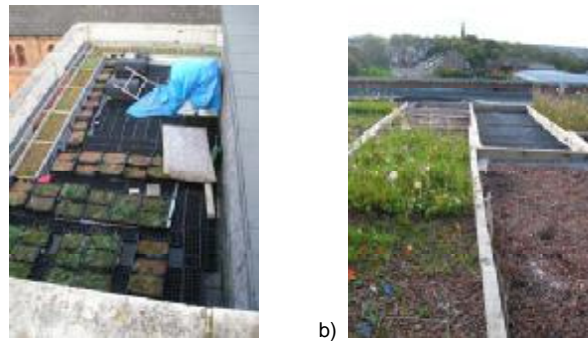


Figure 7 – Trial beds on the Ryokka Project building: a) laid on concrete slab roof, and b) laid on steel framed roof

4 MODELLING TOOLS FOR CATCHMENT-WIDE STORMWATER MANAGEMENT

If widespread implementation of retrofit green roofs is technically feasible, then it is useful to quantify the potential environmental and economic benefits associated with this approach. In Toronto, Gutteridge (2003) suggests that if 6% of the total roof area utilized green roof technology this would provide over 3.6 million cubic metres per year stormwater retention capability. In Vancouver, Graham and Kim (2003) suggest that 50-year watershed retrofit scenarios show that green roofs could effectively mitigate the anticipated effects of climate change, urban densification, and also help to restore watershed health. In Germany and North America financial incentives exist to encourage developers to implement green roofs (Herman, 2003; Liptan, 2003).

However, in order to make catchment-wide predictions of this type, engineers require storm-by-storm response models at high temporal resolution (5 minute intervals or less) that can be integrated with existing urban drainage modelling tools. Currently, no commercial stormwater management tools (e.g. the US EPA's SWMM or Wallingford Software's InfoWorks model) incorporate any capability to explicitly model the storage, attenuation and evapotranspiration characteristics of green roofs as a unique urban surface type. The work described in this paper will ultimately contribute to the development of appropriate green roof modelling tools for UK drainage planners.

5 CONCLUSIONS

Preliminary performance data from the small-scale instrumented green roof test plot confirm that green roofs may be able to provide significant stormwater retention and attenuation in a UK climate. During Spring 2006, when 11 events were monitored, the average volume retention was 34% and the average peak reduction 56.9%.

The key hydrological determinants were found to be ADWP, i and R. Regression-based models have been derived to describe the lumped, whole-storm performance of the system in terms of % volume retention and % peak reduction. In the longer term it is intended that time-dependent physically-based models will be developed to enable drainage engineers to model and utilise green roofs in catchment-wide stormwater management strategies.

Sample data from structural appraisal of a range of flat roof types suggests that retrofitting a green roof will be a feasible option in many cases. Lightweight steel and timber-framed structures may require detailed structural survey and appraisal work to confirm their suitability. However, many concrete roofs will have significant spare capacity, even allowing for the installation of intensive green roofs (i.e. deeply planted vegetation) or wetland features.

Acknowledgements

Much of the data collection and analysis presented in this paper was undertaken by Beatrice Munby, Adam Hemmings and Fred Miles as part of undergraduate dissertations in the Department of Civil and Structural Engineering at The University of Sheffield.

References

- Bauder, 2005, Largest sedum re-roofing project in the UK on Ethelred Estate [online article, <http://www.bauder.co.uk/content/news/dual.asp?sid=1&nid=3&pg=1>, accessed Nov. 2006].
- CIRIA, 2004, *C609 SUDS techniques – hydraulic, structural & water quality issues*.
- Graham P and Kim M, 2003, Evaluating the stormwater management benefits of green roofs through water balance modelling, *Greening Rooftops for Sustainable Communities*, Chicago, 29-30 May, 390-399.
- Gutteridge B, 2003, Toronto's Green Roof Demonstration Project, *Greening Rooftops for Sustainable Communities*, Chicago, 29-30 May, 121-125.
- Herman R, 2003, Green roofs in Germany: yesterday, today and tomorrow, *Greening Rooftops for Sustainable Communities*, Chicago, 29-30 May, 41-45.
- Hutchinson D, Abrams P, Retzlaff R and Liptan, T, 2003, Stormwater monitoring two ecoroofs in Portland, Oregon, USA, *Greening rooftops for sust. communities*, Chicago, 29-30 May, 372-389.
- Köhler M, Schmidt M, Grimme, FW, Laar, M, Paiva VLA & Taveres S, 2002, Green roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics, *Environmental Management and Health*, Vol. 13, Issue 4, 382-391.
- Kolb W, 2004, Good reasons for roof planting – Green roofs and rainwater. Int. Conf on Urban Horticulture, *Acta Horticulturae*, No.643, 295-300.
- Johnston C, McCreary K and Nelms C, 2004, Vancouver public library green roof monitoring project, *2nd Greening Rooftops for Sustainable Communities Conf.*, Portland, 2-4 June, 391-403.
- Liptan T, 2003, Planning, zoning and financial incentives for ecoroofs in Portland, Oregon, *Greening Rooftops for Sustainable Communities*, Chicago, 29-30 May, 113-120.
- Mentens J, Raes D and Hermy M, 2003, Effect of orientation on the water balance of greenroofs, *Greening Rooftops for Sustainable Communities*, Chicago, 29-30 May, 363-371.
- Moran A, Hunt B and Jennings G, 2004, A North Carolina field study to evaluate greenroof quantity, runoff quality, and plant growth, *2nd Greening Rooftops for Sustainable Communities Conf.*, Portland, 2-4 June, 446-460.
- Swan AD and Stovin VR, 2002, A decision-support framework for the design of retrofit SUDS. Proceedings of the *International Conference on Sewer Operation and Maintenance (SOM2002)*, University of Bradford, 26-28 November.
- VanWoert ND, Rowe DB, Andresen JA, Rugh CL, Fernandez RT and Xiao L, 2005, Green roof stormwater retention: Effects of roof surface, slope, and media depth, *Journal of Environmental Quality*, v34, 1036-44.