The Influence of Substrate and Vegetation on Extensive Green Roof Hydrological Performance

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ABSTRACT
The objective of this research was to investigate the hydrological processes occurring in extensive green roof systems through data collected during a continuous monitoring programme of different green roof configurations. Nine green roof test beds (TB) which vary systematically in their substrate composition and vegetation options have been monitored since April 2010 at the University of Sheffield, UK. Three green roof substrates were tested: two commercial substrates manufactured by Alumasc – Heather with Lavender (HLS) and Sedum Carpet (SCS) Substrate were considered alongside a Lightweight Expanded Clay Aggregate (LECA)-based substrate. Three vegetation treatments have been tested: a drought tolerant specie (sedum), a meadow flower mixture and a no vegetation option. Per event retention performance varied depending on the initial water content within the substrate and the characteristics of the rainfall event. Consistent behaviour was observed among the tested green roof configurations with respect to per event retention. Greater retention was associated with HLS and SCS substrates when compared with LECA. Vegetated configurations showed consistently higher retention performance. Sedum vegetation resulted in higher retention performance than Meadow Flower. This was particularly evident on the LECA substrate.

KEYWORDS
Green roof; Stormwater management; Retention; Detention; Substrate; Vegetation

INTRODUCTION
Increasing urbanization and climate change pose important challenges in urban areas. It is recognized that more resilient stormwater management infrastructure is required aiming to restore pre-development hydrological conditions. Green roofs have the potential to deliver significant stormwater management benefits, considering that roof spaces account for approximately 40-50% of the impervious urban surface area (Dunnett and Kingsbury, 2004), for the relative simplicity of installation, and for the potential to be part of a treatment train. This paper focuses on extensive green roofs that have greater potential of wide-scale adoption than intensive green roofs. The limitation of extensive systems is that a shallower substrate has a lower, and finite, stormwater retention capacity (e.g. 20 mm as observed by Stovin *et al*. (2012) in an 80 mm substrate roof) and is more likely to experience restricted moisture conditions and plant stress during prolonged dry periods (Stovin *et al.* 2013). Several studies have aimed at evaluating the hydrological performance of green roofs through field monitoring programmes (see Palla *et al.* (2010), and Stovin *et al.* (2012) for an overview). It

is evident that the roof's ability to retain stormwater is highly sensitive to the initial moisture condition of the green roof system prior to a rainfall event. This is controlled by the evapotranspiration (ET) process during dry periods. Climatic conditions and hydrological regime influence the sustainability, and thus suitability, of extensive green roofs, as shown by Stovin *et al*. (2013). Berretta *et al*. (2014) and Poë *et al*. (2012) showed the influence of substrate characteristics and vegetation on the moisture content behaviour due to ET during dry periods.

The aim of this paper is to investigate the hydrological processes within rainfall events and to study the influence of vegetation treatments and substrate characteristics on per event retention. For this reason a continuous monitoring programme of green roofs test beds has been carried out by the University of Sheffield's Green Roof Centre. This experiment was established in summer 2009 and data have been collected since April 2010.

METHODS

The research was conducted at the University of Sheffield's Green Roof Centre. The test site is located on a fifth-floor terrace of the Sir Robert Hadfield building (53.3816, -1.4773) and consists of 9 green roof test beds (TB) which vary systematically in their substrate composition and vegetation options (Fig. 1).

Each test bed is 3 m long x 1 m wide, installed to a 1.5° slope. The TBs are located at a height of 1 m above the terrace roof surface. The TBs consist of an impervious hard plastic tray base, a drainage layer (ZinCo Floradrain FD 25-E), a filter sheet (ZinCo Systemfilter SF), and one of three substrates (80 mm deep).

Two commercially-available substrates manufactured by Alumasc – Heather with Lavender Substrate (HLS) (TB1, TB4 and TB7) and Sedum Carpet Substrate (SCS) (TB2, TB6, TB9) – were considered alongside a bespoke substrate based on the widely used Lightweight Expanded Clay Aggregate (LECA).

Three vegetation treatments have been tested: sedum as drought tolerant specie (TB1 to TB3), a meadow flower mixture (TB4 to TB6) and no vegetation option (TB7 to TB9). The meadow flower mixture was chosen to provide greater aesthetic appeal and biodiversity potential compared with sedum; it is also expected to have higher water demands.

The experimental setup includes a Campbell Scientific weather station that records hourly wind speed, temperature, solar radiation, relative humidity and barometric pressure. Rainfall depth was measured at one minute intervals using three 0.2 mm resolution ARG-100 tipping bucket rain gauges manufactured by Environmental Measures Ltd. Runoff was measured volumetrically through collection tanks equipped with a Druck Inc. PDCR 1830 pressure transducers. The collection tank located under each test bed was designed for increased measurement sensitivity at the beginning of each rainfall event and to avoid direct discharge on the sensor. The pressure transducers were calibrated on site. A solenoid electronic valve empties the tank when maximum capacity is reached and every day at 14:00. Runoff is recorded at 1 minute intervals. Data are recorded through a Campbell Scientific CR3000 data logger. Moisture content was measured in four test beds (TB1, TB2, TB£ and TB7). Water content reflectometers (WCR) Campbell Scientific CS616 were located at three soil depths at 20, 40 and 60 mm from the surface. More detailed information on the calibration and installation of these sensors is reported in Berretta *et al*. (2014).

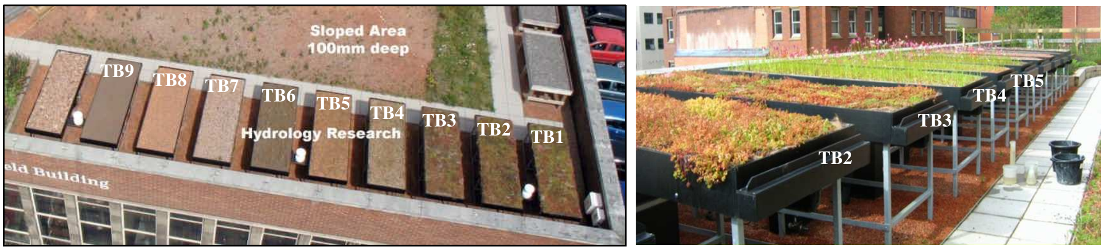

Figure 1. The experimental site at the University of Sheffield, UK

Substrate characteristics

HLS is a semi-intensive commercial substrate which consists of crushed bricks and pumice (ZincolitPlus), enriched with organic matter including compost with fibre and clay materials (Zincohum) (ZinCo GmbH). The SCS Substrate is a typical extensive green roof substrate consisting of crushed bricks (Zincolit), enriched with Zincohum. The organic content in HLS is greater than in SCS. The LECA-based substrate contains 80% LECA, 10% loam (John Innes No. 1) and 10% compost by volume. Laboratory tests of these substrates were carried out according to the *Guidelines for the Planning, Construction and Maintenance of Green Roofing* of the German Landscape Development and Landscaping Research Society (FLL, 2008). The tests performed included Particle Size Distribution (PSD), apparent density (dry condition and at max water capacity), total pore volume, maximum water holding capacity (MWHC), permeability and organic content (Table 1).

Table 1. Substrate characteristics according to FLL testing method

		HLS		SCS		LECA	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Particle Size < 0.063mm	(%)	2.1	1.4	1.4	0.3	0.4	0.0
d_{50}	(mm)	4.7	0.7	5.2	0.3	5.0	0.1
Dry Density	(g/cm^3)	0.95	0.04	1.06	0.05	0.41	0.00
Wet Density	(g/cm^3)	1.36	0.02	1.45	0.07	0.76	0.02
Total Pore Volume	(%)	63.8	1.6	59.8	2.0	84.8	0.0
MWHC (field capacity)	(%)	41.2	2.3	39.1	2.1	35.0	1.6
Air content at MWHC	(%)	22.6	0.8	20.7	4.1	49.8	1.5
Organic Content	(%)	3.8	0.1	2.3	0.5	6.0	0.3

The data series analyzed in this paper include rainfall events monitored from April 2010 to December 2012. Individual events were defined as being separated by continuous dry periods of at least 6 hours. Per event retention has been investigated by using selected rainfall events that include ‘routine’ and ‘significant’ events; the latter being characterized by Return Period (RP) > 1 year. The data series has been analyzed against Sheffield return period data according to the Flood Estimation Handbook (NERC, 1999). Six events are used in this paper for performance comparison purposes. The characteristics of the selected events are reported in Table 2. Three events have RP>1year (13 June and 1 October 2010, 25 August 2011) and the 6 September 2010 has RP>2 years.

Table 2. Rainfall characteristics for the selected events monitored at Sheffield, UK

	Rainfall Duration (h)	Rainfall Depth (mm)	ADWP (h)	Mean Intensity (mm/h)	Peak 5-min Intensity (mm/h)
13 June 2010	8.2	19.2	6.8	2.33	14.4
6 September 2010	9.3	31.6	177.4	3.40	12
1 October 2010	15.3	19.0	33.8	1.24	14.4
25 August 2011	4.7	14.8	95.9	3.14	12
26 August 2011	17.8	11.2	23.8	0.63	9.6
7 September 2011	18.2	8.0	7.1	0.44	9.6

RESULTS AND DISCUSSION

In Fig. 2 the retention performance of the different test beds is reported for the selected events. It is evident that the performance of the investigated configurations is in general consistent for the different events. By looking at configurations with the same vegetation treatment, the impact of substrate characteristics is clear, with higher retention being associated with HLS and SCS compared to the LECA. This can be explained by the higher MWHC and lower total pore volume of the brick based substrates. For example, by looking at the 25 August event, 87.5 and 84.1% retention was measured for TB1 and TB2 and 56.3% for TB3, all of which are characterized by sedum vegetation. For the same event but meadow flower treatment, TB4 and TB5 retained 82.5 and 82.3% of rainfall, against the 51.5% retained by the LECA based substrate.

Within test beds characterized by the same substrate but different vegetation treatment it is possible to observe that higher retention is associated with the vegetated beds and that sedum retained more than meadow flower. For example in the 13 June 2010 event, 86.6, 66.5, and 51.4 were measured respectively in TB1, TB4 and TB7, This is particularly evident in the LECA-based test beds, where the sedum vegetation also showed higher coverage: for the 6 September event, 39.3, 26.5 and 16.3% retention was recorded respectively for TB3, TB6 and TB9.

In general it is expected that higher retention is associated with rainfall events characterized by lower depth. This is the case of the 7 September 2011 event, despite the short ADWP, and 25 and 26 August 2011. By comparing the 1 October and 13 June 2010 events characterized by similar rainfall depth, it is possible to observe that the difference in retention is due to the antecedent ET rates (typical of summer and winter seasons respectively) despite the longer October ADWP. The 1 October event also showed the lowest retention. The ET influence emerges by comparing this event with the 6 September 2010 event characterized by 31.6 mm rainfall depth. During the latter event, 22.3 mm of rainfall were retained by TB1 and 20.2 mm by TB2. The high retention is in this case due to the longer ADWP. These results confirm the findings of Stovin *et al.* (2012), where a maximum retention of circa 20 mm was observed over 29 months monitoring period of a similar 80 mm depth green roof test bed, also in Sheffield UK.

Fig. 3 shows the cumulative rainfall and runoff measured for the nine test beds for the rainfall events of 26 and 27 August 2010 (top graph). It is evident that greater retention performance

is associated with the vegetated HLS and SCS (TB1, TB2, TB4 and TB5). The LECA-based substrate for these events showed lower retention (i.e. higher runoff) than the non-vegetated brick-based substrates.
In Fig. 3 (mid and bottom graphs), the hydrograph, hyetograph and measured moisture content at 20 (top), 40 (mid), and 60 mm (bottom) from the surface of TB1 and TB7 are shown. The two test beds differ only in the presence of vegetation. It is interesting to note that the presence of vegetation clearly influences the retention. As for the detention effect, runoff peaks are slightly delayed in the vegetated configuration (TB1). Similar behaviour for the same configurations was observed from preliminary results by Poë *et al.* (2011).

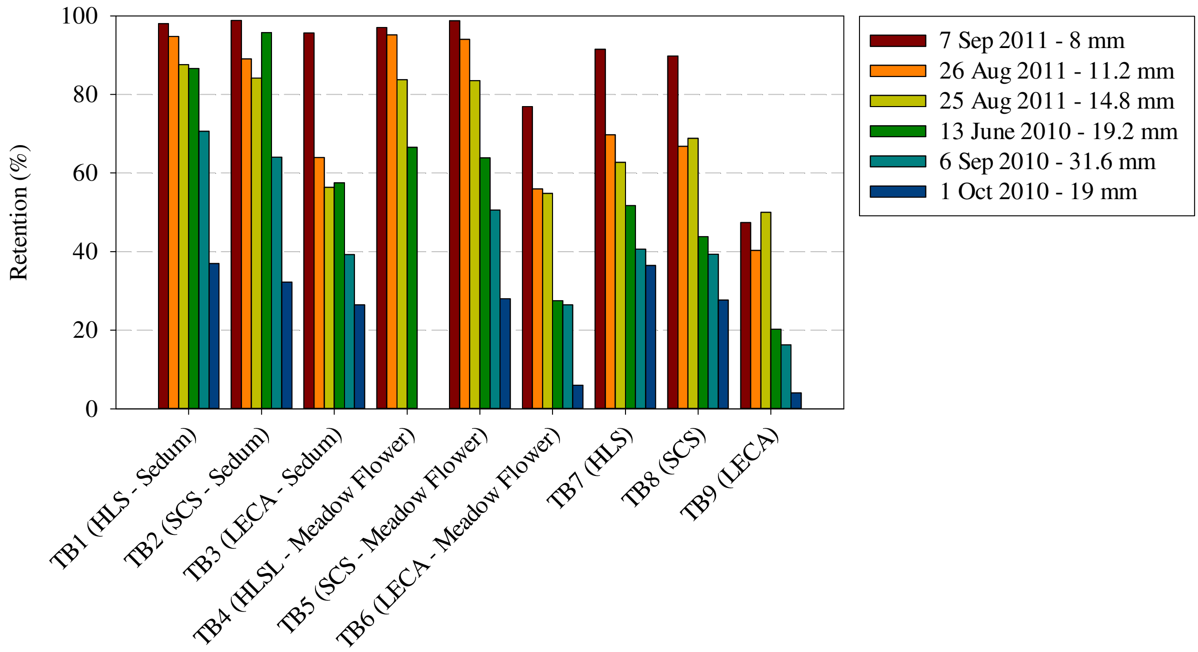

Figure 2. Per event retention performance of the nine green roof systems for selected rainfall events in Sheffield, UK.

From the same graphs it is possible to observe the different initial moisture conditions for the two test beds. The higher initial moisture content of the non-vegetated test bed explains the lower retention performance. The initial conditions are influenced by the evapotranspiration and evaporation (for the non-vegetated test bed) within the antecedent dry period, which regulates the moisture loss rate. Berretta *et al* (2014) investigated the influence of vegetation and substrate characteristics on the moisture loss within dry periods for the same test beds; it was shown that higher moisture loss rates were associated with the vegetated bed, due to plant transpiration, especially in warmer conditions. In the month of August 2011, before the 25 August event, 15 rainfall events occurred, but the total depth was only 14.6 mm and the recorded average temperature was 16.3 ºC. The vegetation also prevented wetting during these minor events, all of which contributed to the maintenance of lower moisture content and higher retention capacity in the vegetated bed.

Different moisture content vertical profiles were observed during the wetting cycle for these events. The presence of vegetation and root systems contributed to the development of higher moisture content gradient. The same results were observed during drying cycles (Berretta *et al.*, 2014). During rainfall events, moisture content increases with depth due to the high permeability that characterized green roofs substrates. Higher moisture content in deeper layers were also observed by Palla *et al.* (2009).

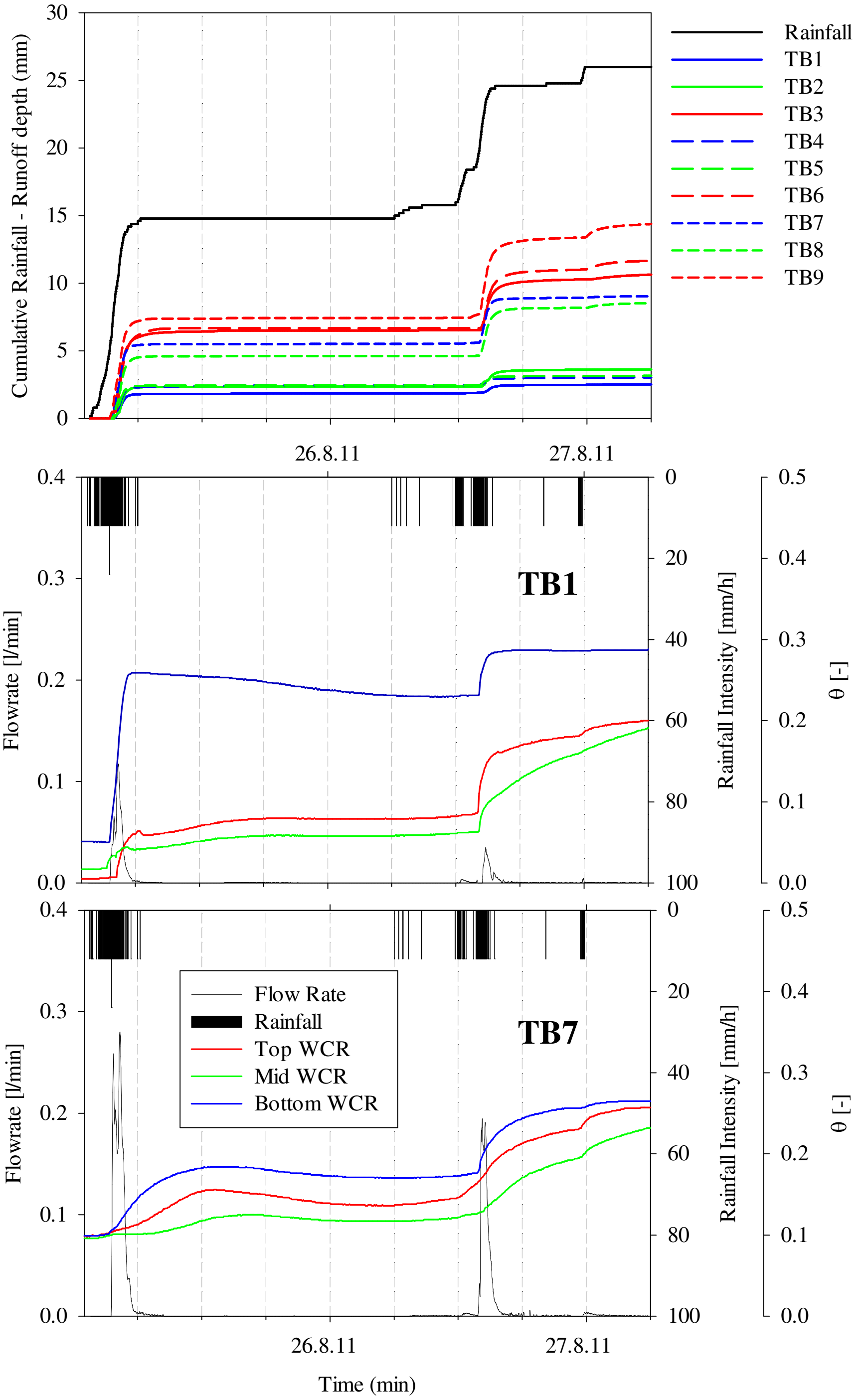

Figure 3. Cumulative rainfall and runoff for the nine test beds for the rainfall events of 26 and 27 August 2010 (top graph). Hydrograph, hyetograph and measured moisture content at 20 (top), 40 (mid), and 60 mm (bottom) from the surface of TB1 (HLS – Sedum) and TB7 (HLS – No Vegetation).

From these graphs, it appears that runoff occurred before the moisture content reached the MWHC of the substrate. This can be explained by the fact the FLL test are performed on pre-saturated substrates and do not take into consideration the presence of the plant root system. Also, the tests are not representative of the field conditions: ageing, compaction or decomposition of organic material can alter the system structure and lead to preferential path for runoff. Differences between laboratory test and performance were also discussed by Fassman and Simcock (2012), who suggested the need for further investigation.

The detention effect of extensive green roofs was investigated within the same project by other researchers by analysing single components and the whole system. In particular Yio *et al*. (2013) research focused on the detention effect of green roof substrates, and through laboratory tests, showed the increasing detention effect due to higher organic matter content and substrate depth. By adding 5% and 15% organic component, increased substrate runoff delay times of 24.4 and 30.1 minutes respectively were observed. Vesuviano and Stovin (2013) focused on the detention effect of commercially available drainage systems and protection mats. These results informed the development of a generic, adaptable two-stage runoff detention model to simulate the complete green roof system including the granular substrate, a hard plastic 'egg box'-style drainage layer and fibrous protection mat (Vesuviano. *et al*, 2013). Eight rainfall-runoff events monitored for the non-vegetated test bed (TB7, TB8 and TB9) were analysed and used for validation of the proposed modelling approach (Vesuviano, 2014). The runoff profiles of the different test beds were generally found to be similar, thus showing no significant differences in detention due to these substrate characteristics. This was especially apparent at time when the available retention capacity was limited. Under these circumstances rainfall is routed exclusively through macropores, and water movement is gravity driven. The same results can be confirmed by Fig. 4, where the hydrographs of the vegetated TB1, TB2 and TB3 are shown together with the hyetograph for the 6 September 2010 event. The greater retention of TB1 and TB2 is evident, but there is no significance difference in detention, with the runoff peak timing and magnitude being similar once the roof has reached the retention capacity.

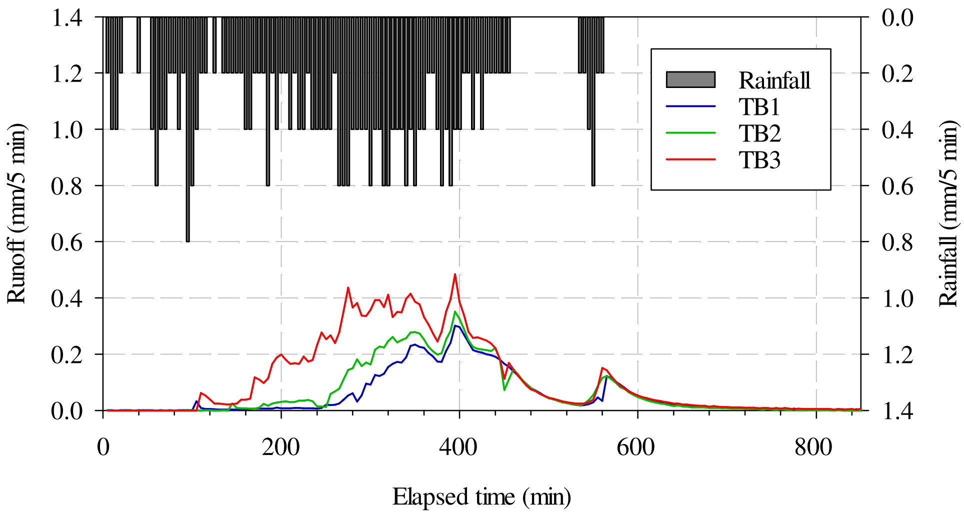

Figure 4. Hydrographs and hyetograph for the 6 September 2010 event for TB1 (HLS – Sedum), TB2 (SCS – Sedum) and TB3 (LECA – Sedum).

CONCLUSIONS

This paper focuses on a comparative study of extensive green roof performance. The study is supported by data collected from April 2010 to December 2012 at the University of Sheffield, UK, in nine test beds that vary systematically in the substrate characteristics and vegetation treatment. The study focuses on per-event retention performance with the aim of investigating the influence of substrate and vegetation treatment. Three green roof substrates were tested: two commercial substrates manufactured by Alumasc – Heather with Lavender (HLS) and Sedum Carpet (SCS) Substrate were considered alongside a Lightweight

Expanded Clay Aggregate (LECA)-based substrate. Three vegetation treatments have been tested: sedum, a meadow flower mixture and a no vegetation option. Retention performance varied depending on the initial water content within the substrate and the characteristics of the rainfall event. Consistent behaviour was observed among the tested green roof configurations for per event retention. Greater retention was associated with HLS and SCS substrates when compared with LECA. Vegetated configurations showed consistently higher retention and sedum vegetation resulted in higher retention performance than meadow flower. This was particularly evident on the LECA substrate. Compared with retention, differences in detention among the test beds were observed to be less significant.

It is clear that per-event retention, while important, especially for events considered 'significant' (i.e. RP>1 year), does not provide an exhaustive characterisation of the performance of a green roof. The described monitoring programme at the University of Sheffield is in progress, with the intention of investigating long-term performance and potential changes due to ageing.

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