# Potential of retrofitting Sustainable Urban Drainage systems using an integrated Geographical Information System-Remote Sensing based approach

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**Key Words**

**Sustainable Urban Drainage; Retrofitting; LiDAR, Terrestrial Laser Scan; flood mapping; Hull**

**Abstract**

Flooding is a major problem in urban areas worldwide. Methodologies that can rapidly assess the scale and identify the reasons causing these flooding events at minimal cost are urgently required. This study has used the City of Kingston-upon-Hull to evaluate the capability of an integrated remote sensing and geographical information system based approach to provide the critical information on the spatial extent of flooding and flood water volumes and overcome the limitations in current monitoring based on ground-based visual mapping and household flooding surveys. Airborne and Terrestrial LiDAR datasets were combined with digital aerial photography, flood assessment surveys, and maps of housing, infrastructure and the sewer network. The integration of these datasets provided an enhanced understanding of the sources and pathways of the flood water runoff, accurate quantification of the water volumes associated with each flooding event and the identification of the optimum locations and size of potential retrofit Sustainable Urban Drainage systems.

## Introduction

Flooding is a major problem in urban areas worldwide with consequent severe economic impacts. In the United Kingdom over 2 million properties are located in floodplains, with an estimated 200,000 of these being classified as at risk because they do not have protection against a 1-in-75 year flood event (Evans et al., 2004). The majority of these properties are in urban areas.

Flood risk managers and decision-makers often face the challenging tasks of designing effective mitigation and adaption strategies in response to low-frequency and unexpected urban flooding arising from extreme storm events, during which the combination of surface water runoff and storm sewer surcharge are the two major sources of inundation. Storm sewer flooding is due to the surcharge of excess water that cannot be drained by the sewer system and is therefore usually localised (Yu and Coulthard, 2015). A significant amount of research into the modelling of storm sewer induced urban flooding has been carried out recently (Yu and Coulthard, 2015) with the accuracy of the modelling dependent on a number of factors including (i) the accuracy of the topography; (ii) inflow to the drainage inlets; (iii) the geometries of the storm sewer pipes and (iv) the direct surface runoff. In many cities the level of information required to fully implement highly accurate urban drainage models are not available. The complexity of the ground topography, due to man-made features, and the interaction of flows with the built environment makes flood modelling in urban areas highly complex and difficult to implement on an operational basis (Mason et al., 2007).

There is therefore an urgent requirement for methodologies that can quantify the scale and identify the reasons causing these urban flooding events that can be implemented quickly and at minimal cost. Once local authorities have an understanding of the causes and the scale of these events they can evaluate the feasibility of implementing mitigation strategies to prevent future flooding events. Retrofit Sustainable Urban Drainage systems (SuDS) offers a potential approach to meet the requirements of flood defence and in addition provide a methodology for sustainable urban drainage (Carter et., 2015; Charlesworth and Warwick, 2011; Dickie et al., 2010; Lamond et al., 2015; Moore and Hunt, 2012; Scholz and Uzomah, 2013 and Woods-Ballard et al., 2007).

SuDS are widely used in Europe and in the US to manage surface water runoff within urban areas. Increasingly SuDS design is incorporated into new developments (Voskamp et al., 2015; Mak *et al.*, 2017). The key objective of SUDS is to route runoff away from homes and businesses and create storage capacity either above or within the ground. SuDS designs often include porous driveways, swales on the road-side or detention basins. Vegetation is also used to encourage loss of water back to the atmosphere through evapotranspiration and to clean up contaminated runoff. In addition to reducing flood risk, SuDS can also deliver water quality and habitat improvements. In older housing developments and industrial sites, retrofit SuDS can be used to reduce flood risk. The design and implementation of retrofit SuDS is receiving increased interest (Sniffer, 2006).

In this study we evaluate the potential of an integrated Geographical Information System (GIS) and Remote Sensing approach to quantify the spatial extent and volumetric scale of flood events, at the city scale, to assist the planning and implementation of retrofit SuDs and subsequently test the feasibility of applying various SuDS measures to mitigate the effects.

## Study Area

The city of Kingston upon Hull (hereafter Hull) is located on the River Hull at its junction with the Humber estuary. The terrain of the city itself is low-lying, with ground elevation ranging from between 2 and 4 m AOD (Coulthard et al, 2007). The mean sea level in the East coast of the UK is above AOD and the Humber estuary experiences a tidal range of c. 6m. Therefore, over 90% of the city is below the high tide level. Until the mid 1960s, a system of open drains and tidally operated gates drained the city, but these were replaced with a combined sewage and drainage system evacuated by three large pumping stations. As a result, the drainage system for the city of Hull is entirely pumped (Coulthard and Frostick, 2010). Hull is protected from fluvial flooding from the River Hull by levees that were built to withstand a 1 in 100-year event, and from marine/tidal flooding through a levee upon the banks of the Humber and a tidal barrage (Coulthard and Frostick, 2010).

In 2007, the city experienced widespread flooding from a pluvial event after rain fell for more than 12 hours on the 25th of June with a total of 110 mm of rainfall (Coulthard and Frostick, 2010). The major cause of the flooding was surface water runoff both locally in the urban area and through the rural lands surrounding the city. Hull has a storm sewer system with a design standard of 1 in 30 years (Coulthard et al., 2007). However, due to the sheer magnitude of the 2007 event, although fully functioning during the event, the storm sewer system was overwhelmed and unable to drain the excess surface runoff. Serious pluvial flooding occurred in a number of locations in Hull during 2007, that affected 8600 homes and 1300 businesses. There have been recurring issues with pluvial flooding throughout Hull since 2007, such as in 2014, but not on the scale of the 2007 event.

A number of locations in and around the city of Hull were considered to evaluate the proposed methodology. In consultation with Hull City Council the Sutton area of Hull, Figure1, located in the north of Hull was selected because of the area's accessibility, land cover, topographic character and history of recent, frequent flooding.

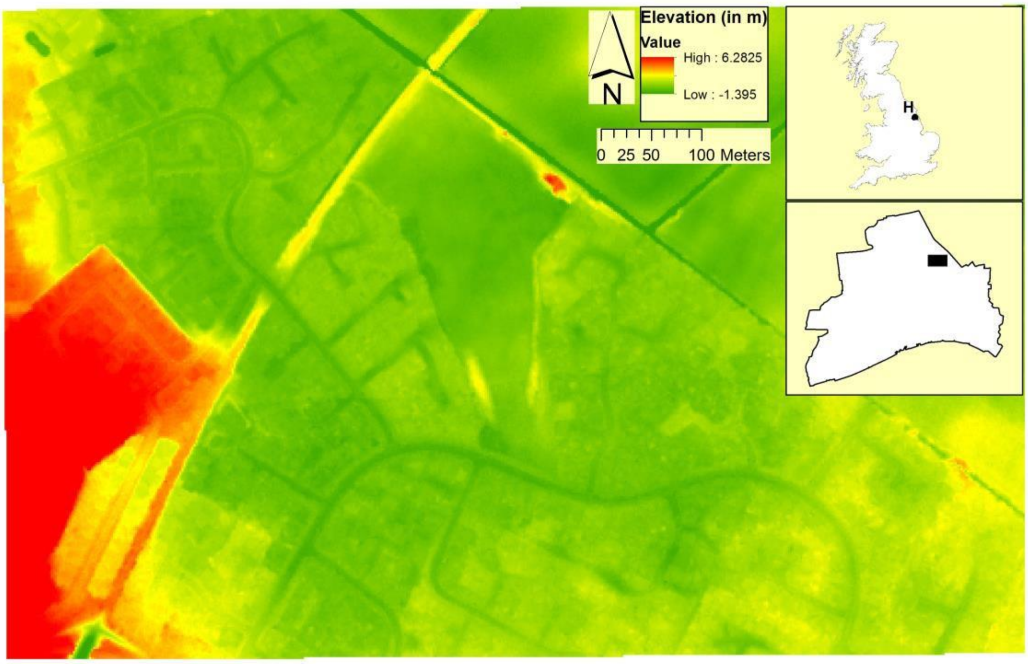


Figure 1: Location of study area (inset maps show UK (H) and Kingston-upon-Hull) and elevation map (in m AOD).

**Flood Volumetric Analysis**

An understanding of groundwater-surface water interaction during extreme conditions is a prerequisite for the characterisation of flood modelling. Developing this requires a wide range of quantitative and qualitative data such as topography, aerial photography, underground drainage, flood records, hydrological and meterological data. These datasets were collected for the Sutton area of the City of Hull from 2007 to 2015 and were used to quantify flood volumes.

**Data collection: topographic**

The lack of topographic data of sufficiently high resolution and accuracy has been a major problem hampering research into urban flood modelling. Airborne scanning laser altimetry (LiDAR) data have now become available at sub-metre spatial resolution and with cm vertical accuracy providing highly resolved digital surface models (DSMs) of the urban environment (Mason et al., 2007). Airborne LiDAR data offers an approach to overcome the limitation in accuracy in urban topographic models and provide the necessary spatial resolution and vertical accuracy.

The airborne LiDAR was acquired by the Environment Agency (EA) after the 2007 flood event. The LiDAR data was provided in two data types: (1) Digital Elevation Model (DEM) and (2) Digital Surface

Model (DSM). The DEM is the "bald earth" topographic surface where any surface features (e.g. trees) are filtered out, whereas the DSM includes all surface features. The data is acquired as a point cloud however the EA provided the DTM and DSM data of the City of Hull in raster format at a spatial resolution of $2m^2$ (Figure 2). There are a number of locations within the study area with elevations below or very near AOD. Location A is -0.3 m AOD; Location B varies between 0.05 and 0.1 m AOD with Location C having elevations of between -0.08 and 0.07 m AOD. There are a number of other locations with low elevations e.g Location D (-0.01 m AOD); Location E (elevations -0.17-0.08 m AOD), and in what is thought to be a paleo-channel in a wooded strip along the west side of the playing fields (F), where elevations are as low as -0.13 m AOD. There is high spatial variability in the slope angle caused by minor topographic features such as kerbs with a few marked slopes associated with banks near railways and ditches.

The key parameter to be derived from the airborne LiDAR is the topography of the land surface that controls the flow direction and accumulation of surface runoff. Resolving the land surface elevation directly from airborne LiDAR is complicated considerably by the effects of buildings and vegetation on the DEMs derived from the LiDAR point cloud. As the LiDAR data from the EA was provided in raster format removal of the effects of buildings and vegetation could not be carried out at the interpolation stage (Miliaresis and Kokkas, 2007).

Approaches that removed vegetation and buildings from the raster datasets were therefore required. If digital data of the buildings at very high spatial resolution is available, as in this case, then this can be utilised to extract the extent of buildings from the DEMs and DSMs. If these type of datasets are not available then the extent of the buildings needs to be extracted from the LiDAR derived DEM and DSMs directly using an image-based segmentation algorithm (Xiao et al., 2014).

While this study benefited greatly from the availability of relatively recent airborne LiDAR there are a number of situations where airborne LiDAR representative of the current topographic situation might not be available. This might be due to airborne data either never been acquired or having

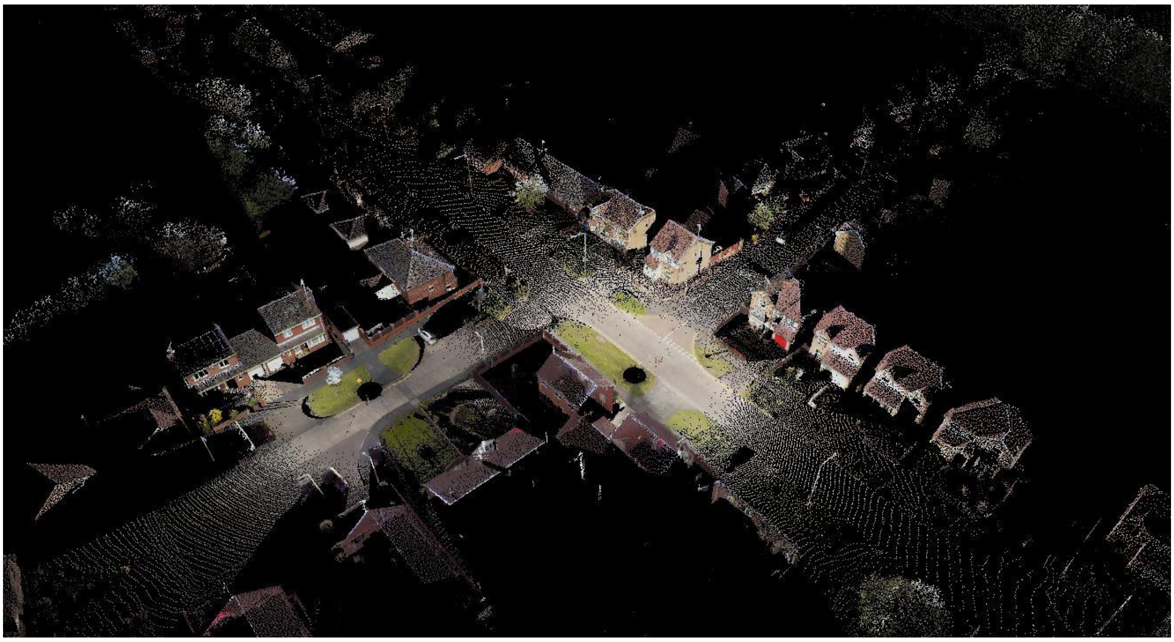


Figure 2. The ground LiDAR data outputs consist of a digital elevation model with colour digital photographs rendered onto the digital elevation model.

been acquired before major recent urban development. In these situations Terrestrial Laser Scanning (TLS) offers a potential low cost, highly flexible solution. The TLS data for this study was acquired in May and June 2015, using a Topcon GLS-2000, over the central part of the study area, along the roads and the open ground, which have been most affected by flooding. The data was collected from six locations where the TLS system was setup. An array of calibration targets was setup to provide very accurate distance correction. A LEICA System 1200 Differential Global Positioning System (dGPS) was used to obtain very accurate location and topographic information on the location of the dGPS base station and the calibration targets. The point clouds were merged using Scanmaster$^{\text{TM}}$ software and georeferenced using post-processed positions of tiepoints. Point clouds were also coloured using digital photographs obtained from a camera built into the scanner, taken coincident with each scan (Figure 2). The TLS scans have a point spacing of 6.3 mm at 10 m range. The combined point cloud was analysed using the ENVI LiDAR$^{\text{TM}}$ analysis software enabling DEMs at particular elevation intervals to be extracted.

The extent of the area studied using the TLS datasets was much smaller than the area analysed using the airborne LiDAR datasets due the time available and the difficulty in gaining access to all the locations that would be required for complete coverage (Figure 3).

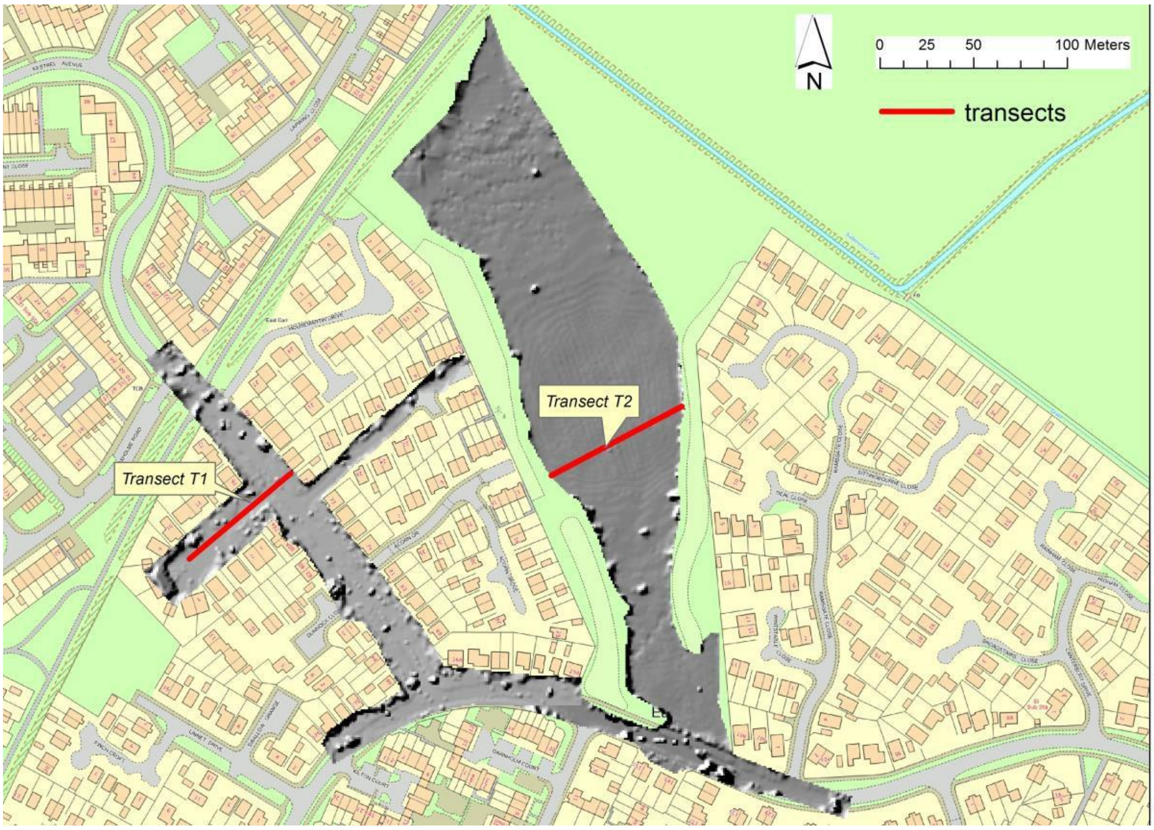


Figure 3: The extent of the TLS scans with location of Transects T1 & T2 marked.

**Data collection: flooding extent**

The extent of the flooding was derived from a number of data sources. The locations of both the roads and the buildings flooded were provided in analogue map format by Hull City Council. The extent of the flooding in the Sutton Study area in 2007 and 2014 were then derived by integrating the locations of both the roads and the buildings flooded and drawing an outline. Aerial photographs acquired during or soon after a flooding event were used to resolve areas of standing or saturated ground. Aerial photographs from 2007 and 2014 have identified that the playing fields area (indicated by F in Figure 4) stores substantial volumes of rainwater run-off during flood events.

The extent of the 2014 flooded area is significantly smaller than, and is enclosed within, the extent of the 2007 flood event (Table 2) suggesting a similar cause/source and pathways for the flood water to propagate. The focus of the flooding events appears to be the central / southern part of the playing field area (Figure 4). There is also evidence of a palaeo river channel along the south west edge of the playing field area (indicated by P in Figure 4).

## Flood Volume Modelling

The methodology employed to carry out the flood volumetric analysis involved mapping out the spatial extent of the flood event then deriving a digital elevation model of the surface of the flooded area and finally calculating the volume of water in the flooded area by subtracting the baseline topography from the surface topography of the flooded area.

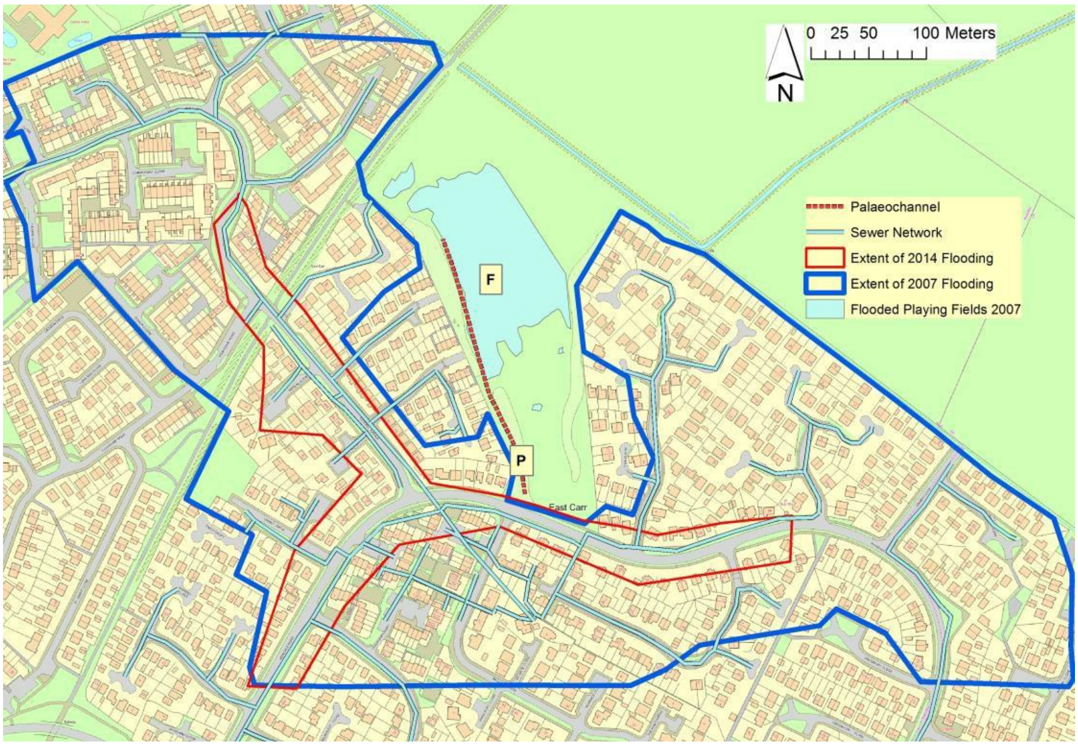
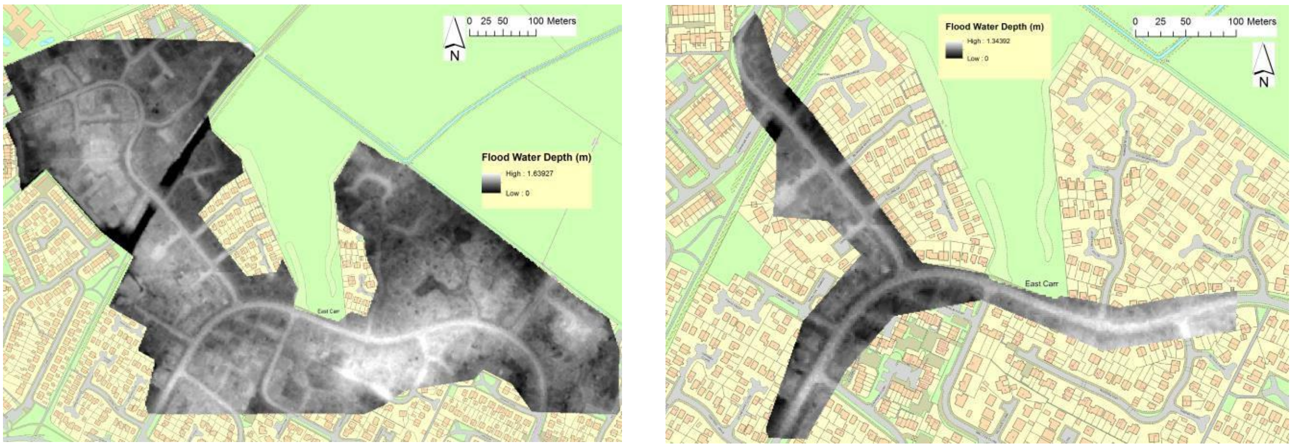


Figure 4 : Extent of flooding in the Sutton Area in 2007 and 2014 with sewer network

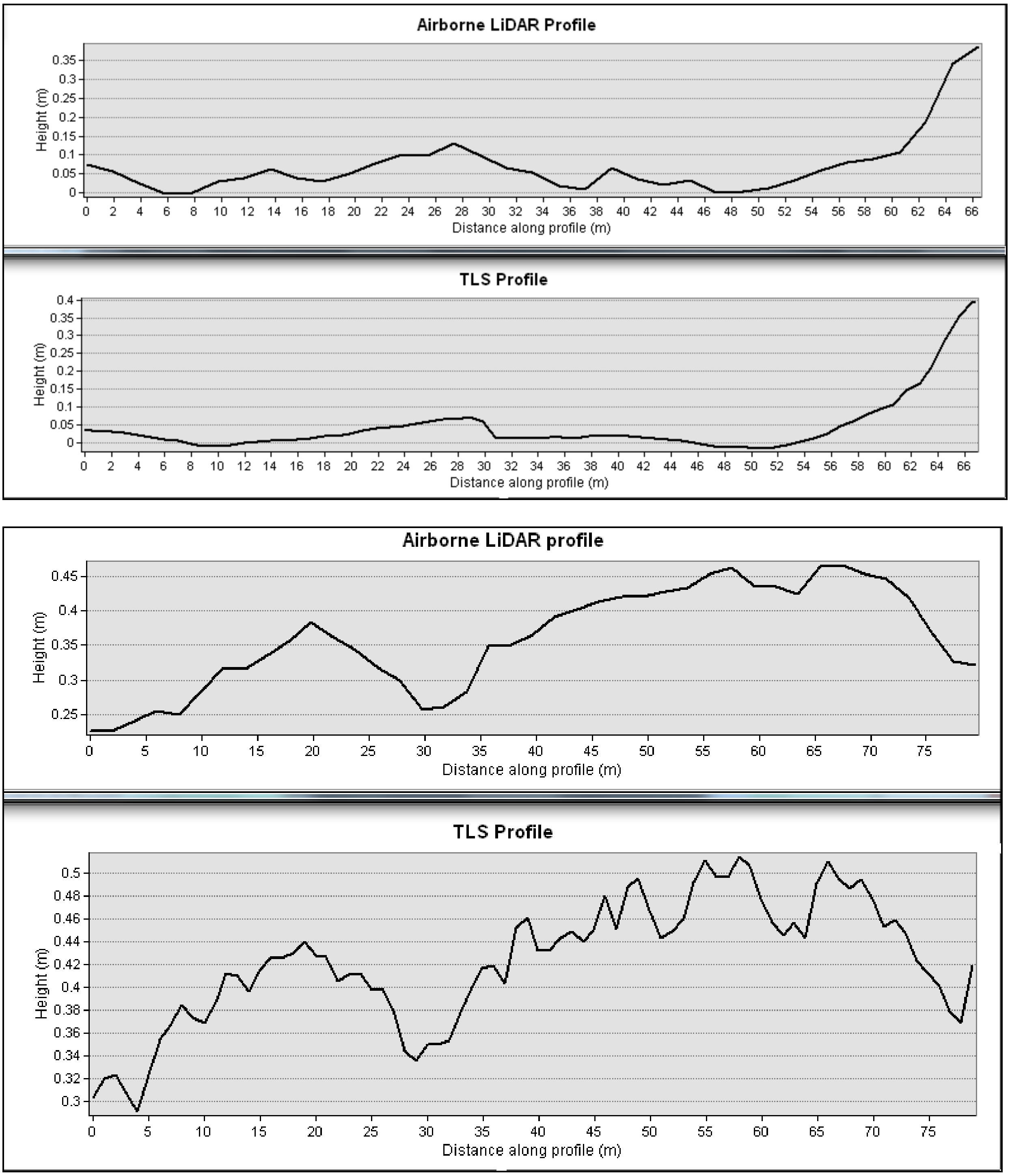
The airborne LiDAR derived DEM was used for the baseline topography for calculation of the flood volumes. The flood water heights along the edges of the flood affected areas for the 2007 and 2014 events were resolved and DEMs of the heights of the flood water level over the entire flood area were generated using a spline interpolation. The area, volume and maximum depth of the flood water related to the 2007 and 2014 events could then be calculated (Table 1) by removing the airborne LiDAR derived DEM from the DEMs of the flood water heights from 2007 and 2014 (Figures 5a and 5b).

| Year | Area ($m^2$) | Volume ($m^3$) | Maximum depth of flood water (m) |
|---|---|---|---|
| **2007** | **66,799** | **30,512** | **1.639** |
| **2014** | **9,507** | **2674** | **1.343** |

**Table 1** : Area, volume and maximum depth of the flood water related to the 2007 and 2014 events.



Figures 5a and 5b: Interpolated Water Depths for the 2007 2014 flood event



Figures 6a and b: Airborne LiDAR and TLS profiles along transects T1 and T2 (Figure 1)

The Airborne LiDAR dataset covered the entire City of Hull whereas the TLS was much more spatially limited. The airborne LiDAR produced very accurate topographic maps and the derived transects did show the important micro-topographic features in Sutton with changes in elevation of 20cm over transects of 75m being resolved. The TLS topographic datasets had a much higher spatial sampling resolution enabling topographic changes and drainage features to be identified more clearly.

To quantify the effect of this difference in topographic accuracy on the volume of flood water topographic transects at two locations (T1 & T2 in Figures 3 and 6) and the difference in the DEMS in the area covered by both the Airborne and TLS were used. The mean height difference in the T1 and T2 transects between the airborne and TLS data was 0.052 m while the mean height difference between the DEMs was 0.065 cm. The TLS dataset provided significantly higher spatial resolution data which provided a very accurate representation of the real surface topography. Combing both the 2007 and 2014 results of flood volumetric modelling the TLS-based DEMs will increase accuracy by 14.6 %. For the 2007 flood event the difference in the volume of the flood waters resolved would be 4,454 $m^3$ out of a total volume measured of 30,512 $m^3$ while for the 2014 flood event there would be a difference of 390 $m^3$ out of a total volume measured of 2,674 $m^3$ if the level of topographic accuracy provided by the TLS was available for the entire study area.

## Discussion

The estimates of the flood water volumes associated with each flood event provides the basis for analysis of options for retrofit SuDs. In this study the 2007 and 2014 floods produced approximately 30,512 and 2,674 $m^3$ respectively. The 2007 flood is characterised as a 1-in-150 year event (Coulthard and Frostick, 2010) whereas the 2014 scale flooding occurs on a 2-year recurrence cycle.

An enhanced understanding of the sources and pathways of the flood water runoff enables identification of the optimum locations and size of potential retrofit SuDs. The lack of any sewer network in the middle section of the study area (Figure 4) is providing no outlet for water accumulating in the middle section of the study area which is demonstrated by the large amount of standing water present after the 2007 flood event. The micro topography of the middle section of the study area introduces an additional problem as it slopes quite significantly towards the west diverting any runoff down to a paleo-channel feature that runs north-to-south along the western side of the playing fields (Figure 4) suggesting connectivity between the lower lying part of the playing fields and adjacent housing and roads on the western and southern edges.

With the constraints of implementing major engineering projects within an urban environment and a very limited budget the likelihood is that a SuDS system capable of coping with flood water volumes associated with the 2 year repeat events is significantly more likely to be implemented by Hull City Council. A relatively low-cost option with limited visual impact which could accommodate the 2,700 $m^3$ flood water volumes associated with the 2-year recurrence events would be the deepening of the palaeo channel along a length of 270m, with a width of 10m and to a depth of 1m (Figure 7). This would provide a water accumulation volume sufficient to hold the flood water until it could be safely released into the sewer network. Retrofitting such a SUDS would also provide an opportunity to introduce increasingly popular vegetated SuDS techniques which to reversing habitat fragmentation by acting as wildlife corridors and buffer zones to connect and protect separated and isolated habitats (Mak et al., 2017) with only limited visual impact on the landscape. To accommodate the 30,000 $m^3$ flood water volume associated with the 2007 event would require that the palaeochannel be made significantly wider (30m) and deeper (3m), (Figure 7).

## Conclusion

The results of this study have demonstrated that an integrated Geographical Information System-Remote Sensing based approach has the ability to quantify the scale of urban flood events, enhance

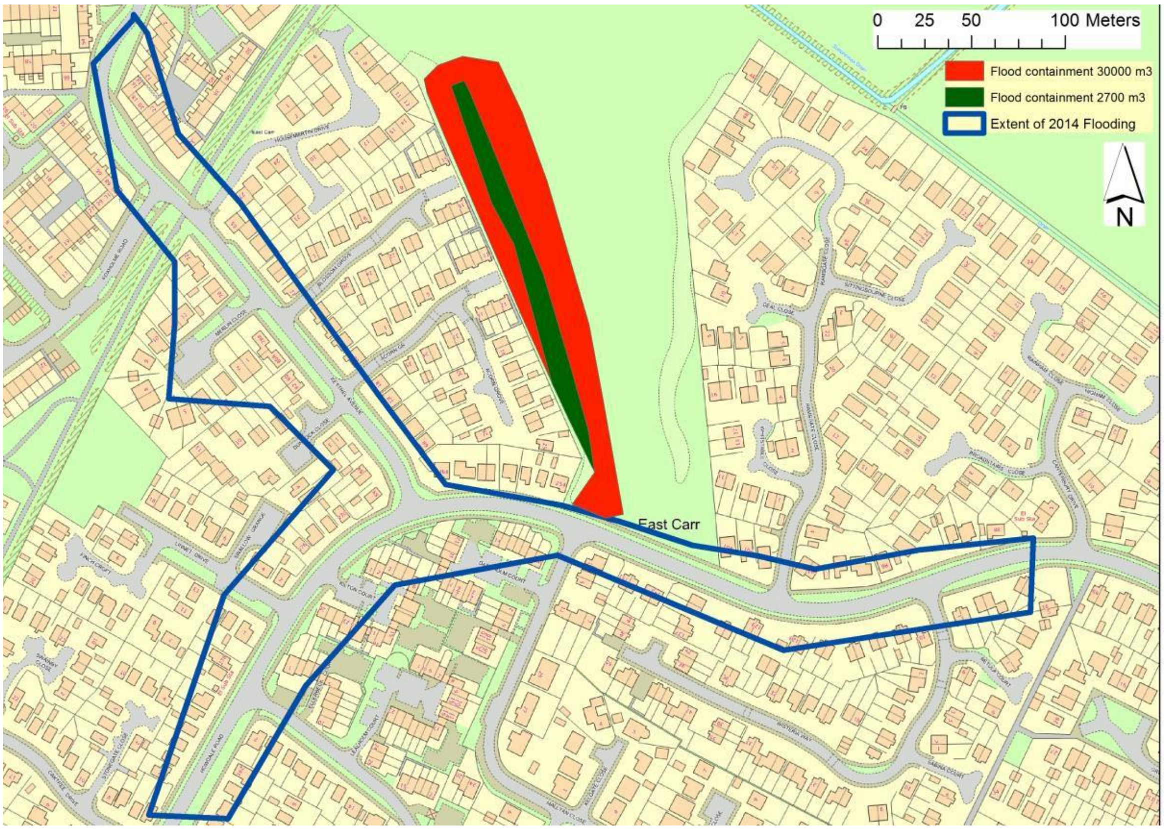


Figure 7: Location of potential retrofit flood water containment facilities (2700 and 30,000 $m^3$ volume) with extent of 2014 flooding.

understanding of the causes of these flood events and assess the options for retrofitting SuDS.

The results of the Airborne LiDAR have been demonstrated to be very accurate and suitable for deriving accurate estimates of the spatial extent and the volume of water associated with the 2007 and 2014 flood events in Sutton. The TLS based surveys produce much higher spatial resolution and more accurate topographic surfaces than the airborne LiDAR but take considerably longer to acquire and require complete access to the locality in order to acquire the data. While the TLS based approach would be too time-consuming and costly for city scale mapping it could supplement the airborne LiDAR dataset at locations where the topography had been changed significantly since the acquisition of the airborne LiDAR dataset, where it had proved impossible to acquire accurate airborne LiDAR datasets, where the spatial extent of the survey area was relatively limited or where a very accurate estimate of the flood water volumes was required.

Integration of the LiDAR derived DEM and DSMs with housing, sewer and other spatial datasets enables identification of locations where flooding events are likely to originate. This approach also enable the spatial extent of the areas affected by the flooding and the volume of water causing the flooding to be resolved.

While airborne LiDAR provides a methodology for acquiring complete, accurate surface topographic datasets over city scales it is costly and is often difficult to arrange overflights quickly enough to map flood events. UAV-based imaging approaches, such as LiDAR and digital photogrammetric cameras, offer many significant advantages including their relatively low cost, rapid deployability and capability to provide very accurate information on the extent of flooding at landscape scales. UAV-based approaches can map flooding extent directly without having to contact households to register their flood damage which often leads to significantly underreported because of the implications for obtaining future home insurance cover.

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